iCV TA&K
Technology Advisory
& Knowledgebase

2024

Global Quantum Computing Industry Development Prospect

February 2024

Quantum Annual Series Report

Foreward

Pioneering the quantum era, shaping the future of the industry collectively.

In 2023, we observed numerous advancements and breakthroughs in the global quantum computing arena, propelling humanity into an era of computation unparalleled in history.

Undoubtedly, we saw the thriving evolution of large AI models, with quantum computing quietly playing a role in the backdrop in 2023. Quantum computing has the capacity to expedite and refine the computational processes of large-scale models. While it may not yet confer monumental capabilities, it introduces fresh perspectives and tools for addressing intricate problems, showcasing vast potential for interdisciplinary integration and innovation.

Beginning this year, there has been a noticeable shift in the focus of our report. Whereas we previously placed a significant emphasis on technological advancements in universities and research institutes, considering them the primary drivers of progress in quantum computing, we are now witnessing an increasing involvement of commercial organizations in the quantum computing domain. Consequently, we have reverted to our initial intent, placing primary emphasis on the advancements made by businesses and industries.

Regarding quantum chip technology, diverse development has emerged as a pivotal driver for industry competition. Countries are heavily investing in supporting various technological routes, including superconducting, ion traps, photons, neutral atoms, and semiconductors, resulting in distinctive developmental advantages. The growing maturity of quantum computing cloud platforms is progressively reducing the threshold and cost of quantum computing, offering users more accessible services. This advancement will empower a broader range of industries and fields to harness the full potential of quantum computing, continually expanding its application scope and influence.

In the realm of quantum chip technology, diverse development has emerged as a crucial catalyst for industry competition. Nations have dedicated substantial support to various technological pathways, including superconducting, ion traps, photons, neutral atoms, and semiconductors, establishing unique developmental advantages. The growing maturity of quantum computing cloud platforms is progressively diminishing the threshold and cost of quantum computing, delivering more user-friendly services. This advancement will empower a broader array of industries and fields to fully harness the capabilities of quantum computing, continually broadening its application scope and influence.

Nevertheless, we must confront the reality of a relative downturn in financing activities within the quantum computing industry in 2023. In the face of unfavorable macroeconomic conditions, financing transactions have dwindled, and international competition in the quantum field is intensifying.

Finally, as we stand at this challenging yet opportunistic juncture, we maintain confidence and optimism for the industrial development of quantum computing in 2024. Let us come together and witness the flourishing growth of the quantum computing industry.

ICV Frontier Technology Consulting Director, Senior Vice President

Jude Green

Declaration

01 The content and viewpoints presented in this report strive to be independent and objective. The information or opinions expressed herein do not constitute investment advice; therefore, please exercise caution when referring to them.

02 This report aims to summarize and present significant events that occurred in the global quantum sub-sector technology and industry during the year 2023. It relies primarily on publicly available data and information, as well as the compilation of publicly accessible data. Additionally, it combines the global economic development status at the time of publication to provide predictive descriptions of potential short-term impacts.

03 This report focuses on relevant content within the quantum sub-sector industry that occurred between January 1, 2023, and December 31, 2023, based on local time reporting and the time of initial event publication. Reports of the same content or highly similar content, if spanning across different years, are not considered significant events occurring in 2023.

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Acknowledgements

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XANADU	华翊量子	本源量子 ORIGIN QUANTUM
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Microsoft	SPINQ 量旋科技	中电信量子集团 CHINA TELECOM QUANTUM GROUP
QUDOOR 启科量子	中科酷原 CAS COLD ATOM	rigetti
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atom computing	Infleqtion	PsiQuantum
PASQAL	ZWDX 中微达信	Q-CTRL

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Overview of Industrial Development in 2023

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Overview of Industrial Development in 2023

01 Quantum computing chips and software algorithms are developing vigorously

This section selects the ten most important advancements in the field of quantum computing in 2023, based on criteria such as technological innovation, practical benefits, and leadership in scientific research. These advancements include first successful applications, effective experimental verifications, novel architecture designs, parameter optimization, practical utility enhancements, adoption rates and impact, as well as significant scientific breakthroughs and extensive media coverage. The overall progress is presented in two main directions: quantum computing chips and software algorithms/cloud platforms.

Figure: Ten Global Quantum Computing Advancements in 2023

Quantum Computing Chips

The number of qubits and quantum volume	Coherence time	Quantum Chip Architecture
Quantinuum's H-Series quantum computer has set three consecutive records for quantum volume (QV): 217, 218, and 219, marking the highest reported quantum volume to date. IBM has released its first quantum computing processor, Condor, with over 1000 qubits, boasting 1,121 qubits. It is based on the previous flagship product Eagle chip architecture.	The University of Maryland has successfully created flux quantum bits (qubits) on a sapphire chip, achieving a coherence time of 1.48 milliseconds, the current highest record, with a fidelity of 99.991%.	IBM has introduced a modular quantum computer that combines scalable low-temperature infrastructure with classical servers, enabling a supercomputing architecture for computation. Building on this architecture, IBM has released the 133-qubit scalable chip, Heron.
QUANTINUUM / IBM Q	University of Maryland	IBM Q

Transmission and Storage	Quantum Error Correction
Sussex University collaborates with Universal Quantum to achieve rapid and reliable transmission between microchip modules, achieving a success rate of up to 99.999993% and a connection speed of 2424 times per second, setting the current highest record.	Four research teams from the Shenzhen Quantum Research Institute, Tsinghua University, Fuzhou University, and the Southern University of Science and Technology used custom frequency comb pulses to manipulate auxiliary qubits, improving the efficiency of quantum error correction by exceeding the break-even point by about 16%. QuEra achieved 48 logical qubits capable of detecting and correcting any errors that occur during entangled logic gate operations.
University of Sussex / Universal Quantum	Shenzhen International Quantum Academy / Tsinghua University / Fuzhou University / Southern University of Science and Technology / QuEra Computing Inc.

Software Algorithm Cloud Platform

Hybrid Computing and Large Models	Fault-Tolerant Algorithms	Quantum Cloud Platform
NVIDIA has released the DGX Quantum system, which combines CUDA Quantum and H100 NVL technologies, providing an acceleration platform for generative AI large models like GPT through quantum-classical hybrid computing.	Quantinuum has implemented fault-tolerant algorithms using logical qubits on its H1 quantum computer. They calculated the ground-state energy of a hydrogen molecule using "random quantum phase estimation" technique.	Q-CTRL's error suppression technology, known as Q-CTRL Embedded, has been integrated into the IBM Quantum Cloud Services. Now, users can simply toggle a switch to reduce error rates.
NVIDIA	QUANTINUUM	Q-CTRL

02 The integration of high-level computing and quantum computing has realized

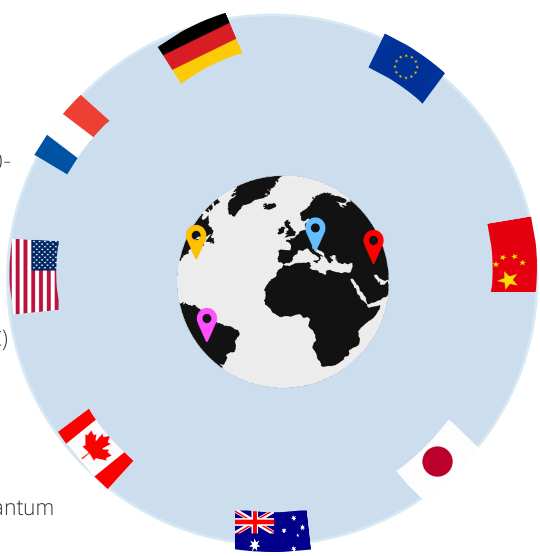
In 2023, Quantum-superfusion has transitioned from theory to initial practical implementation and shows signs of deepening development. Quantum-superfusion primarily relies on cloud platforms to provide computational power externally, serving as a complementary form of computing to traditional supercomputing centers. It offers diverse, flexible, and efficient computational resources, empowering various industries with stronger computing capabilities and facilitating broader exploration of the potential value of quantum computing.However, challenges such as hardware stability and algorithm optimization persist in the convergence of quantum computing and supercomputing. To achieve quantum-superfusion, further exploration and experimentation are needed across various dimensions, including compatibility and integration, software and algorithms, and resource management and scheduling.

Figure: Events in the Advancement of Quantum Superfusion in 2023

Germany has initiated the Euro-Q-Exa quantum computer tender, with the system to be hosted and operated by the Leibniz Supercomputing Centre (LRZ) and integrated into the SuperMUC-NG supercomputer.

Under the European High Performance Computing Joint Undertaking (EuroHPC JU), the High Performance Computing and Quantum Simulation (HPCQS) project enables users to validate their HPC-QC fusion applications through nodes in each member state.

In France's Hybrid Quantum Initiative (HQI), the French national high-performance computing center (GENCI) has purchased Pasqal's 100-qubit quantum computer.



Origin Quantum has partnered with the Shanghai Supercomputing Center to establish the Yangtze River Delta Quantum Computing Collaborative Innovation Center.

NVIDIA collaborates with Germany's Jülich Supercomputing Centre (JSC) and ParTec to establish a laboratory for developing classical-quantum hybrid supercomputers.

China Telecom has launched the "Tianyan" Quantum Computing Cloud Platform, based on a super-quantum hybrid cloud architecture, achieving the fusion of "Tianyi Cloud" supercomputing capabilities with 176-qubit superconducting quantum computing capabilities.

The Quebec Digital and Quantum Innovation Platform (PINQ²) inaugurates the IBM Q System One, enabling PINQ² to offer hybrid computing methodologies through the high-performance computing center established in Sherbrooke.

The Pawsey Supercomputing Research Centre in Australia and Xanadu, a Canadian company, have signed a memorandum of understanding to provide researchers with state-of-the-art hybrid computing capabilities.

The RIKEN Institute for Physical and Chemical Research plans to integrate with the Fugaku Supercomputer around 2025.

Figure: Global Computational Centers and Related Laboratories Integrating Existing Quantum Computers with Classical Computers

CEA and CNRS
It integrates quantum computing capabilities into the Joliot-Curie supercomputer using the Atos Quantum Learning Machine (QLM).

CESGA
It constructs a cluster system based on the Fujitsu 34-qubit quantum computing simulator on the "PRIMEHPC FX700" supercomputer.

NCSA
It integrated NVIDIA's CUDA Quantum

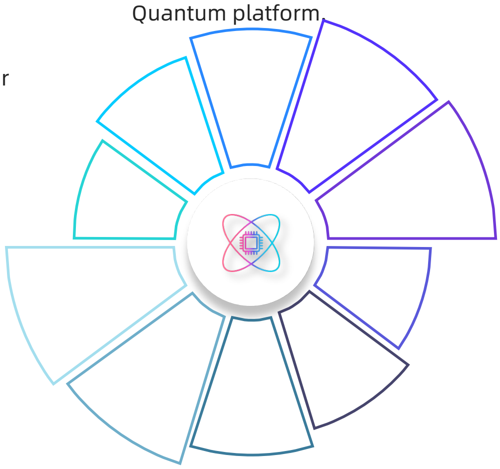
ORNL
It applies the Atos Quantum Learning Machine (QLM) and participates in the CUDA Quantum testing program.

Argonne National Laboratory in the United States
It applies the Atos Quantum Learning Machine (QLM).

Brazil SENAI-CIMATEC
It integrates quantum computing capabilities into the supercomputer using the Atos Quantum Learning Machine (QLM).

Indian Institute of Advanced Computing
It has reached a cooperation agreement with Atos to share the results of the Quantum Learning Machine (QLM).

IT CSC in Finland
Their VTT's 5-qubit superconducting quantum computer HELMI ("Pearl") is connected to the European supercomputer LUMI ("Snow") and utilizes the NVIDIA CUDA Quantum platform.



Pawsey Supercomputing Centre in Australia
It pairs quantum accelerators with the HPE Cray Ex supercomputer Setonix, showcasing and testing hybrid models of quantum and classical computing.

Jülich Supercomputing Centre in Germany
They have the most tightly integrated modular supercomputing architecture concept

Leibniz Supercomputing Centre in Germany
They collaborate with Atos and HQS to research the integration between HPC and QC.

Quantum Computing Engineering Research Center in Anhui Province, China
They decompose, schedule, and allocate computing tasks between quantum computers and supercomputers.

National Supercomputing Centers in Zhengzhou and Shanghai, China
They collaborate with Origin Quantum and China Mobile (Suzhou) Software to jointly build an advanced quantum-superfusion computing platform, providing quantum-superfusion cloud integration services.

National Institute of Advanced Industrial Science and Technology (AIST) in Japan
They are partners with NVIDIA and integrate CUDA Quantum into their supercomputing platform.

Institute for Molecular Science in Japan
They integrate Fujitsu's quantum computer with the "Fugaku" supercomputer.

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The integration of global supercomputing centers with quantum computers is accelerating. Various types and scales of supercomputing centers, ranging from large national research institutions to small enterprise laboratories, are actively exploring integration with quantum computers. This integration not only enhances computational capabilities and efficiency but also broadens application areas. For instance, complex problems in fields such as bioinformatics, physics simulation, and financial engineering can be solved more accurately and efficiently through the combination of supercomputing and quantum computing. Furthermore, this integration drives the development of new algorithms and applications, such as quantum machine learning and quantum optimization, demonstrating the immense potential of combining supercomputing and quantum computing.

The HPC+QC hybrid cluster mode is an important direction for the future of high-performance computing. This mode integrates traditional supercomputers and quantum computing resources, making high-performance computing more flexible and efficient. In this mode, more complex and high-precision calculations and simulations can be achieved, promoting the development of scientific research, engineering technology, and industrial innovation. The advantage of this mode lies in its ability to fully utilize the powerful capabilities of traditional supercomputers in handling classical problems while leveraging the unique advantages of quantum computers in handling quantum problems. In the future, seamless integration of supercomputers and quantum computers can be achieved, complementing each other's strengths and providing robust computational support for solving complex problems. With technological advancements and application expansion, it is foreseeable that the HPC+QC hybrid cluster mode will play an increasingly important role in the future computing landscape.

03 Major telecommunication operators are competing to deploy quantum computing

In 2023, major telecommunications operators worldwide have significantly increased their investment and research efforts in the field of quantum computing. They have conducted in-depth research on various types of quantum computers such as superconducting and ion trap, reflecting the recognition of the potential value of quantum technology in enhancing network performance and strengthening secure communication. Moreover, these telecommunications operators' involvement in the quantum computing field goes beyond research, as they actively seek technical and business collaborations.

Figure: Global Telecommunications Operators Developing Quantum Computing

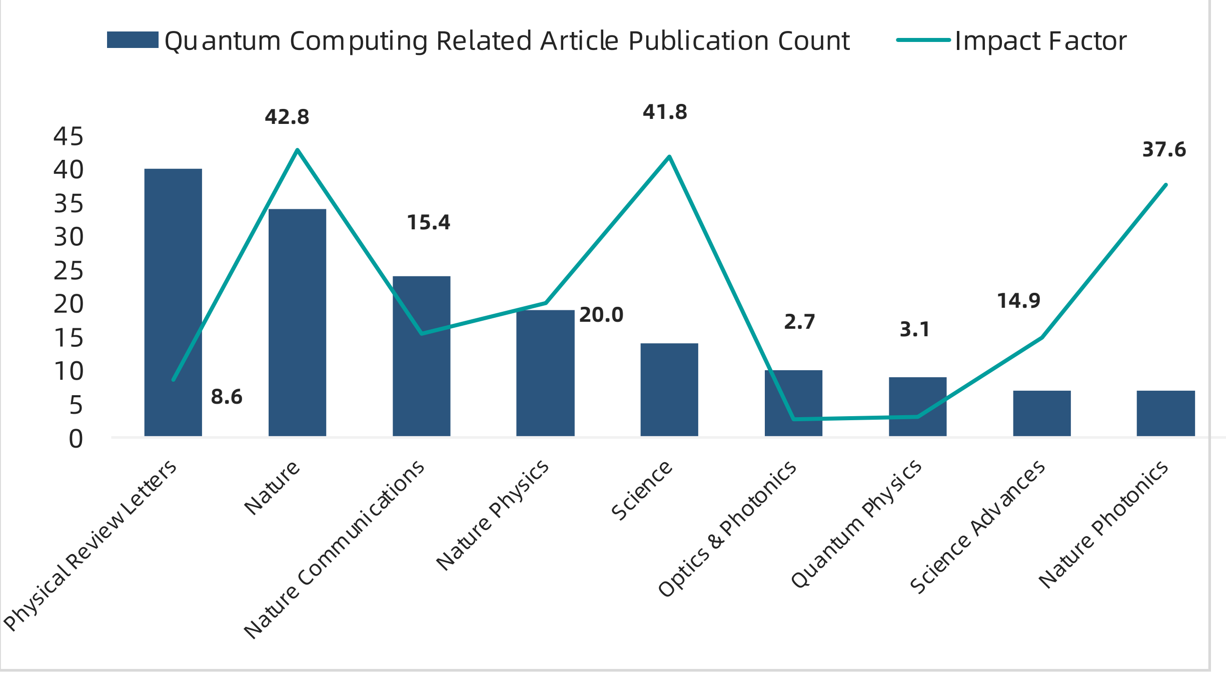
Country	Company	Basic information
China	中国电信 CHINA TELECOM	Launched the "Tianyan" quantum computing cloud platform, which possesses "quantum supremacy" capabilities and integrates supercomputing capabilities.*
	中国移动 China Mobile	Team up with China Electronics Technology Group Corporation (CETC), we have launched the largest-scale quantum computing cloud platform in China. Introducing the "Wuyue" quantum computing cloud platform.*
Japan	NTT	Collaborate with the National Institute of Advanced Industrial Science and Technology (AIST), Fujitsu, and other research partners to successfully develop Japan's first superconducting quantum computer.*
	SoftBank	Join the Quantum Innovation Initiative Consortium operated by the University of Tokyo and validating telecommunications use cases using IBM quantum computers.*
South Korea	LG U+	Collaborate with the Korea Advanced Institute of Science and Technology (KAIST) and Qunova Computing to optimize 6G low-orbit satellite networks using D-Wave quantum computers.*
Australia	Telstra	Currently investing in the field of quantum computing through SQC (Quantum Computing Company), but not conducting independent research.*
Germany	Deutsche Telekom	A wholly-owned subsidiary of DT launches its quantum-as-a-service product, providing access to quantum computing expertise and IBM quantum computing resources.*
UK	BT	Explore how quantum computers can benefit applications such as circuit switching, packet routing, signal processing, and antenna beam control.*
	vodafone	Collaborate with IBM to explore quantum computing technology and quantum secure cryptography, helping to validate and advance potential quantum use cases in telecommunications.
Italy	TIM GRUPPO TIM	Utilize quantum computing to optimize radio unit planning and execute quadratic unconstrained binary optimization algorithms on D-Wave quantum computers.

Note: * Indicates Progress in 2023

The global telecommunications operators are showing a trend of cross-border cooperation and open sharing in the field of quantum computing, aiming to maintain a leading position in future technology competition. Currently, telecommunications operators worldwide are building quantum computing ecosystems, promoting active participation of professionals and enthusiasts in the quantum field through open cloud platforms and attracting enthusiasts to participate. This openness and ecosystem construction help drive further development of the entire quantum computing field and also indicate that quantum computing technology is expected to play an increasingly important role in the telecommunications sector, bringing new breakthroughs in network performance, communication security, and other aspects.

04 Active research is yielding frequent scientific achievements

Figure: Publications in Top Journals Related to Quantum Computing in 2023



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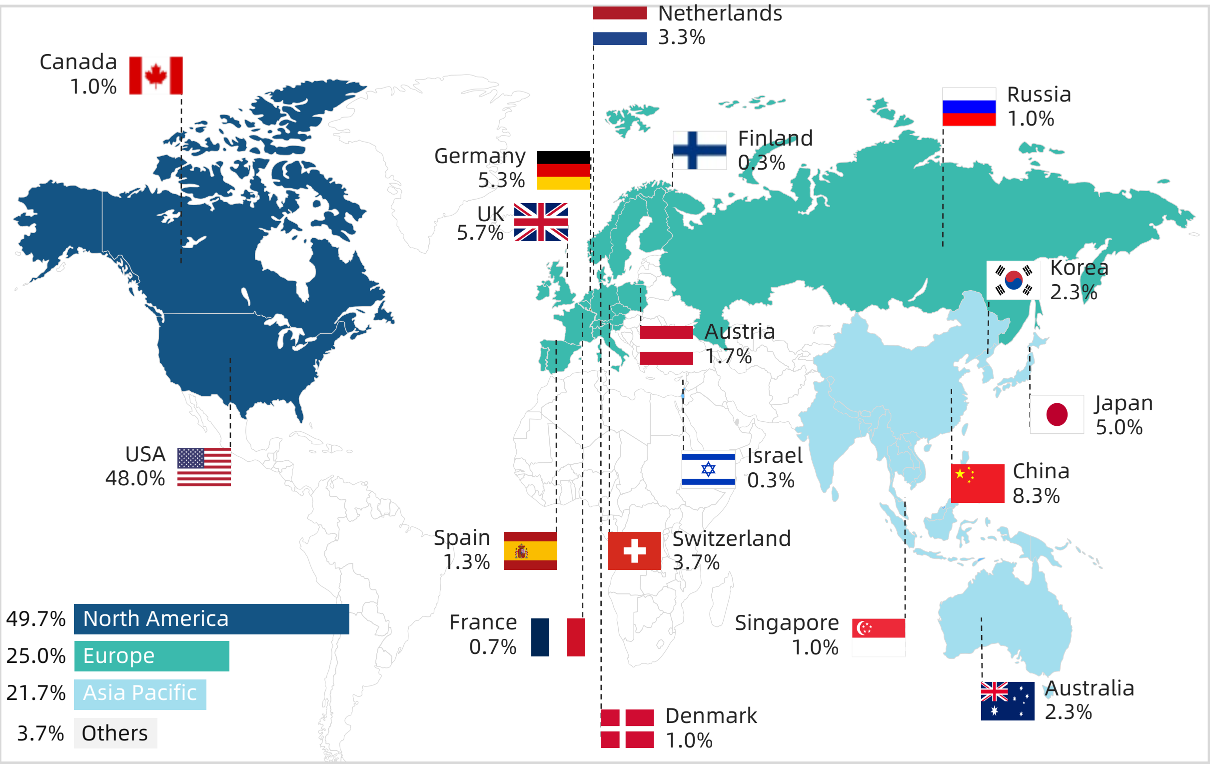
Note: Only the top ten journals by publication count are presented here. For more details, please refer to Appendices.

The figure illustrates the number of articles related to quantum computing published in major journals during the first half of 2023, along with their corresponding impact factors (data sourced from the latest SCI impact factors for 2023). Analyzing and comparing these data can provide an evaluation of the academic contributions and impact of these journals in the field of quantum computing, offering guidance for researchers in selecting suitable journals for publishing their research findings.

There exists a certain relationship between the number of articles published and the impact factor in the field of quantum computing, but it is not absolute. Some journals boast both a high publication count and a high impact factor, signifying substantial academic contributions and widespread influence. Notably, comprehensive journals such as Nature and Science exhibit elevated publication counts and impact factors, primarily attributed to their academic standing, rigorous peer-review processes, and comprehensive coverage of interdisciplinary research.

Conversely, other journals maintain a lower publication count yet sustain a high impact factor. For instance, PRX Quantum, a distinguished journal specializing in quantum physics, exhibits a lower publication count while maintaining a commendable impact factor. Conversely, certain journals with a high publication count may have a relatively low impact factor, owing to factors such as a specific research focus, a smaller audience base, or issues related to peer-review and academic quality.

Figure: Countries of Corresponding Authors Publishing in Top Journals Related to Quantum Computing in 2023



Notes: Data on Quantum Computing Field Publications in the Figure are Sourced from Top Journals such as Nature, Science, Physical Review Letters, etc. See Appendices for Details

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The data on the geographical location of corresponding authors of quantum computing-related articles published in top journals in 2023 provide crucial clues about the participation and influence of different countries and regions in quantum computing research.

From the perspective of the country where the corresponding author's institution is located, the United States leads with a total of 144 articles, accounting for approximately 48% of the total publications. This reflects the international leadership of the United States in most aspects of quantum computing technology, attributed to its long-standing research strength and government emphasis on quantum computing technology, establishing its international position in the field of quantum computing.

China ranks second with 25 articles, accounting for about 8%, indicating China's rapid progress in basic scientific research and cutting-edge technology, having achieved significant milestones in quantum computing technology. The growing number of articles published by Chinese research institutions in international journals demonstrates China's increasing influence on the international stage. Other countries such as Japan, Germany, and the United Kingdom also have a considerable number of publications, indicating their active participation in global quantum computing research and their high international influence in certain specialized fields.

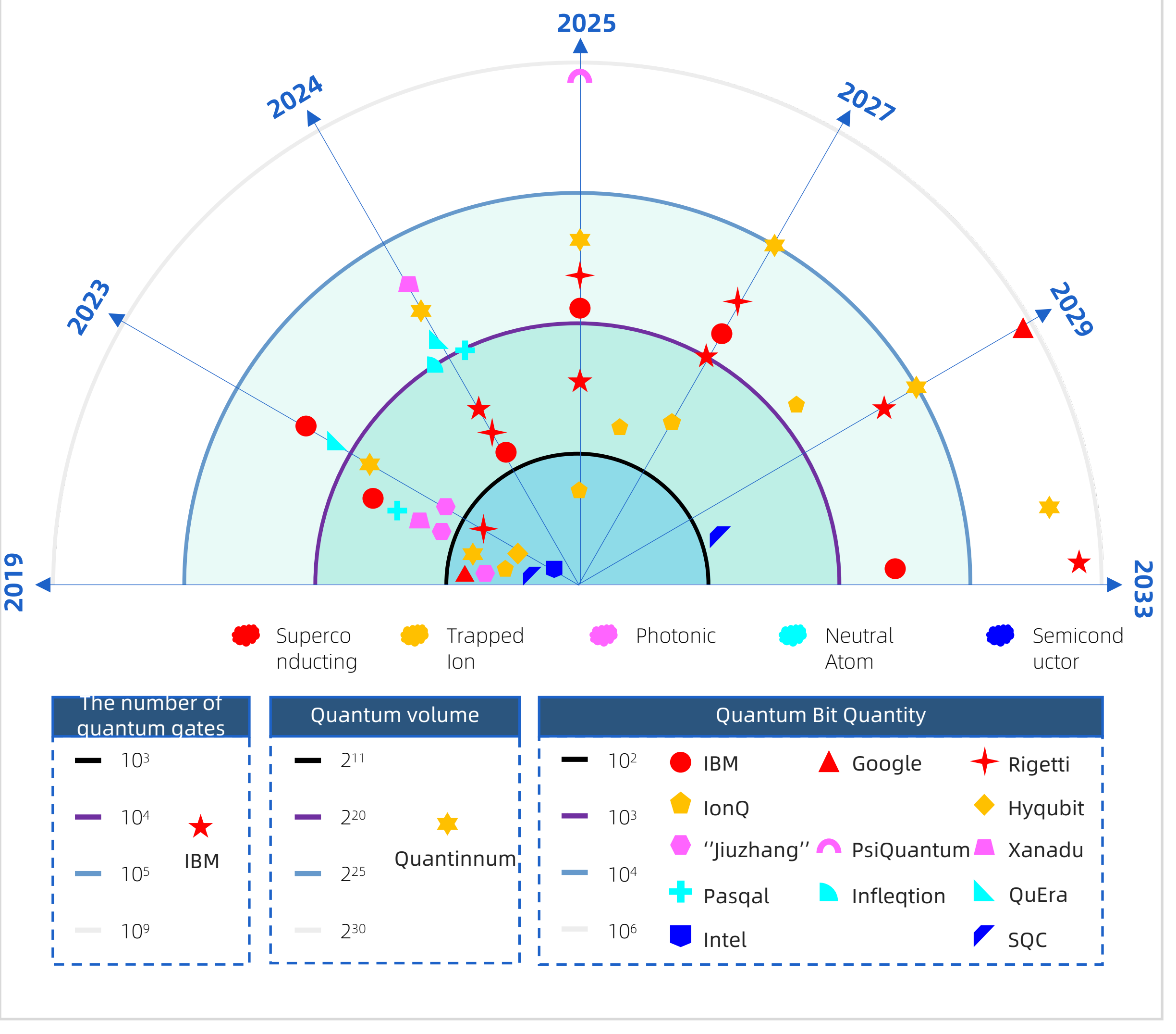
From the perspective of the geographical location of the corresponding author's institution, North America ranks first, accounting for approximately half of the total publications, reflecting the leadership of the United States in this region and Canada's contributions to quantum computing. Europe follows closely with 25% of research activities in this field, demonstrating Europe's significant position and activity in quantum computing research. The Asia-Pacific region accounts for 21.7%, indicating its rapid development and importance in quantum computing research. Contributions from other regions are relatively minimal.

International collaboration on a global scale is crucial for advancing research and applications in quantum computing. By cooperating and sharing resources and knowledge, countries and regions can accelerate technological progress and innovation. Therefore, strengthening international cooperation and exchanges will be an important trend for the future development of quantum computing.

05 Hardware development roadmaps are continuously being updated

Quantum circuits are commonly measured using three main metrics: circuit size, circuit depth, and qubit count. Circuit size corresponds to the number of quantum gates in the circuit, circuit depth corresponds to the parallel runtime of executing the quantum circuit, and qubit count corresponds to the spatial cost of the quantum circuit. These three metrics typically cannot be simultaneously optimized, especially considering the trade-off between depth (time) and qubit count (space).

Figure: Development Stages and Hardware Roadmap of Quantum Computing (Units: Quantum Bit Quantity)



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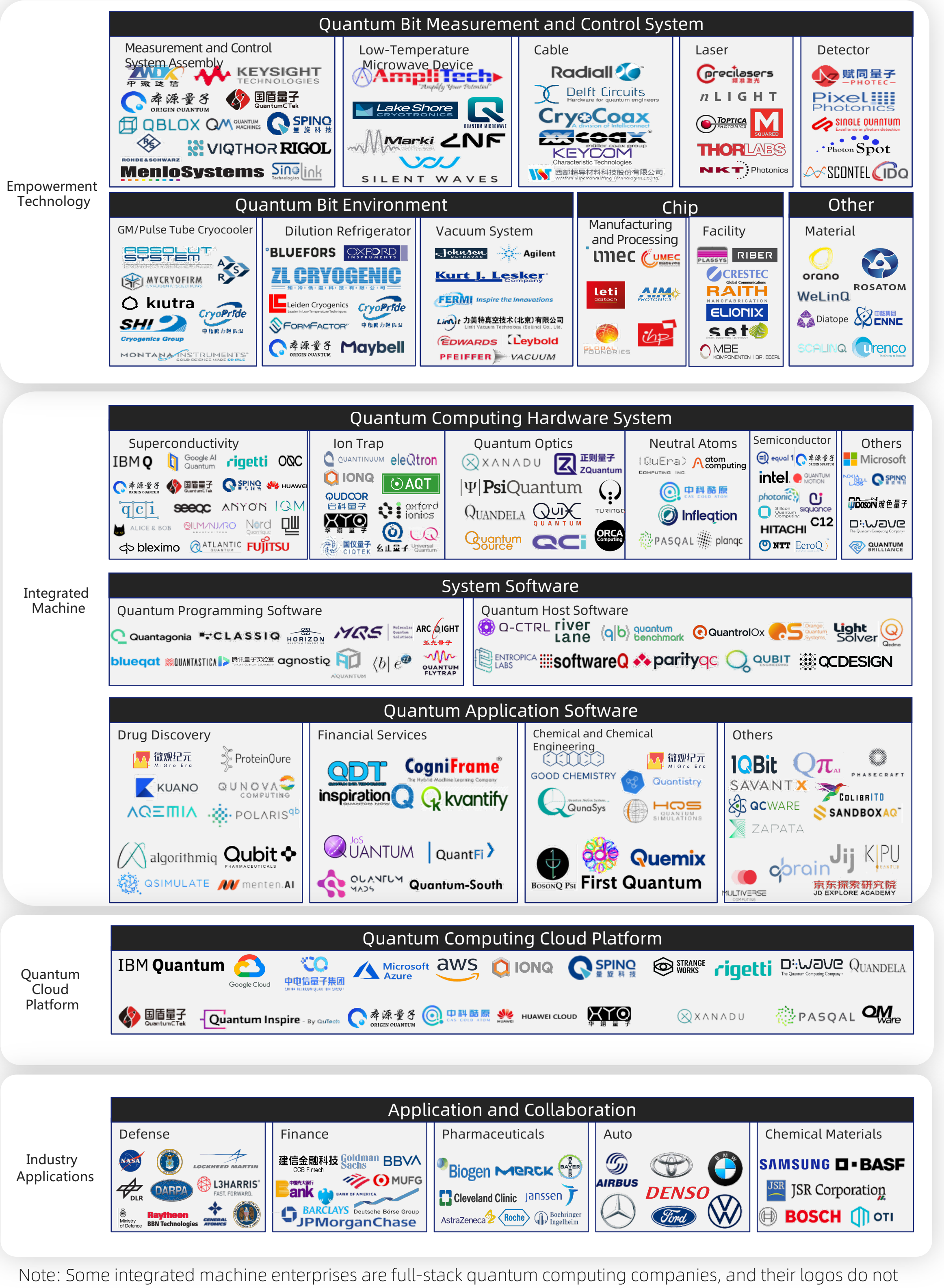
For example, in terms of the number of quantum gates, IBM is positioned in the second concentric region, which corresponds to 10^4 in 2024, with an estimated 5000 gates, and is projected to reach the maximum concentric region, 10 billion quantum gates, by 2033. In regard to the number of qubits, IBM falls within the third concentric region, expected to have 2000 qubits.

06 The number of companies related to the industry chain is increasing yearly

Figure: Quantum Computing Industry Chain Diagram



Note: Some integrated machine enterprises are full-stack quantum computing companies, and their logos do not appear in the software algorithm-related section. Research institutes and universities are not within the scope of consideration for the enterprise ecosystem.

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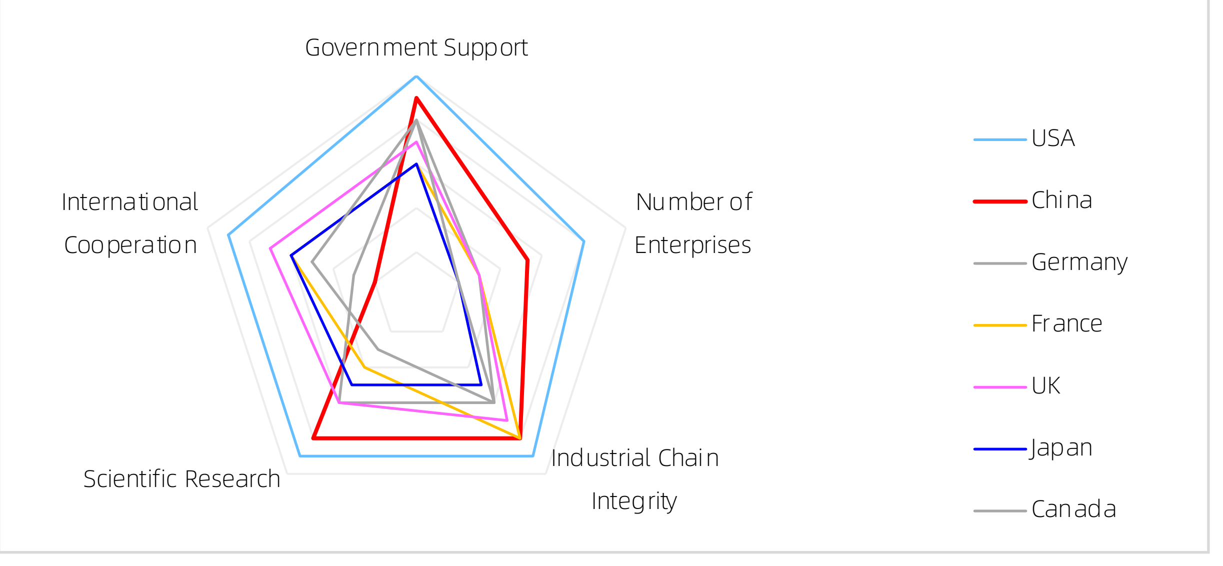
07 Ecosystem construction is increasingly perfected

The global quantum computing field is exhibiting a trend of multipolar development, with the United States and China emerging as the primary leaders in the quantum computing industry chain.

Figure: Global Quantum Computing Ecosystem Development (2023)



Note: Please refer to Appendices for assessment model.

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The United States has a significant advantage in the quantum computing industry chain. The government's high regard for and strong support of quantum computing have led to the growth of numerous enterprises, including notable companies such as IBM, Google, Microsoft, and Amazon. The United States maintains a leading position in various fields such as superconducting, ion trap, and photonic quantum computing. Its research innovation and active cooperation place it at the forefront globally in terms of technological prowess and leadership capabilities.

China has experienced rapid growth in the quantum computing field. Government support and investment have driven the increase in the number of enterprises, including Tencent, Huawei, and other major internet companies. In recent years, China has gained significant advantages in areas such as photonic quantum computing, rapidly improving its technological level and competitiveness. However, amid the intensifying competition between China and the United States, particularly in areas like quantum chips and ultra-low-temperature equipment, China still lags behind the United States significantly.

Germany, France, and other European countries demonstrate a positive trend in quantum computing ecosystem development. The German government's Quantum Technology Action Plan aims to become a global leader in quantum technology, providing funding and strategic frameworks. Germany ranks among the top globally in terms of the number of quantum computing enterprises, with advanced technological capabilities, particularly in areas such as ion traps and neutral atoms. However, compared to the United States, there are still technological gaps, and coordination and integration within the European Union need to be addressed. France strongly supports quantum computing through documents like the National Quantum Technology Strategy. However, compared to the United States and China, there is still a gap in investment and output, and it falls slightly short in hardware and software capabilities compared to Germany.

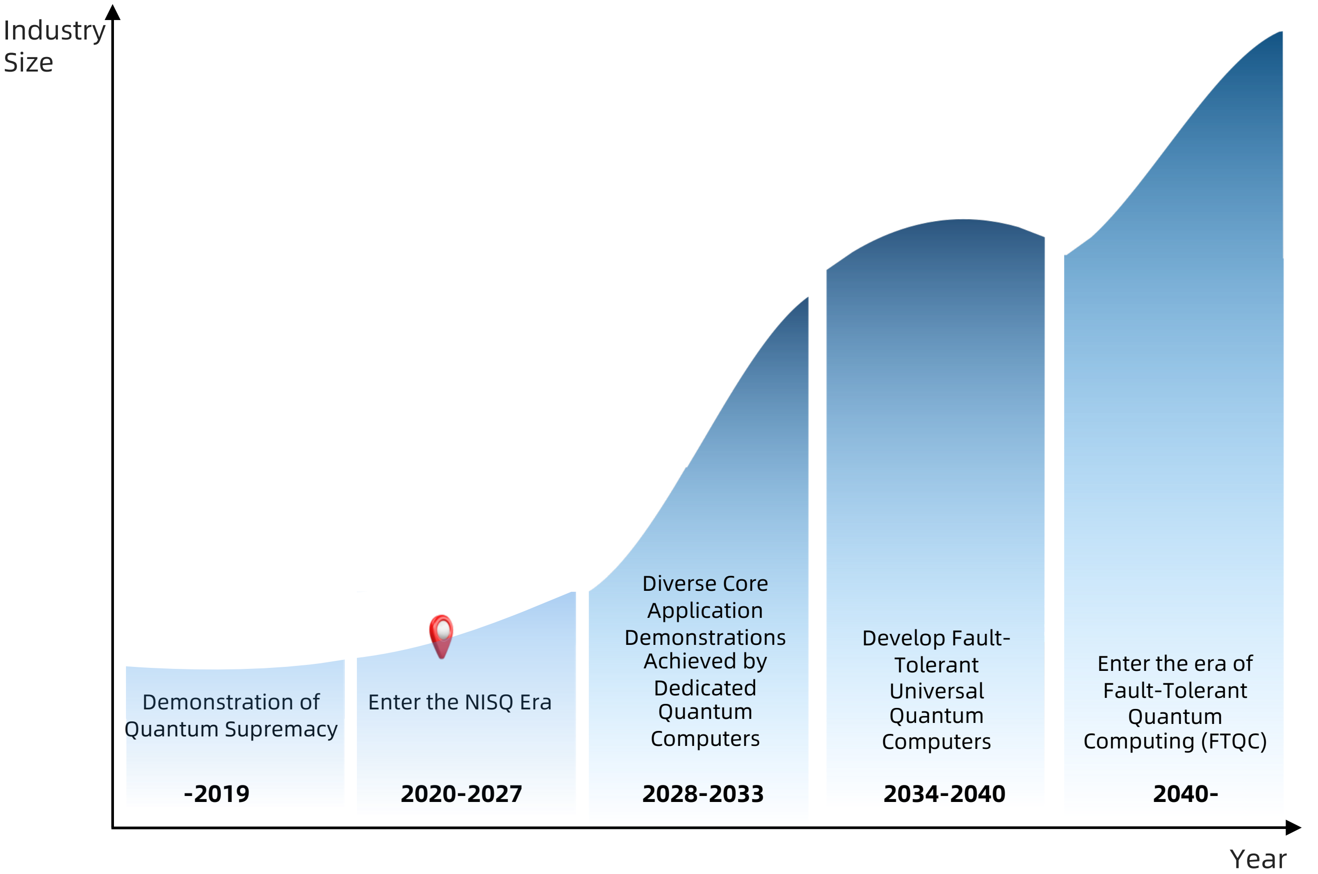
The United Kingdom, Japan, Canada, and other countries are also making strides in quantum computing development. The UK government's Science and Technology Framework and National Quantum Strategy aim to consolidate its position as a technology superpower, but it still faces shortcomings in scale and types of quantum computers compared to the US and China. Japan emphasizes practical and industrial applications through its Quantum Future Industry Innovation Strategy but still has some disadvantages in quantum software and services. Canada has launched a national quantum strategy, with strong government support, especially in the photonic quantum technology route, although it lags slightly behind the US in hardware and software capabilities.

08 The industry development is poised to enter a period of rapid growth

Currently, quantum computing is undergoing rapid development. Major technology companies and research institutions are investing significant resources to drive breakthroughs and applications in quantum computing technology. While there are still some challenges in hardware, such as optimizing measurement and control systems, increasing the number and quality of quantum bits, and mitigating interference between quantum bits, significant progress has been made along their respective technology paths, laying the foundation for further industry development. For example, IBM's introduction of the scalable Quantum System 2 architecture and its corresponding Heron chip continues to lead the global superconducting technology route. The successful construction of "Jiuzhang III" signifies significant progress in controlling the stability and entanglement properties of quantum bits, enabling quantum computers to excel in solving specific problems.

ICV predicts that the quantum computing industry will enter a period of rapid growth in the next 3 to 4 years. With continuous upgrades in quantum computing hardware and optimizations in algorithms, more software and hardware companies will venture into the quantum computing field, driving widespread applications across various industries. Quantum computing will first have a significant impact on industries such as finance, healthcare, and materials science, bringing about disruptive innovations to downstream sectors. Meanwhile, competition and collaboration within the industry chain will intensify, with investment, innovation, and substantial market demand serving as key drivers for industry advancement. Governments and businesses will also collaborate to increase research and development investment in order to secure a competitive edge in the global quantum computing arena.

Figure: Illustration of the Development Cycle of the Quantum Computer Industry



Period of Transformation

- Led by mature companies in the computing sector, preliminary concept validation is achieved.
- IBM established a dedicated quantum computing research team as early as the 1990s, while the Google team first demonstrated quantum supremacy.
- Representative companies: IBM, Google, Intel, Microsoft and others

Initiation Phase

- Startup companies and a majority of research institutions are beginning to engage in hardware development and error correction, advancing the development of various technical pathways comprehensively.
- Representative companies：Rigetti、IonQ、Quantinnum、Xannadu、QuEra、ORIGIN QUANTUM、QuantumCTek

Growth Phase

- Dedicated quantum computers for various technical pathways continue to emerge, and quantum software companies in the midstream and downstream sectors will experience rapid growth during this stage.
- Priority will be given to replacing classical computers in various fields such as finance, medicine, chemical engineering, automotive, and machine learning, resulting in multiple core application

Maturity Phase

- The advantages and disadvantages among various technical pathways are gradually being amplified, potentially converging into one or a few specific routes, while the cost of error correction is significantly reduced.
- Driven by the demand for new application scenarios in downstream sectors, the industrial chain is further refined, leading to an increase in the upstream's influence in the industrial chain. The expansion of production lines continues until supply and demand reach equilibrium.

Decline Phase

- The error rates in computations are approaching or becoming smaller than those of classical computers, and the number of quantum bits is expected to reach the million-level.
- Even as the computer industry enters the era of fully fault-tolerant quantum computing, quantum computers and classical computers will continue to coexist, each leveraging its strengths. They are not in a completely substitutive relationship.

02

Integrated Quantum Hardware

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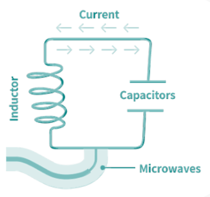
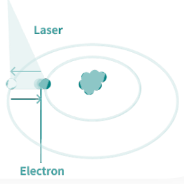
02
Hardware System

01 Core Progress of Quantum Computing in 2023

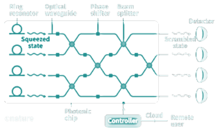
In 2023, various institutions conducted numerous explorations in the field of quantum computing. Researchers focused on optimizing noise levels, connection distances, and decoherence times to improve the quality of quantum bits. Significant breakthroughs were made, particularly in areas such as quantum error correction, quantum storage, quantum algorithms, integration of quantum with AI large models, and material exploration, driving the advancement of quantum computing technology.



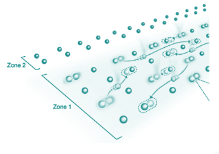
Superconducting Quantum Computing Route: Over the past year, superconducting technology remains the most prominent route, with rapid technological breakthroughs placing it at the forefront among all routes. IBM released its first quantum computing processor, Condor, surpassing 1000 qubits, with a total of 1,121 qubits. Additionally, IBM introduced a modular quantum computer that combines scalable cryogenic infrastructure with classical servers, achieving a supercomputing architecture for computation. Based on this architecture, IBM also launched Heron, a scalable 133-qubit chip.



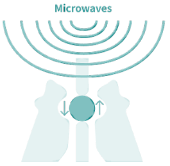
Ion Trap Quantum Computing Route: Quantinuum's H-Series quantum computer has continuously set new records for three consecutive Quantum Volume (QV) milestones: 217, 218, and 219, marking the highest reported Quantum Volume records to date. IonQ has achieved 29 algorithmic qubits on the barium platform.



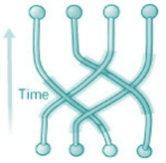
Photon Quantum Computing Route: A team from the University of Science and Technology of China (USTC) has demonstrated the quantum computing advantage of the "Jiu Zhang" algorithm. They successfully solved two graph theory problems and subsequently built a prototype called "Jiu Zhang III," which consists of 255 photons, showcasing the potential of photonic quantum computing.



Neutral Atom Quantum Computing Route: Atom Computing is set to release its second-generation neutral atom quantum computer. The company has already created an atomic array with 1225 sites on its quantum computing platform, currently filled with 1180 qubits.



Semiconductor Quantum Computing Route: Intel has unveiled a quantum chip named Tunnel Falls, featuring 12 qubits, fabricated using mainstream CMOS (Complementary Metal-Oxide-Semiconductor) technology. This chip consists of 12 quantum dots and can be configured with 4 to 12 spin-based qubits. Its purpose is to enable research laboratories to construct larger systems using various topological structures, particularly for testing quantum error correction schemes.



Topological Quantum Computing Route: Microsoft has made three significant announcements in the field of quantum computing. Firstly, the company declared the achievement of the first milestone on its roadmap towards a quantum supercomputer. Secondly, Microsoft aims to complete the construction of a quantum supercomputer within the next 10 years. Lastly, the company anticipates compressing 250 years of progress in chemistry and materials science into the next 25 years.

Quantum Error Correction
Collaborative innovation between enterprises and research institutions propels performance advancements

In 2023, researchers achieved significant advancements in quantum computing by leveraging auxiliary quantum bits, error mitigation techniques, and extending surface code logic quantum bits. These technologies effectively reduced error rates, thereby enhancing the reliability and precision of quantum computation. This progress stands as a pivotal step towards realizing fault-tolerant quantum computing. Additionally, the exploration of diverse error correction methods and strategies has introduced novel perspectives and directions for the research and development of quantum bit correction techniques.

Google Quantum AI

Google's Quantum AI team has employed surface code error correction technology. By combining multiple quantum bits into a logical qubit, they have achieved a balance between gain and loss in quantum error correction. This approach has been demonstrated to significantly reduce error rates, reaching the logical error rates required for achieving universal quantum computation.

PsiQuantum

The Psiquantum research team has introduced an active volume compilation technique for photon-based quantum computers. This approach utilizes optical components and optical interference for error correction of quantum bits and quantum gates. It has the capability to reduce the time and cost of executing quantum algorithms by a factor of 50, while also automatically optimizing network structure and resource allocation.

Researchers from Southern University of Science and Technology, Shenzhen Quantum Research Institute, Fuzhou University, and Tsinghua University applied pulses with a customized frequency comb to auxiliary quantum bits, surpassing the error correction break-even point by approximately 16%.

IBM Q

IBM has achieved accurate results for complex quantum circuits on a 127-qubit processor through error mitigation methods. This breakthrough allows the processor to surpass classical computers even without error correction.

Q-CTRL

Q-CTRL has announced that its embedded software is now integrated as an option into IBM Quantum's "Pay-As-You-Go Plan," enhancing the practicality and performance of quantum computing.

These achievements have a significant impact on enhancing trust and credibility in quantum computing, highlighting the crucial role of quantum bit error correction technology in the future development of quantum computing. Fault tolerance has always been a crucial issue in quantum computing. The cost of fault-tolerant algorithms is typically high, involving issues between physical and logical qubits, as well as the time cost of basic operations. Despite the relatively faster operational speed of superconducting qubits, there still exists a considerable gap compared to classical computing. Other types of quantum bits, such as ion qubits, operate at even slower speeds. Therefore, a balance between fault tolerance and execution efficiency is necessary in the development of quantum computing.

Despite the significant progress made in error correction by certain institutions in 2023, quantum computing hardware remains in a stage of small-scale, noisy operations. This implies that, in practical applications, the accuracy and reliability of quantum computing still face certain limitations. While the application of error correction techniques can improve computational precision, noise remains a constraining factor in large-scale quantum computing tasks. Therefore, addressing the challenges of the small-scale, noisy phase requires ongoing research and innovation. For instance, the use of two-dimensional addressing techniques can help overcome crosstalk issues, enhancing the isolation between quantum bits. Moreover, by intensifying research on hardware quality and scale, coupled with continuous improvements in error correction technologies, the reliability and stability of quantum computing can gradually be enhanced.

Quantum Chips
The simultaneous surge in quantum bit quantity and quality exemplifies the industry's rapid advancement, ensuring sustained high-speed development

In 2023, various companies and research institutions achieved breakthroughs in chip architecture design, quantum chip manufacturing, integrated photonics, and neutral atom quantum processors. Leveraging different types of quantum bits and chip architectures, such as superconducting, photonic, and ion qubits, researchers overcame performance bottlenecks related to quantum volume, fidelity, and connectivity. These advancements in turn laid the hardware foundation for realizing quantum supremacy and fault-tolerant quantum computation. Furthermore, these technologies explored the advantages and potential of different types of quantum bits and chip architectures, offering diverse options for the design and manufacturing of quantum chips.

IBM has unveiled the Condor quantum computing processor, boasting over 1000 qubits with a total of 1121 quantum bits. In addition to Condor, IBM has introduced a modular quantum computer architecture that combines scalable cryogenic infrastructure with classical servers, achieving a supercomputing framework for quantum computations. Furthermore, IBM has released the scalable Heron quantum chip with 133 qubits.

PsiQuantum has collaborated with the UK Science and Technology Facilities Council (STFC) to jointly develop the next generation of high-power, low-temperature modules. Additionally, PsiQuantum has partnered with SkyWater Technology to co-develop photonic quantum chips.

Quantinuum has achieved a quantum volume of 524,288 (2^19) on its H1-1 quantum processor. Furthermore, on the H2 processor, they have demonstrated a novel material state characterized by non-Abelian topological order.

The collaboration between the University of Science and Technology of China and Peking University has successfully achieved the preparation and verification of a cluster state with 51 superconducting qubits. This breakthrough sets a new world record for the number of genuinely entangled qubits in all quantum systems. Moreover, it marks the first demonstration of a measurement-based variational quantum algorithm.

Lawrence Berkeley National Laboratory and AQT (Alpine Quantum Technologies) have jointly developed Fluxonium quantum bits, showcasing superior performance compared to the currently widely used superconducting qubits.

Hyqubit has unveiled the first-generation commercial prototype HYQ-A37 of their ion trap quantum computer. This system achieves programmable universal quantum logic gate sets and adiabatic quantum computation. At its highest capability, it can maintain a one-dimensional ion crystal, consisting of up to 92 Ytterbium-171 ions, for several hours without ion loss.

Origin Quantum, in collaboration with a team from the University of Science and Technology of China (USTC), has achieved ultrafast manipulation of silicon-based quantum spin qubits. The collaboration has also developed and validated a responsive theoretical approach applicable to different coupling strengths and multi-qubit systems. Furthermore, by adjusting parameters such as microwave drive frequency and amplitude, the teams achieved arbitrary energy level structures, enabling high-speed and noise-resistant control of quantum bits.

Qudoor, in collaboration with Sun Yat-sen University, has conducted research on PT-symmetric quantum bits, achieving the quantum speed limit. This research has been practically applied on a 50-qubit ion trap quantum computing project.

The team at the University of Science and Technology of China has successfully built a quantum computing prototype named "Jiuzhang III" consisting of 255 photons. This prototype, addressing mathematical problems related to Gaussian boson sampling, is over a trillion times faster than the world's fastest supercomputer. Once again, it has set a new world record in the field of optical quantum information technology.

Collaborating to develop the third-generation ion trap quantum processor, utilizing MAGIC (Multi-Axis Global Ion Control) technology to deliver a high-performance Quantum Processing Unit (QPU). Through a jointly designed strategy, the functionality of ion trap-based quantum computers continues to enhance. Future access will be provided to industrial and scientific users via cloud services.

Announcing the launch of the second-generation neutral atom quantum computer in 2024: an atomic array with 1225 sites has been created on its quantum computing platform, currently populated with 1180 quantum bits.

The realization of 48 logical quantum bits has been achieved, enabling the detection and correction of any errors that may occur during entangling logic gate operations.

The achievements in advancing quantum computing hold significant value and relevance for both its development and practical applications. However, presently, achieving large-scale systems requires addressing coupling and interaction challenges among quantum bits to ensure system stability and controllability. Quantum chips continue to face numerous challenges and issues, including strategies for realizing larger and higher-performance quantum systems, overcoming noise and instability in quantum systems, and the manufacturing and processing of high-quality quantum materials.

Artificial Intelligence and Machine Learning
The fusion of quantum and large-scale models opens up new avenues for innovative thinking.

In 2023, companies were actively exploring new approaches and applications for quantum machine learning. The integration of quantum computing and machine learning harnesses the advantages of quantum computation to address complex problems beyond the capabilities of traditional computing. For instance, researchers achieved simultaneous scheduling and optimization of quantum and classical computing resources using technologies like the VQNet 2.0 framework, CUDA Quantum, and H100 NVL. This approach improved the efficiency and performance of machine learning, providing a hybrid computing solution for solving complex AI problems.

Google Quantum AI

Google collaborates with the University of Luxembourg and BIFOLD to jointly develop machine learning algorithms for handling complex quantum systems.

rigetti

Rigetti collaborates with Moody's and Imperial College London to propose a novel approach for predicting economic recessions. They employ a combination of quantum-enhanced data transformation and classical feature kernel methods in machine learning techniques.

QUANTINUUM

Quantinuum has released an updated version 0.3.0 of its quantum natural language processing tool, λambeq. This update enhances functionality and user experience through integration with PennyLane.

IONQ

IonQ plans to optimize ion trap technology by increasing the number and density of quantum bits. They predict achieving quantum advantage in quantum machine learning by the year 2024.

NVIDIA

NVIDIA's DGX Quantum, leveraging CUDA Quantum and H100 NVL, provides an accelerated solution for language model training and deployment, enhancing the speed of training and deployment for models like GPT.

These achievements have a significant impact on fostering the collaborative development of quantum computing and AI. The current applications of AI in the research domain are still unfolding, holding enormous potential for addressing intelligent problems, emotional aspects, and human-machine interaction. However, the integration of quantum computing with large-scale AI models faces numerous challenges and issues at this stage. These challenges include overcoming noise and instability in quantum systems, adapting to different types of AI tasks and data, and evaluating and validating the superiority of quantum computing in the AI domain.

Interacting with AI through natural language may offer additional possibilities for problem-solving and application development. Presently, quantum computers still grapple with error rates and noise, requiring more stable and controllable quantum bits to support large-scale machine learning tasks. Quantum machine learning necessitates algorithm design and optimization tailored to the unique properties of quantum computing, alongside simplified and unified programming frameworks to expedite development and application.

Other
Principles and exploration of new materials have been verified, paving the way for diverse development directions

Utilizing topological insulators, researchers have validated the anomalous Hall effect, Majorana particles, and the existence of novel physical phenomena and materials such as room-temperature superconductivity in materials like lutetium-hydrogen-nitride. This provides theoretical and experimental support for exploring these new phenomena and materials. Furthermore, these materials offer possibilities for the development of novel quantum devices and quantum computing platforms based on topological insulators and Majorana particles. Additionally, they present opportunities for the development of low-power, high-speed, and high-density superconducting circuits and devices. This not only expands the concepts and scope of quantum computing but also provides new avenues for improving existing superconducting technologies.

TEXAS
The University of Texas at Austin

The University of Texas at Austin has validated the anomalous Hall effect in topological insulators, providing theoretical and experimental support for exploring new physical phenomena and novel materials.

Researchers at the Pritzker School of Molecular Engineering at the University of Chicago have developed a new tool to aid in understanding the origin of electronic states in the design of materials. This signifies a further step in utilizing materials for future applications in quantum technology.

南京大學
NANJING UNIVERSITY

Nanjing University has not observed superconductivity in lutetium-hydrogen-nitride compounds under near-room-temperature conditions, providing theoretical and experimental support for exploring new physical phenomena and novel materials.

TUDelft Delft University of Technology

Quantum physicists at Delft University of Technology have, for the first time, demonstrated the possibility of controlling and manipulating spin waves on a chip using superconductors. These tiny waves in magnets may offer alternatives for electronic devices in the future.

A research group at Columbia University in New York accidentally discovered a superatomic material called Re6Se8C2, composed of rhenium, selenium, and chlorine. It is the fastest and most efficient semiconductor to date, allowing electrons in experiments to move several micrometers in less than a nanosecond.

These achievements contribute to advancing quantum physics and quantum information science. In the future, room-temperature superconductivity has the potential to enhance the efficiency and performance of quantum bits, expand the scale and stability of quantum systems, reduce the manufacturing and maintenance costs of quantum computers, and increase their availability and reliability. However, the current technical approach to achieving room-temperature superconductivity mainly involves extremely high pressure, significantly limiting its feasibility and controllability in practical applications. In the near term, room-temperature superconductivity may not have significant implications for superconducting quantum computing, as other factors such as temperature noise, coherence length, and material processing still need consideration in quantum computing. Looking ahead, it is essential to remain attentive to new technological discoveries that may bring forth additional possibilities.

Commercial Applications
Interdisciplinary collaboration, driving industrial development

In 2023, companies across various sectors initiated collaborations, focusing on utilizing quantum computing technology to address complex problems and laying the foundation for large-scale commercial applications.

Despite the rapid progress in the commercialization of the quantum computing industry in 2023, the exploration of its advantages across various sectors is vigorously underway. However, addressing this challenge at the current stage may require several years. Therefore, engaging in discussions with industry-leading companies is crucial to understanding the current state and future development directions of quantum computing. Throughout this process, a thorough analysis of time complexity, problem scale, and the differences between quantum and classical algorithms for each specific problem is essential. Identifying the practical intersections where quantum advantage can be achieved becomes a key focus.

Google Quantum AI

By providing funding and sharing quantum computers with the University of Chicago and the University of Tokyo, the aim is to drive the commercialization of their quantum computing-related technologies. This collaborative partnership is designed to jointly develop a 10-year quantum computing project, laying the foundation for the commercial application of quantum computing.

Ψ PsiQuantum

PsiQuantum has signed a contract with the Defense Advanced Research Projects Agency (DARPA) of the United States Department of Defense to participate in the Public Utility-Scale Quantum Computing (US2QC) program. This collaboration aims to expedite the company's construction of the first practical-scale quantum computer, leveraging DARPA's resources and guidance to drive innovation and applications in quantum computing.

QUANDELA

Quandela successfully installed its first quantum computer, MosaiQ, at the OVHcloud data center in Europe. This marks a significant milestone for the leading European photonic quantum computing company, providing a quantum platform to industrial clients.

KPMG has announced its participation in the IBM Quantum Network, aiming to further explore how quantum computing can bring future opportunities to KPMG professionals and clients.

IonQ has acquired a company focused on developing the next generation of network quantum computing architecture and a full-stack quantum compiler. This acquisition is intended to support AWS with a new backend, featuring the Aria system equipped with 25 algorithmic qubits. Additionally, IonQ has entered into a $25 million contract with the U.S. Air Force Research Laboratory (AFRL).

Together with BMW Group, Airbus has initiated a global quantum computing challenge named "Quantum Traffic Exploration" to address the most pressing challenges in the aviation and automotive sectors.

The integration of CUDA Quantum into its platform has led to new partnerships with various entities in the quantum industry. Notable partners include quantum hardware companies such as Anyon Systems, Atom Computing, IonQ, ORCA Computing, Oxford Quantum Circuits, and QuEra. In addition, collaborations extend to quantum software companies Agnostiq and QMware. Furthermore, partnerships have been established with over 120 enterprises, including several supercomputing centers, marking a significant entry into the quantum business sector.

Quantinuum collaborates with Microsoft Azure Quantum, KPMG, Ford, HSBC, and many others across various domains. This collaboration includes projects in quantum algorithm development, electric vehicle battery material simulation, potential revenue research in the banking sector, unveiling of new laboratories, quantum chemistry simulation, sustainable transportation research, and the release of a quantum Monte Carlo integration engine.

IBM has upgraded the service capabilities of its cloud service platform; it has formed an ecosystem network community with over 250 institutions; collaborated with Moderna to leverage quantum computing and artificial intelligence in researching mRNA vaccines, accelerating the discovery of new messenger RNA vaccines and therapies; entered into a strategic partnership with Ernst & Young (EY), with EY becoming a member of the IBM Quantum Network, gaining access to IBM's quantum computing systems to address complex business challenges.

The new corporate brand and name for ColdQuanta signify the company's shift from researching and developing quantum technologies to applying them for commercial purposes. In 2023, the company successfully collaborated with multiple partners, including the Japanese Quantum Moonshot Program, Riverlane, and L3Harris.

Sandbox AQ has strategically collaborated with leading enterprises such as NVIDIA, NOVONIX, EY and others, aiming to drive innovation in areas like drug development, battery design, and clean energy. Concurrently, by establishing strategic partnerships, including collaborations with universities and educational institutions, the company is committed to fostering talent development and promoting quantum and STEM education. Sandbox AQ has made substantial progress in advancing the sustainable development of the artificial intelligence and quantum technology ecosystem, promoting innovation, and contributing to employment growth.

SpinQ Technology has entered into a strategic partnership with Ping An Bank to explore new scenarios for the application of quantum computing in fintech. The company has undergone a comprehensive business upgrade, unveiling a range of products including superconducting quantum chips, quantum chip EDA software, superconducting quantum control and measurement systems, quantum software programming frameworks, and cloud platforms. Additionally, QuantumScape has successfully delivered a superconducting quantum chip to a research institution in the Middle East, marking China's first export of superconducting quantum computing chips overseas.

Qudoor has unveiled a modular ion trap quantum computing engineering machine, establishing in-depth collaboration with the China Mobile Research Institute in various areas such as mobile communication and computational power networks. Qike Quantum has also partnered with the Shanghai Computer Software Technology Development Center to establish the Shanghai Quantum Software Technology Research and Verification Center. As a founding member, the company participated in the establishment of China's first Quantum Computing Industry Intellectual Property Alliance. Additionally, Qike Quantum signed an agreement to join the computational capability scheduling platform in the Greater Bay Area, covering Guangdong, Hong Kong, and Macau.

Origin Quantum collaborates with Ping An Bank to conduct research and implementation of quantum financial algorithms in the field of financial fraud. Through real-world validation on quantum computers, the application of quantum algorithms in financial operations is expected to enhance the computing speed for anti-fraud and anti-money laundering activities, significantly improving the intelligence level of banking financial services.

Quantum Education

By offering educational products like teaching machines, organizing competition training camps, and establishing practical training centers, efforts are being made to collectively nurture professionals in the field of quantum computing

In 2023, the advancement of quantum computing education continued, but the field of quantum studies, being relatively new and interdisciplinary, particularly lacks comprehensive undergraduate programs in universities. To address the shortage of industry talents and keep pace with industry development, some companies have provided educational institutions with quantum computing equipment, online platform resources, and even practical opportunities within the enterprises. This aims to offer students better learning resources and environments, introducing new training models.

Currently, the training of quantum talents mainly focuses on cultivating highly specialized talents in the fields of science and technology. However, as the quantum industry emerges as a future industry, the shortage of talents extends beyond scientific and technical expertise to include various supporting talents in engineering, management, marketing, and other areas. Solutions for training these diverse talents are still relatively limited.

IBM has announced a collaboration with the University of Chicago, Keio University, the University of Tokyo, Yonsei University, and Seoul National University to collectively support quantum education initiatives in Japan, South Korea, and the United States.

SpinQ Technology has released the next generation of its portable nuclear magnetic quantum computer flagship products, the Gemini Mini Pro and the Triangle Mini. They organized the second "Quantum Cup" Quantum Computing Challenge Camp, implemented quantum computing education solutions in Shenzhen Middle School and Guilin No.1 High School, and delivered educational-grade quantum computers to the Bandung Institute of Technology in Indonesia and the National Autonomous University of Mexico.

Xanadu has signed a memorandum of understanding with Queen's University in Canada, aiming to develop quantum computing educational tools and provide educational programs to prepare students for careers in the field of quantum computing.

QuantumCTek has collaborated with High School Affiliated to University of Science and Technology of China (USTC) and Hefei No. 10 High School to jointly establish Quantum Science Exploration Laboratory and Quantum Information Innovation Laboratory. These initiatives aim to meet students' theoretical learning and experimental needs in quantum science and technology. Additionally, through activities such as popular science lectures, they explore training models for quantum information technology at the high school level.

Infleqtion Corporation has launched the mini MOT V2, a compact vacuum system designed for neutral atom research and quantum application development. This system offers the capability to control quantum states and can be utilized for academic research and physics education.

CAS cold atom and the School of Mathematics and Physics at China University of Geosciences (Wuhan) have signed a "School-Enterprise Cooperation Agreement" and held a ceremony for the awarding of internship practice bases.

Origin Quantum has developed a VR teaching system designed for popular science education in universities. This system helps users gain a deep understanding of quantum technology, comprehend the evolution of quantum bit states, and engage in practical activities by building superconducting quantum computers. The company has also organized the "Sinan Cup" Quantum Computing Programming Challenge to support talent development in quantum computing for universities and enterprises.

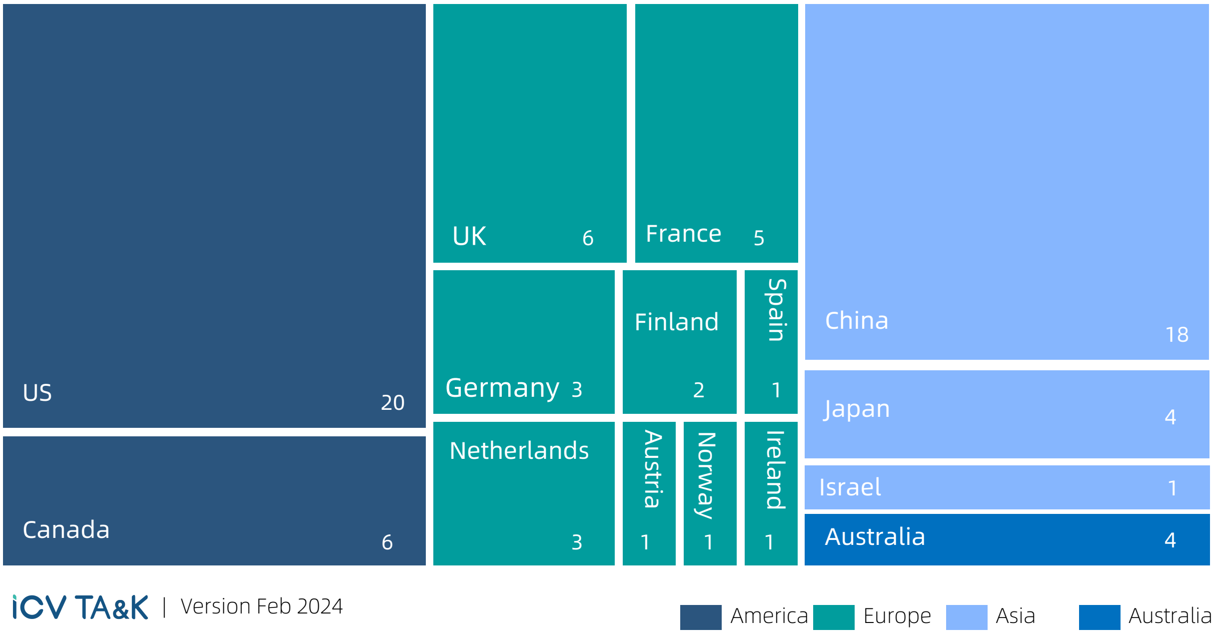
Sandbox AQ collaborates with over 30 universities, businesses, and educational organizations to expand AI and quantum training. These institutions engage in formal or informal partnerships with the company to enhance their artificial intelligence, quantum, and STEM courses.

02 The Global Landscape of Competition among Quantum Computing Hardware Manufacturers

The Global Distribution of Quantum Computing Hardware Manufacturers

There are a total of 76 quantum computing hardware companies globally, with North America accounting for 34.21%, Europe for 30.26%, Asia for 28.95%, and other regions for 6.58%.

Figure: Global Distribution of Complete Machine Enterprises in 2023



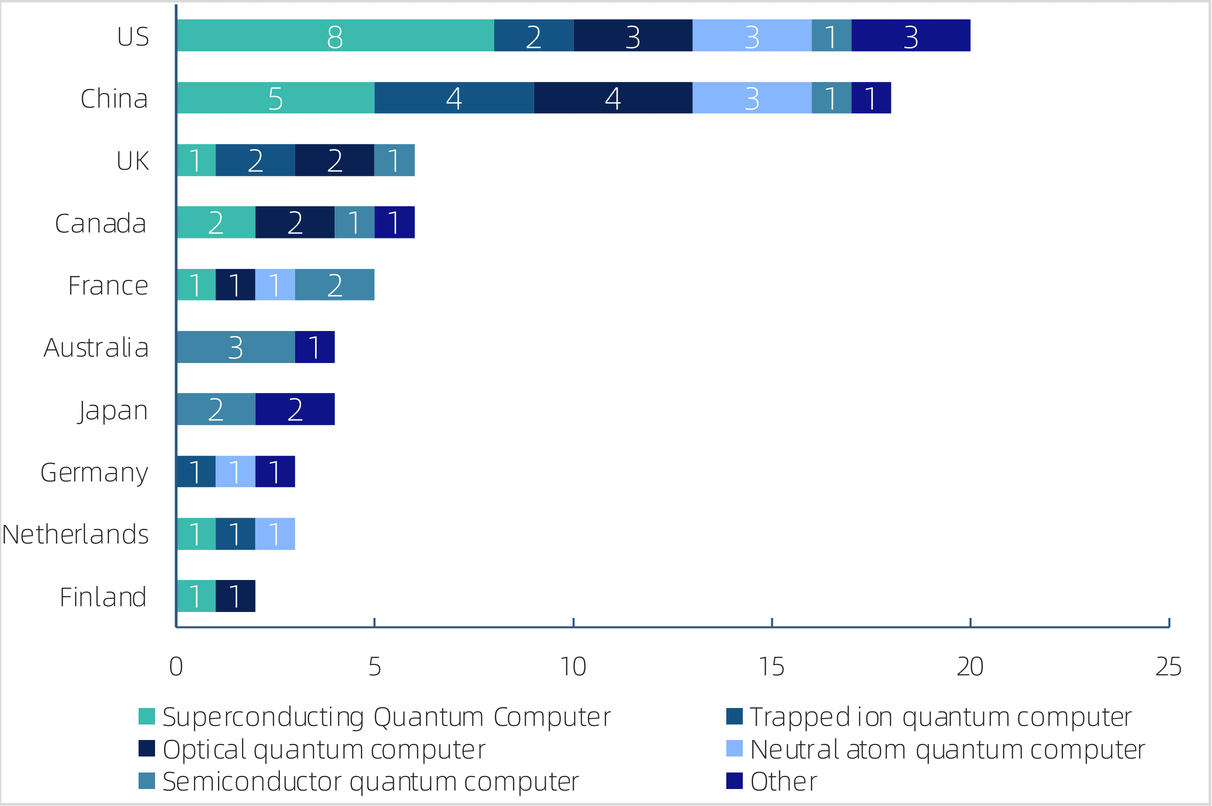
North America is the largest market for midstream quantum computing hardware, with the United States having 20 companies, accounting for 26.3% of the global market, and Canada having 6 companies, representing 7.9% globally. The strength of North America lies in its robust research and innovation capabilities, along with a high level of attention and investment in quantum computing. Companies in North America utilize diverse physical platforms such as superconducting, ion trap, and photonic to build quantum computers, forming a competitive and diversified market landscape. Representative companies in the region include IBM, Google, Microsoft, Amazon, Intel, Rigetti, IonQ, Xanadu, and more.

Europe is the second-largest market for midstream quantum computing hardware, with a total of 23 companies distributed across countries like France, Germany, the United Kingdom, the Netherlands, Finland, etc. Europe's strength lies in its diverse and collaborative market environment, as well as its long-term planning for quantum computing development. European companies also use various physical platforms, including superconducting, ion trap, photonic, neutral atoms, etc., to construct quantum computers. These companies often receive funding and support through the European Union's Quantum Flagship program and national quantum initiatives, collaborating with academia and industry. Representative companies in the region include Pasqal, Quandela, and more.

Asia is the third-largest market for midstream quantum computing hardware, with a total of 20 companies, mainly concentrated in China and Japan. Asia's strength lies in its vast and rapidly growing market demand, along with active exploration and application of quantum computing. Companies in Asia primarily use superconducting and photonic physical platforms to build quantum computers, with superconducting dominating the market. Asian companies develop their technologies and products through government investments and support, collaborating with academia and industry. Representative companies in the region include Tencent, Huawei, Fujitsu, and more.

Distribution of Technical Routes in Hardware Whole Machine Enterprises

Figure: Distribution of Technology Routes of Whole Machine Hardware Enterprises in Major Technology Countries around the World in 2023



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The United States is the country with the largest number of midstream quantum computing hardware companies, exhibiting the most diverse distribution of types. The U.S. holds an undisputed leadership position in the quantum computing field, characterized by cutting-edge technology, abundant resources, extensive collaborations, diverse applications, and a well-established ecosystem.

The midstream companies in the U.S. cover all physical platforms, including superconducting, ion trap, photonic, neutral atoms, semiconductor, and topological insulator, forming a diversified and competitive market landscape. The strength of midstream companies in the U.S. lies in their robust research and innovation capabilities, coupled with a high level of attention and investment in quantum computing. The U.S. government has made significant investments and support for quantum computing, establishing multiple quantum information science centers and quantum industry alliances, fostering close collaboration with academia, industry, and the military.

China is the second-largest country in terms of the number and types of midstream quantum computing hardware companies. China demonstrates strong catching-up and development capabilities in the quantum computing field, boasting a massive market and a relatively complete industrial chain. Chinese midstream companies span across various physical platforms, including superconducting, ion trap, photonic, and neutral atoms, creating a diversified and competitive market landscape.

03 Development Trends of Quantum Computing Machine Enterprises

The future development trends of enterprises in the middle of quantum computing mainly include the following aspects:

Technological Innovation

With the continuous advancement of quantum computing technology, midstream integrated companies are poised to encounter heightened technical challenges and a myriad of technical opportunities. For instance, the pivotal role and significance of quantum error correction technology in the future development of quantum computing underscore the importance of enhancing the trustworthiness and reliability of quantum computations. However, the current state of quantum computing hardware remains at a small-scale, noisy stage, signifying that in practical applications, the accuracy and reliability of quantum computing still face certain limitations. Therefore, midstream integrated companies must continuously elevate their technical capabilities and innovation prowess, while also engaging in collaborative efforts and knowledge exchange with other technology providers. This collaborative approach is crucial for collectively propelling the development and innovation of quantum computing technology.

Market Demand

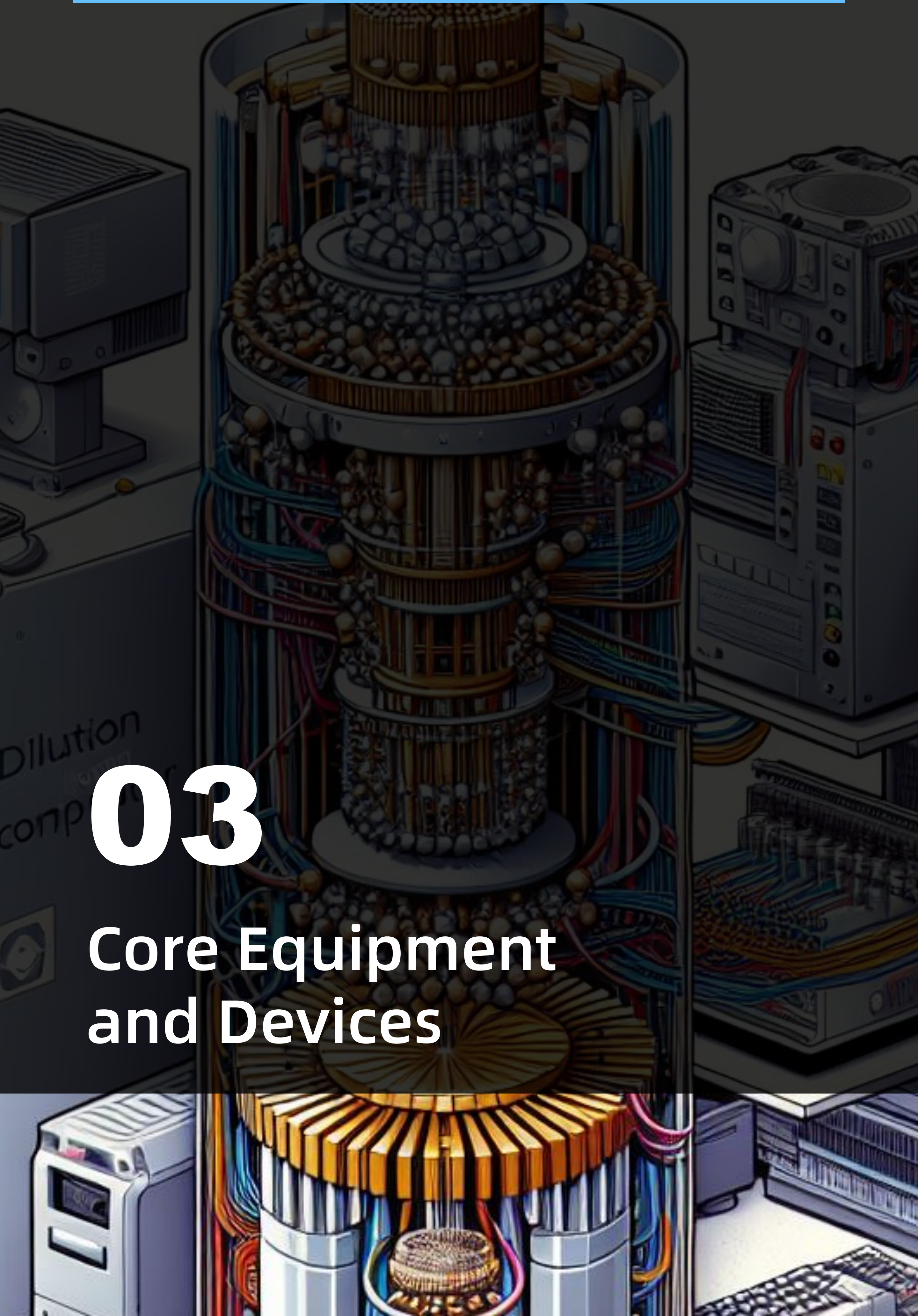
As quantum computing applications continue to expand, midstream integrated companies will face greater market demand and numerous market opportunities. For example, the synergistic development of quantum computing and the field of artificial intelligence (AI) has significant implications. Currently, the application of AI in scientific research is still unfolding, with immense potential in addressing challenges related to intelligent problem-solving, emotions, and human-computer interaction. However, the integration of quantum computing with large-scale AI models still encounters various challenges and issues at the current stage. Therefore, midstream integrated companies need to continuously adjust their market positioning and development strategies, while also collaborating and exchanging insights with other market participants. This collaborative effort is essential for collectively propelling the development and innovation of quantum computing applications.

Policy Environment

As the importance and impact of quantum computing continue to rise, midstream integrated companies will face increased government investment and support, along with the possibility of encountering more government regulations and restrictions. Different countries and regions may have distinct policy environments and changes that can have varying effects on the development and competition of midstream integrated companies. Therefore, these companies need to continuously monitor and adapt to policy environments and changes. Additionally, collaboration and communication with policymakers and policy implementers are crucial to collectively drive the development and innovation of quantum computing policies.

Collaboration and Communication

With the continuous development and innovation in the quantum computing industry, midstream integrated companies will encounter a growing number of collaborators and competitors. For instance, various quantum computing companies have independently developed a complete system of software, adopting a full-stack development approach using different programming languages and frameworks. This situation may lead to redundant investments and resource wastage. Therefore, midstream integrated companies need to continually establish and maintain their own collaborative relationships and competitiveness. Additionally, collaboration and communication with other partners and competitors are essential to collectively drive the development and innovation of the quantum computing industry.



03

Core Equipment and Devices

Contents

03
Core Equipment and Devices

01 Major Progress in Quantum Computer Core Devices in 2023

In 2023, the development of core components in the field of quantum computing has rapidly progressed, with various technologies and products continuously emerging. Finland's Bluefors expanded its influence in the manufacturing and sales of cryogenic equipment by acquiring Cryomech in the United States and Rockgate in Japan. Significant advancements were made by the Institute of Physics, Chinese Academy of Sciences, and the Shenzhen International Quantum Research Institute in low-temperature, low-noise amplifiers, and helium-free dilution refrigerators, crucial for the stable operation of quantum computers. Furthermore, research achievements from the National Institute of Standards and Technology (NIST) and the National Institute of Information and Communications Technology (NICT) in Japan opened up new possibilities for photon detection and laser color control in quantum computers. Research outcomes from the University of Minnesota and Quantum Machines provided novel design and improvement solutions for the circuit components and low-temperature sample holders of quantum computers. These advancements pave the way for the large-scale application of quantum computing in the future, indicating that the future of quantum computing is filled with boundless possibilities.

Figure: Quantum Computing Core Equipment and Device Progress in 2023

Qubit Environment

- Bluefors acquired the American cryogenic equipment manufacturer Cryomech and the Japanese cryogenic equipment distributor Rockgate.
- ZL Cryogenic has successfully developed a continuous operation dilution refrigerator with a record-breaking minimum temperature of 8.5 mK. The refrigerator exhibits a cooling capacity of 480 micro-watts at 100 mK without the need for liquid helium.
- China Shipbuilding Heavy Industry Group (CSIC) Pride has delivered the first dilution refrigerator, completing on-site installation, commissioning, training, and acceptance at the customer's location. The dilution refrigerator, developed by the Institute of Physics, Chinese Academy of Sciences (CAS), achieves a continuous operating minimum temperature of 7.5 mK and a cooling capacity of 450 micro-watts at 100 mK, without the use of liquid helium.
- The SL400 developed by Origin Quantum can provide an extremely low-temperature environment below 12 mK and a cooling capacity of not less than 400 micro-watts at 100 mK.
- Maybell has introduced the Big Fridge, featuring a sample volume of over 130 liters at a minimum temperature of 10 mK and a cooling capacity of 1000 micro-watts at 100 mK.

Quantum Measurement and Control System

- NIST has employed the same input laser source on a chip to generate multiple laser colors, thereby enhancing the chip's efficiency and power output.
- QuiX Quantum showcased for the first time a fully integrated entangled quantum light source on a chip.
- Beijing Academy of Quantum Information Sciences employed, for the first time, an extremely narrow-band interference circuit method, reducing the noise of single-photon detectors.
- CryoCoax has developed a high-density multi-channel coaxial cable based on the SMPM interface that can be installed on dilution refrigerators.
- NICT in Japan has developed a superconducting wide-band single-photon detector.
- Origin Quantum has released a ruthenium oxide temperature sensor and an impedance-matched quantum parametric amplifier.

Quantum Chip Manufacturing

- The new Enchilada Trap chip produced by the Microsystems Engineering, Science, and Application Fabrication Facility at Sandia National Laboratories is capable of storing and transmitting up to 200 quantum bits.
- IMEC and Xanadu announced a partnership to develop the next generation of photonic quantum bits (qubits) based on ultra-low-loss silicon nitride (SiN) waveguides.
- The IMEC research team has achieved over 100 microseconds of coherence time and an average single-qubit gate fidelity of 99.94% by employing an overlapped Josephson junction design. This was accomplished through improvements in the manufacturing process and optimization of structural surface treatment steps.

other

- DOE's Ames National Laboratory collaborates with the Superconducting Quantum Materials and Systems Center (SQMS) to research the interfaces and connectivity of nanoscale Josephson junctions.
- The superconducting diode device developed by the University of Minnesota Twin Cities campus is more energy-efficient and capable of simultaneously processing multiple signals, thereby enhancing the scalability of quantum computing.
- Quantum Machines has introduced a PCB-based modular low-temperature sample holder designed for superconducting quantum chips. It supports 8 GHz RF signal connections.

Dilution Refrigerator
Mergers and acquisitions, continuous iterations of product optimization, and the continued influx of start-ups

In the field of quantum computing, the dilution refrigerator industry is witnessing a competitive and thriving trend globally. To achieve a leading position, countries need to overcome technological bottlenecks and address shortcomings. For Western countries, the primary technological breakthroughs come from increasing the cooling capacity and optimizing architectures for quantum computers. The acquisition and collaboration strategies between Western companies, such as Bluefors acquiring Cryomech, highlight the urgent need to gain core technology and market advantages. The medium-term goals for European and American dilution refrigerator companies include achieving large space, high cooling capacity, and meeting the structural requirements for distributed quantum computing.

In the case of dilution refrigerators in China, although the start was later, continuous investment in research and development has led to the successful development of high-performance dilution refrigerators. This signifies the rise of China's ultra-low temperature refrigeration technology in global technological competition. With this progress, China's position in the field of quantum computing is gradually strengthening, injecting more vitality into global technological innovation competition.

The vigorous development in the field of quantum computing provides significant opportunities for the development of extremely low-temperature systems in China, but it also poses a series of challenges. Compared to the international advanced level, China still has some gaps in core technologies, such as in pulse tube refrigerators, core component distillation chambers, spatial layout in the mK temperature zone, and heat leak optimization, providing ample room for improvement. On the other hand, the competitiveness of China's dilution refrigerators in the global market needs more time to be tested. Although it takes time for Chinese products to enter the market, through research and development, these products are expected to meet significant global demands, enhance the corresponding technological levels, and achieve a competitive position in the high-end instrument and equipment sector. The key lies in whether China can grasp international standards with limited resources, making its products competitive in the international market.

Overall, in the past year, various Chinese teams have made significant progress in dilution refrigerator research and are gradually approaching the performance level of top global commercial machines.

Qubit Measurement and Control System

Reinforcement learning is enhancing the collaborative development of superconducting measurement and control systems, accelerating the research and development process of optical measurement and control system devices through silicon nitride and silicon photonics integration.

The development goal of the quantum computing measurement and control (QM&C) system is to assist in achieving fault-tolerant quantum computing, ensuring the execution of quantum algorithms in noisy quantum systems. To achieve this goal, QM&C systems need functionalities such as high-fidelity quantum gate operations, efficient quantum error correction encoding, and fast quantum feedback control. Existing superconducting quantum measurement and control systems can be classified into two generations. The first generation is primarily composed of devices capable of directly generating and receiving simulated microwave signals. While these systems are easy to implement, the lack of feedback control limits their scalability and programming capabilities. In 2017, the research team at Delft University of Technology proposed the QuMA microarchitecture, which can generate real-time, precisely timed control signals, combining flexible programming with feedback control capabilities and better scalability. Such hardware systems based on custom digital logic, especially those utilizing instruction sets, are referred to as second-generation quantum measurement and control systems. Leading measurement system suppliers internationally, such as Zurich Instruments, Keysight Technologies, have introduced second-generation quantum measurement and control system products. Chinese second-generation quantum measurement and control system products have also been introduced since 2021.

The main challenge currently faced by the quantum control system architecture is achieving programmable feedback control with extremely low feedback delay (on the order of picoseconds or even shorter), while ensuring the scalability of the measurement and control system. The development of quantum software and quantum control architecture should ideally be closely aligned, but the two directions are currently evolving relatively independently, leading to practical issues of mismatched capabilities. Coordinating the development of quantum software and quantum measurement and control systems for seamless integration poses another challenge for quantum computer engineering. At present, reinforcement learning, as a subfield of machine learning, has demonstrated advantages in numerical calculations in quantum physics, including quantum state preparation, quantum circuit design, and fault-tolerant quantum computing. Therefore, reinforcement learning may be an effective means to address existing issues in quantum measurement and control systems.

In optical measurement and control systems of quantum computing, lasers typically possess high stability, precise tuning capabilities, and low drift to ensure the accuracy and reliability of quantum information. Future development of lasers will focus on integrated photon devices (silicon photonic integrated chips), aiming to create lasers with different wavelength frequencies on a single chip. Although the color conversion efficiency of silicon nitride microresonators is still relatively low, significant improvements in efficiency and power output can be achieved by enhancing chip-level color conversion lasers. This facilitates the goal of generating lasers of different colors using the same laser source.

In the realm of detectors, silicon nitride photonics is also a crucial development direction. By introducing new technologies such as racetrack waveguides, researchers have successfully improved the performance of silicon nitride microresonators, addressing the efficiency reduction issue caused by mode competition. Additionally, superconducting wide-band photon detectors (SWSPD) represent a promising new type of photon detector. The innovative structural design allows for efficient photon detection, with a bandwidth more than 200 times wider than traditional superconducting nanowire photon detectors (SNSPD).

The development of SWSPD signifies a significant advancement in the field of photon detectors, focusing on improving photon detection efficiency by enhancing the structure of the detector. However, accompanying challenges include ensuring stability and reliability while maintaining high detection efficiency. Future research may involve further optimizing detector structures and improving manufacturing processes to enhance precision and overcome these challenges.

Other
Silicon germanium quantum materials help improve energy efficiency, and wafer-level integration becomes a key challenge

Globally, the field of quantum computing materials and related auxiliary devices is rapidly advancing, exploring methods for the preparation, fundamental properties, and corresponding quantum devices of silicon and germanium quantum computing materials. The research on these materials involves key technical issues such as the formation of quantum dots, charge control, and spin manipulation. The collaboration between Ames National Laboratory and the Superconducting Quantum Materials and Systems Center (SQMS) is driving the study of the properties of superconducting quantum materials, further expanding the frontiers of quantum computing. The University of Minnesota Twin Cities has developed a novel superconducting diode with higher energy efficiency, capable of simultaneously processing multiple signals and integrating a series of gates that control energy flow, enhancing the scalability of quantum computers. These research and development efforts indicate that the United States is moving towards a deeper understanding and improvement of quantum computing components.

As the world's largest producer of electronic components, China faces challenges of having a large but not strong industry, with a shortage of companies in the quantum materials and related device sector. These companies tend to be smaller in scale, with a later start in technology research and development, and there exists a significant gap in industrialization capabilities compared to international advanced levels.

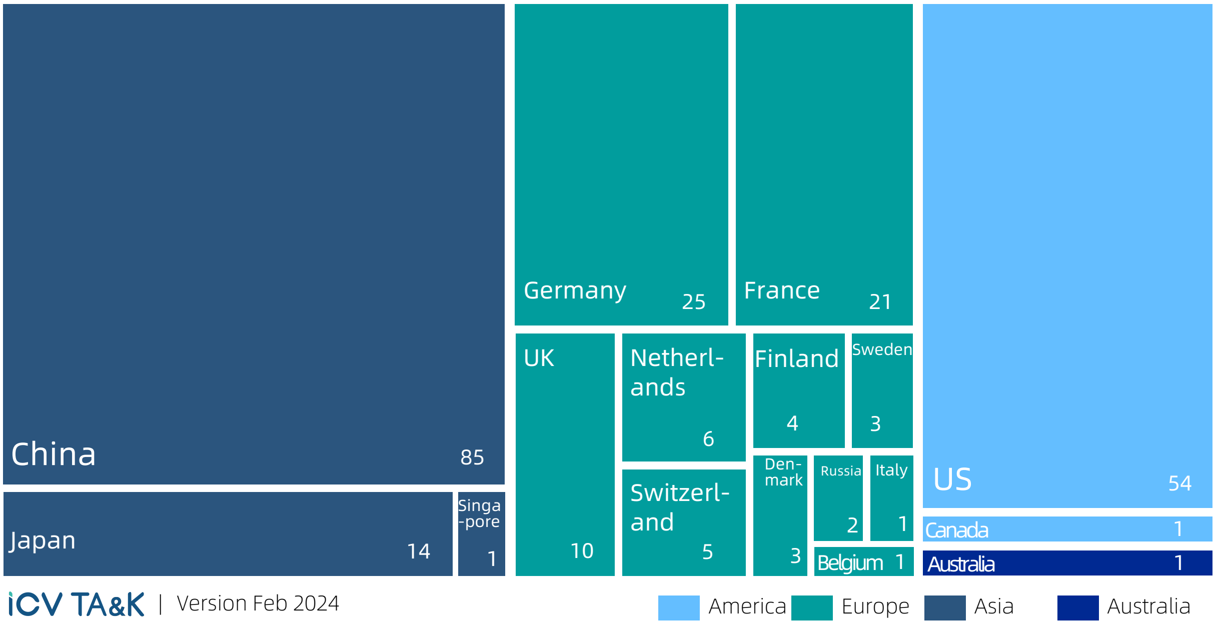
In the future, the research on materials for quantum computing chips will mainly focus on achieving wafer-scale controllable preparation of atomic-scale silicon-germanium quantum materials. Factors such as defects, stress, atomic occupation, atomic steps, isotope purity, and the controllable preparation of nanowire structures and components will be crucial in influencing the properties of quantum bits and integration.

02 The Competitive Landscape of Global Quantum Computing Enabling Technology Companies

Global Distribution of Enabling Technology Companies

As of the end of 2023, there are a total of 238 companies globally engaged in upstream empowering technologies for quantum computing. Among them, China has the highest number of enterprises, reaching 85, accounting for 35.7% of the total. Following closely is the United States, with 54 companies, representing 22.7%. Germany ranks third with 25 companies, constituting 10.5%. France and Japan are positioned as the fourth and fifth respectively, with 21 companies (8.8% of the total) and 14 companies (5.9% of the total). Other countries actively involved in this field include the United Kingdom, the Netherlands, Switzerland, Finland, Sweden, Denmark, Canada, Russia, Israel, Italy, Belgium, and Singapore.

Figure: Global Distribution of H1 Enabling Technology Companies in 2023



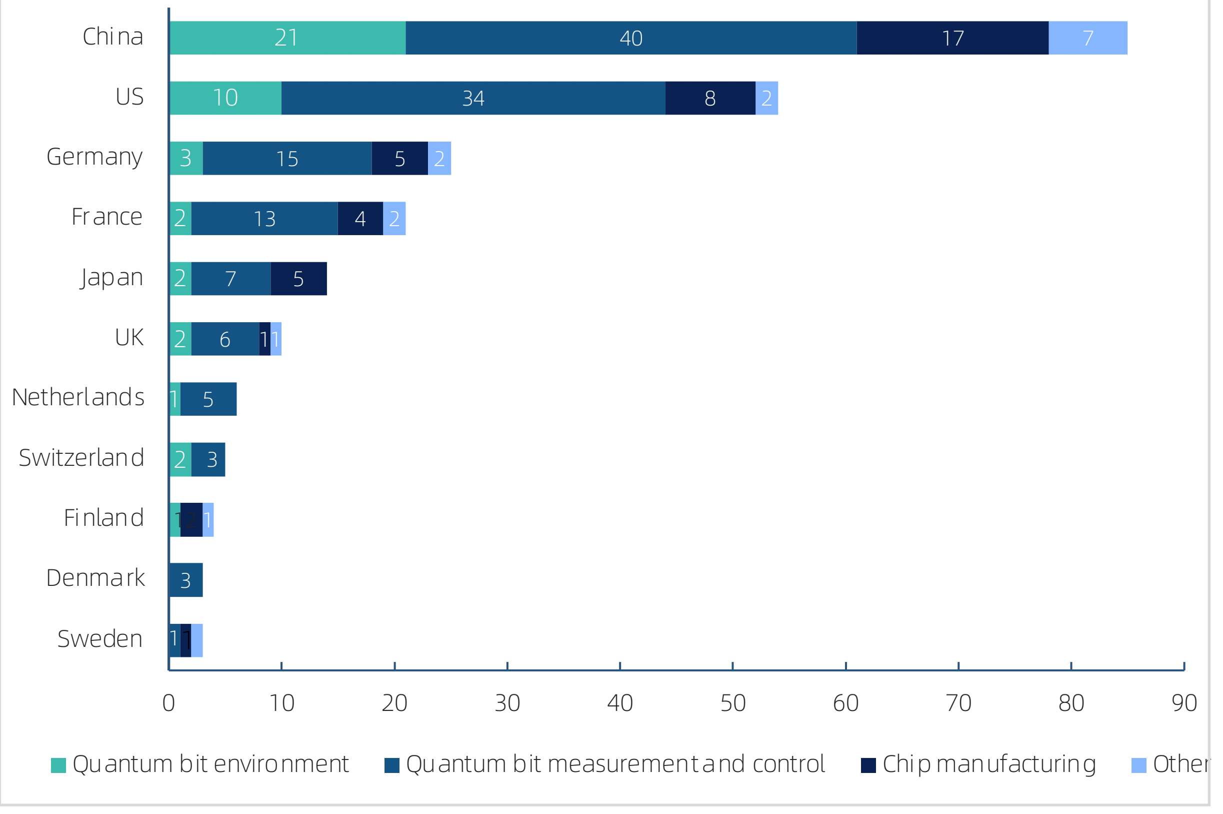
The Asia-Pacific region leads in the number of companies engaged in upstream empowering technologies for quantum computing, accounting for approximately 42.0% of the total. The majority of these enterprises are concentrated in China and Japan, both of which place high importance on and provide substantial support for quantum computing. These countries have formulated corresponding strategic documents and invested in the establishment of quantum technology laboratories and research centers. Chinese companies mainly focus on low-temperature equipment, quantum computing control systems, vacuum devices, lasers, and other areas, demonstrating rapid technological progress and strong competitive capabilities. Representative companies in the Asia-Pacific region include SHI Cryogenics Group and Shanghai Precision.

Europe ranks second in the number of companies involved in upstream empowering technologies for quantum computing, constituting 33.6% of the total. Enterprises in this region cover all aspects of empowering technologies, showcasing high technological levels and strong innovation capabilities. European companies are primarily concentrated in countries such as France, Germany, and the United Kingdom, all of which have their own quantum plans and strategies, with substantial government investments and support. The European Union provides a unified platform and resources, facilitating cross-border collaboration and competition. Representative companies include Bluefors, Qblox, Quandela, LIGENTEC and others.

In the Americas, there are 56 companies engaged in upstream empowering technologies for quantum computing, accounting for 23.5% of the total. These companies cover all aspects of empowering technologies, with the highest technological levels and leading capabilities. The majority of enterprises are concentrated in the United States, which is a global leader and pioneer in the field of quantum computing. The U.S. government invests significantly in and supports quantum computing, establishing multiple quantum information science centers and quantum network alliances, collaborating closely with academia, industry, and the military. Representative companies in the Americas include Form Factor, Keysight, Photon Spot, IPG PHOTONICS and others.

Distribution of Global Enabling Technology Enterprise Types

Figure: Global Distribution of Types of Technology Enterprises Empowered by Major Technology Countries in 2023



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In terms of the cross-distribution of countries and types of empowering technologies, enterprises engaged in upstream empowering technologies for quantum computing exhibit different preferences in different countries.

Regarding the quantum bit environment, countries such as China, the United States, and Germany have a relatively higher number of enterprises, indicating strong capabilities and development advantages in the field of quantum bit environment technology.

In the quantum bit control system aspect, similarly, China and the United States have a significant number of enterprises, showcasing their leading positions in this technological field.

In the chip manufacturing sector, the United States, Germany, and other countries dominate, with a relatively larger number of enterprises, signifying their high technological levels and market shares in the field of quantum computing chip manufacturing.

From the perspective of the balance between countries and types, there are differences in the balance level of enterprise types engaged in quantum computing upstream empowering technologies across different countries. High-balance countries, such as China, have a relatively even distribution of enterprises across different types, indicating a comprehensive and balanced development in quantum computing upstream empowering technologies. Low-balance countries, such as Germany and Japan, have significant differences in the number of enterprises across different types, revealing outstanding development in specific technological areas, while other areas are relatively weaker.

This difference may be closely related to factors such as each country's research foundation, market demands, technological innovation, strategic choices, and resource allocation. The distinct development focus and strengths in various areas of quantum computing upstream empowering technologies reflect the unique position and competitive advantages of each country in the global quantum computing industry.

03 Quantum Computing Enabling Technology Enterprise Development Trends

The development of upstream empowering technologies in quantum computing is closely related to each country's strategic awareness and ecosystem construction regarding quantum computing. Countries with strong strategic awareness and ecosystem construction for quantum computing, such as the United States, China, France, Germany, and the United Kingdom, tend to have a higher number of enterprises and higher technological levels in upstream empowering technologies.

Technological Innovation

With the continuous advancement of quantum computing technology, enterprises in upstream empowering technologies will face challenges in improving efficiency, reducing costs, and enhancing compatibility. The development of quantum computing chips will focus on increasing the number of quantum bits, reducing error rates, and optimizing silicon-based integrated photonics quantum chip technology. Research on materials and auxiliary devices will concentrate on exploring silicon and germanium quantum computing materials and improving superconducting quantum materials. To achieve efficient and highly compatible quantum computing, coordination and integration of quantum software, quantum control architectures, and quantum measurement and control systems will be key technological development directions. Reinforcement learning may become an effective means to address issues in quantum measurement and control systems.

The United States leads in the field of quantum computing, with significant government investments and support, leading to the establishment of multiple quantum information science centers and quantum network alliances. North American enterprises exhibit the highest technological proficiency and leadership capabilities.

Market Demand

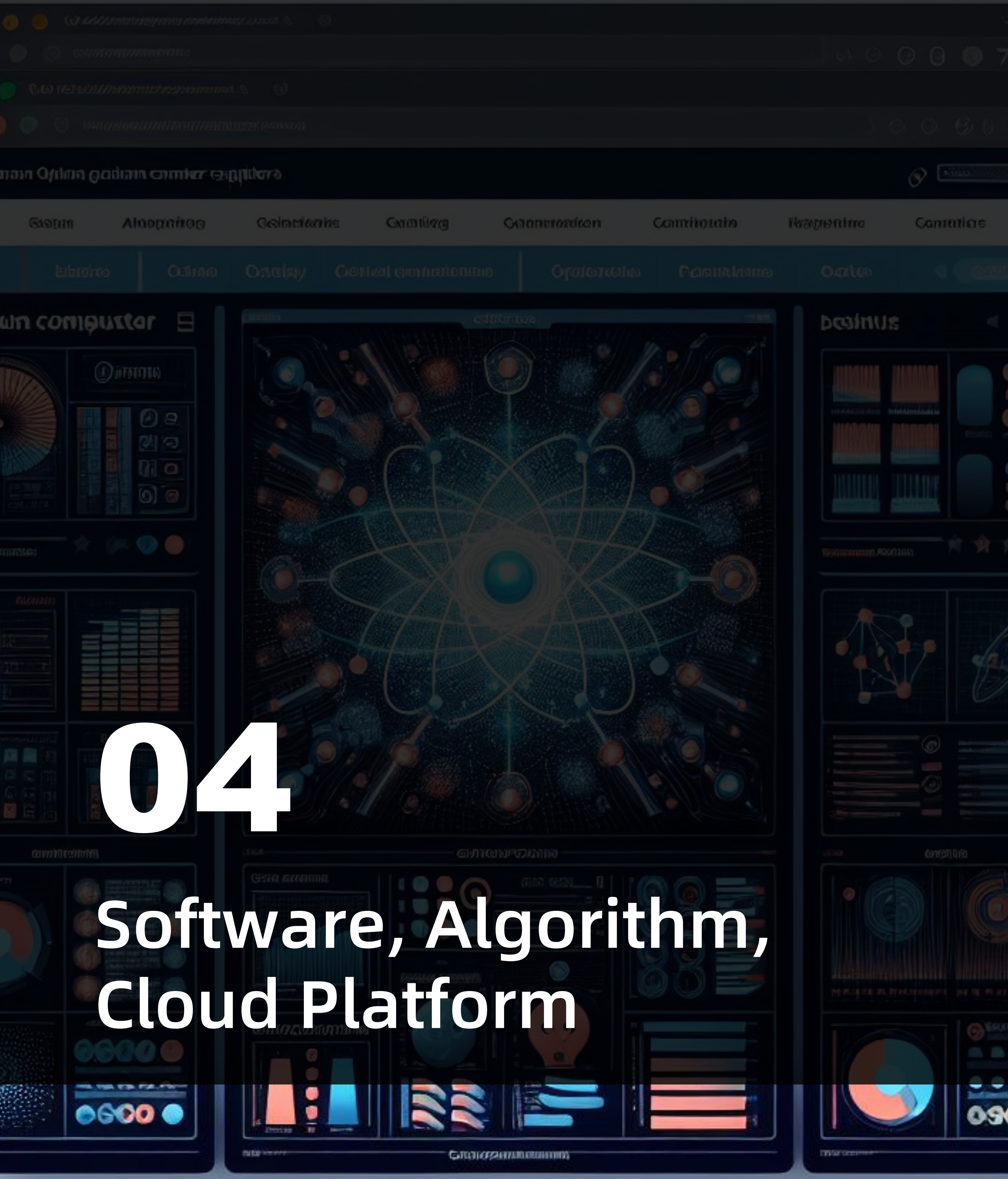
The future market demand is expected to move towards greater personalization and customization. Enterprises must continuously strengthen research and innovation to meet the rising demand for quantum computing devices and services in the market. Companies should focus on improving the efficiency and reducing the costs of quantum computing devices, as well as introducing more diverse, intelligent, and secure services and platforms to adapt to the evolving market. By gaining in-depth insights into customer needs, enterprises can provide specialized quantum computing solutions tailored to different industries and application domains. This approach will drive upstream empowering technology enterprises in the market to offer more innovative and targeted products and services.

Policy Environment

Some countries and companies have already secured leading positions in specific areas, such as the United States in quantum bit measurement and control and Finland in quantum bit environments. These nations and enterprises, backed by government policies, are likely to consolidate their advantages further and make breakthroughs in other types of quantum technologies. Simultaneously, other countries and companies may need to accelerate their pace to catch up, diversifying and learning across various types of quantum technologies to achieve balanced and optimized development.

Collaboration and Communication

In the future, international cooperation will be a key factor in promoting the development of quantum computing upstream enabling technologies. Through cross-border collaborations and acquisitions, businesses can expand their capabilities and technological reserves, enhancing their competitiveness in the global market. Inter-country cooperation may encompass joint research projects, knowledge exchange, and standardization efforts, all contributing to the collective prosperity of the global quantum computing industry. Different countries exhibit preferences and strengths in various aspects of quantum computing upstream enabling technologies. Some may excel in hardware development, while others may focus more on quantum software or related services. This diversity will foster the healthy development of the global quantum computing ecosystem, allowing nations to collaborate and share strengths for global complementarity.



04

Software, Algorithm, Cloud Platform

Contents

04
Software, Algorithm, Cloud Platform

01 Differences Between Quantum Computing Software and Classical Software

Figure: Differences between Quantum Computing Software and Classical Software

	Programming Software	Operating System
Quantum	**Quantum programming framework** • A software tool that provides predefined codes and libraries to help developers write more efficient and reliable code • Introduce the elements and concepts of quantum computing and treat the quantum chip as a special device or object **Quantum compiler** • Translating quantum algorithms into machine language that can be executed on hardware • Due to the limitations of quantum hardware topology, mapping and routing are unique and important parts of quantum compilation. **Virtual machine** • Use classical computers to simulate the operation of quantum computers • Quantum virtual machines provide convenient tools for analyzing and debugging quantum algorithms and quantum programs, and also help verify the correctness of quantum hardware.	**Quantum error correction system** • Multiple physical qubits encode "logical qubits" to protect quantum information from errors caused by decoherence • QPU needs error correction **Quantum calibration system** • Automatic calibration of quantum chip and quantum pulse parameters • QPU requires calibration due to errors and instabilities **Quantum waveform system** • Control waveforms for quantum hardware • The quantum measurement and control system uses analog signals **Quantum task scheduling system** • Scheduling quantum tasks • There are many constraints on task parallelism in quantum chips (such as crosstalk)
Classic	**Classic programming framework** • The programming framework of classical computers is based on deterministic logic, which executes instructions sequentially **Classic compiler** • A compiler for a classical computer is designed to convert a high-level programming language into low-level machine code that executes a deterministic sequence of instructions **Cirtual machine** • Classic computers operate based on deterministic logic and their behavior is completely predictable, so there is no need for a virtual machine to simulate hardware behavior.	**Classic error correction system** • Modern CPUs generally do not require error correction **Classic calibration system** • The manufacturing process and design of modern CPUs are so advanced that errors and instability generally do not need to be calibrated. **Classic waveform system** • Classic processors use digital signals **Classic task scheduling system** • The task scheduling of classical computers relies on the laws of classical physics. Each task can only represent one number at a certain time.

Note: Some content is referenced from "Software Architecture for Quantum Computing Systems - A Systematic Review" by Arif Ali Khan, Aakash Ahmad, Muhammad Waseem, Peng Liang, Mahdi Fahmideh, Tommi Mikkonen, Pekka Abrahamsson.

02 Major Advances in Quantum Computing Software in 2023

In January, collaboration with Ciqtek in the fields of quantum algorithms and integrated computing platforms was initiated. In September, in partnership with Afana Bio, the "MiQro RNA Drug Design Platform" was launched, marking the first domestic drug design platform based on quantum computing and biopharmaceuticals.

In February, the Palace open-source software platform was introduced. This platform is capable of performing 3D simulations of complex electromagnetic models and supports the design of quantum computing hardware.

In February, the Quantum Software Development Kit (SDK) version 1.0 was released, aimed at enabling developers to interface with the quantum computing stack and prepare for programming quantum algorithms to be executed on quantum hardware.

In March, Caltech, Stanford, and Google launched the new platform BlueQubit, enabling researchers to rapidly test quantum algorithms and providing seamless and efficient access to quantum hardware.

In March, the software development kit Qristal SDK, along with the high-performance simulator Qristal Emulator, were integrated into the quantum accelerators within HPC (High-Performance Computing) data centers.

In April, a more powerful quantum simulator, mqvector, was launched, along with the newly released GPU simulator mqvector_gpu, supporting a wider range of quantum gates to facilitate the development of new quantum algorithms by users.

In April, the quantum chemistry software pyChemiQ was released; in July, the new generation of quantum computing operating system, Benyuan Sinan PilotOS, was launched, supporting batch processing of quantum computing tasks and cooperative computing beyond quantum capabilities. Users can directly perform local quantum computing programming without the need for internet connection, achieving a "plug-and-play" experience with the software.

In May, Eviden, a subsidiary of Atos, launched the quantum computing product Qaptiva, aimed at enabling the development and use of real-world applications using the best-in-class quantum computing technology.

In June, the Chalmers University of Technology in Sweden developed a free open-source software that facilitates new discoveries in the field through advanced simulation and analysis of quantum components.

In August, Q-Tech Quantum and the Shanghai Software Center proposed a quality assessment framework for quantum simulator software, evaluating the performance of simulators based on seven criteria including functionality and performance efficiency. To verify its effectiveness, this benchmark test was implemented on representative quantum simulator platforms and compared their simulation capabilities across different algorithmic paradigms, thereby validating the framework's effectiveness.

In August, QuantrolOx announced the launch of its first product, Quantum Edge, which is capable of automatically adjusting and optimizing superconducting quantum computers.

Trends in Quantum Computing Software Development

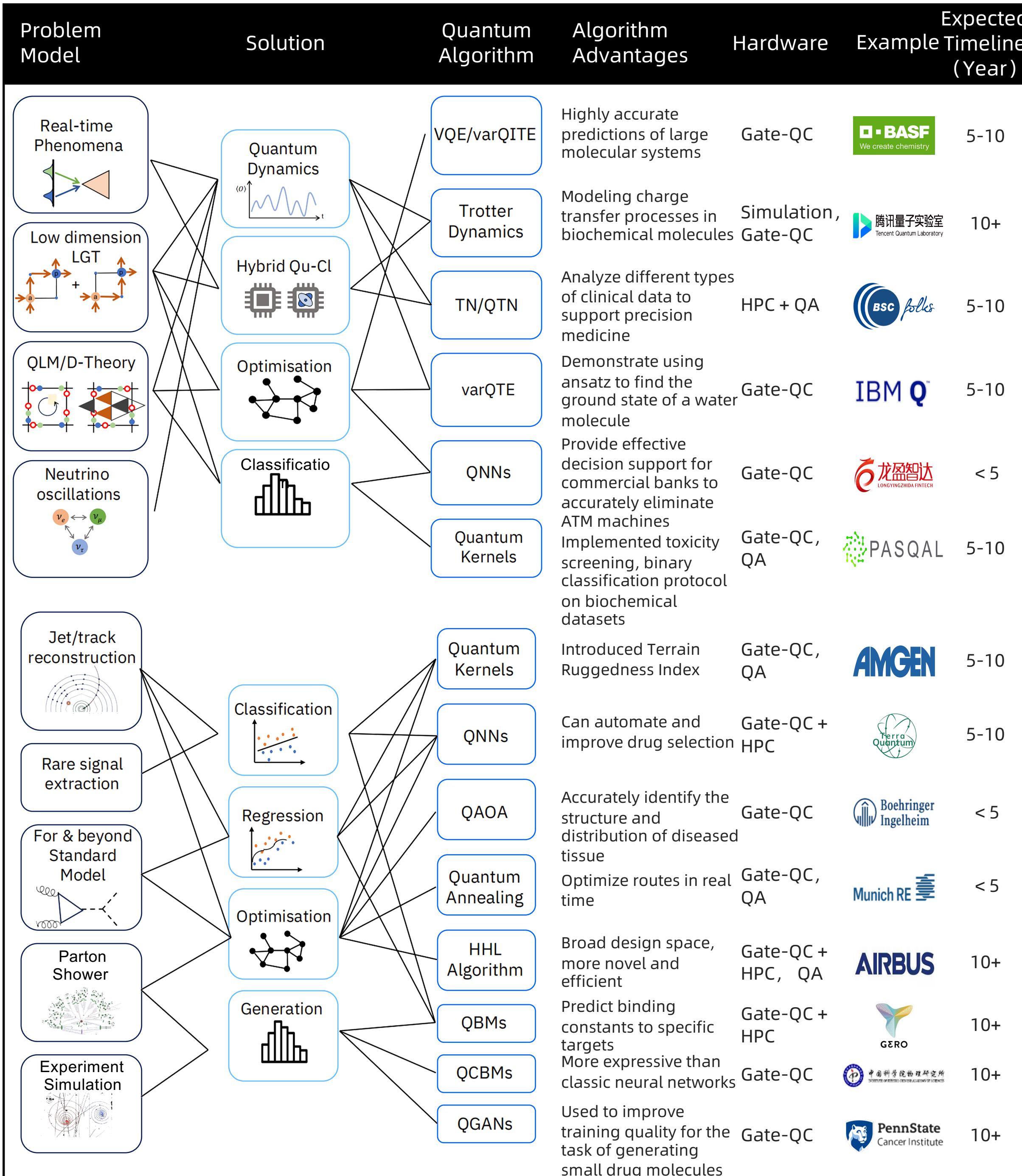
The overall market landscape remains stable, with companies vying to innovate and introduce new offerings.

From a global perspective, the development of open-source platforms for quantum computing software is becoming increasingly sophisticated. In recent years, both technology giants and start-ups in Europe and America have been developing and offering a variety of open-source platforms for quantum computing software. These platforms allow developers and users to access and utilize quantum computing resources for the design, testing, and optimization of quantum algorithms. Platforms such as IBM's Qiskit, Intel's QAT, and Amazon's Braket are currently among the more well-known and popular open-source platforms for quantum computing software. Each supports different quantum computing hardware and cloud services, offering various quantum programming languages and tools. Among these, Qiskit, known for its early launch, user-friendly interface, and tight integration with IBM's quantum hardware systems, still holds a dominant position. As the future of quantum computing becomes more certain, some large traditional IT companies, like NVIDIA, have made significant entrances into the quantum computing field. Leveraging their strength and resources, they have rapidly developed and formed collaborations with a multitude of ecosystem companies in a short period. User habits have gradually formed over the years, and an ecosystem around these platforms is being established, making it challenging for any new platform to break through the existing market structure.

The future direction of quantum computing software development will not only be based on the current and foreseeable future level of quantum computing hardware but will also focus on improving computational correctness, optimizing the efficiency of compilers and runtime systems, modular program design, and enhancing debugging tools. Additionally, the support capability for classical-quantum collaboration will need to be considered. These directions will help establish a more flexible and scalable quantum computing software ecosystem, build a closer collaboration between hardware and software, and enhance the practicality of quantum computing.

03 Classification of Quantum Algorithms and Corresponding Hardware Requirements with Anticipated Application Deployment Timelines

Figure: Classification of quantum algorithms and their corresponding hardware requirements and application implementation time



Note:

- VQE: Variational Quantum Eigensolver, varQITE: Variational Quantum Iterative Time Evolution, Tortter Dynamics: Time evolution based on Trotterized time propagation operators, TN: Tensor Network, QTN: Quantum Tensor Network, varQTE: Variational Quantum Time Evolution, QNN: Quantum Neural Network, QAOA: Quantum Approximate Optimization Algorithm, HHL Algorithm: Quantum algorithm for systems of linear equations, QBM: Quantum Boltzmann Machine, QCBM: Quantum Circuit Born Machine, QGANs: Quantum Generative Adversarial Networks
- Source: Industry quantum computing applications, Quantum Technology and Application Consortium - QUTAC; Quantum Computing for High-Energy Physics: State of the Art and Challenges. Summary of the QC4HEP Working Group, Alberto Di Meglio

04 Major progress in quantum computing algorithms in 2023

腾讯量子实验室 Tencent Quantum Laboratory

In February, research focused on how to design quantum circuits for the preparation of specific quantum states, as well as how to improve quantum circuits for unitary matrix synthesis. By introducing auxiliary quantum bits, efficient quantum circuits were realized under various connectivity constraints of quantum bits, achieving asymptotically optimal depth and size in the complexity of quantum circuits for quantum state preparation, controlled quantum state preparation, and unitary matrix synthesis.

ByteDance 字节跳动

In April, a team from Peking University applied a neural network-based experimental wave function in a fixed-node DMC, which can accurately calculate various atomic and molecular systems with different electronic properties.

KIPU Quantum

In June, a two-year R&D agreement was reached with PASQAL to optimize the functionality of quantum algorithms and enhance the quantum efficiency for enterprises. The company developed the first "algorithm compression technology," which reduces the length of quantum algorithms.

seeqc

In July, it was announced in collaboration with HQS Quantum Simulations that a certain algorithm had been successfully run on the company's full-stack quantum computing system, SEEQC System Red. This system has shown tremendous potential for achieving commercially useful quantum advantage in the short term.

Q-CTRL

In July, in collaboration with Oxford Quantum Circuits (OQC), a significant enhancement in quantum hardware performance was demonstrated while running complex algorithms. Q-CTRL's error suppression software can reduce hardware errors and instability, enabling users to achieve optimal results from the hardware when executing quantum algorithms.

QUANTINUUM

In November, a novel tensor network algorithm was proposed, aimed at optimizing key components of adiabatic quantum computing (quantum circuits). The research team conducted classical optimization on parametric quantum circuits of fixed depth, encapsulating both adiabatic time evolution and counter-adiabatic driving over multiple time steps simultaneously.

微观纪元 MIQro Era

In December, by using a "relationship tree" approach, the main greedy algorithms for the maximum cut problem were categorized. Through numerical performance studies on different types of graphs, it was discovered that Prim-class algorithms perform better on generally dense graphs, while Kruskal-class algorithms show superior performance on sparser graphs.

Trends in Quantum Computing Algorithm Development

Under current hardware conditions, there is a comprehensive consideration of the balance between the fault tolerance cost of NISQ algorithms and algorithm performance.

These achievements are of significant importance for expanding the influence and value of quantum computing. However, due to the current limitations of hardware levels, NISQ algorithms remain the main research direction in the field of quantum computing. Due to the limitations and noise of NISQ devices, the actual application effects of algorithms may be significantly impacted. It necessitates further strengthening research and analysis on the effects, precision, and time complexity of NISQ algorithms, to grasp their applicability, limitations, and areas for improvement, providing more reliable guidance and support for the development of quantum computing software.

The development direction of quantum computing algorithm design can be summarized as follows:

First, they design more suitable quantum computing algorithms for different quantum computing hardware platforms and technical routes to improve the efficiency and reliability of quantum computing. For example, for different physical implementations such as superconducting quantum computing, photonic quantum computing, ion trap quantum computing, and silicon-based quantum computing, design optimized quantum logic gates, quantum error correction codes, quantum compilers, etc.

Second, they design more general and efficient quantum computing algorithms for different application domains and problems to expand the application range and influence of quantum computing. For example, for optimization problems, machine learning problems, cryptographic problems, simulation problems, and other types of issues, design quantum algorithms that have a quantum advantage or combine with classical algorithms to form more powerful hybrid algorithms.

Third, they design more flexible and robust quantum computing algorithms for different quantum computing resources and conditions to adapt to the actual environment and needs of quantum computing. For example, for limited resources such as the number of quantum bits, quantum coherence time, quantum communication bandwidth, design more resource-efficient quantum algorithms, or utilize technologies like quantum compression, quantum random access to improve the utilization rate of quantum resources.

05 Progress of Quantum Computing Cloud Platform in 2023

Enhanced Performance Enables Exploration of Applications

The quantum computing cloud platform provides a new way to access quantum computing systems. The backend of the quantum computing cloud platform includes quantum (physics) processors and quantum simulators. The current quantum processors that cloud platforms can provide include superconducting, optical quantum, ion trap, neutral atom.

Figure: Main progress of quantum computing cloud platform in 2023

Institute	Time	Progress
Microsoft Azure	March 2023	For the first time, quantum computing and classical computing can be seamlessly integrated in the cloud. It enables the development of applications that mix classical and quantum codes.
PASQAL	March 2023	Launch of Quantum Discovery, a neutral atom quantum computing exploration platform, including access to a quantum simulator and 100-qubit quantum processing unit.
IBM **Quantum**	May 2023	Launched the Osprey quantum processor with 433 qubits, and launched the 133-qubit Heron quantum processor with modular scalable performance in December.
北京量子信息科学研究院 Beijing Academy of Quantum Information Sciences	May 2023	Released a new generation of quantum computing cloud platform "QUAFU", providing access to superconducting quantum computing chips containing 136, 18 and 10 qubits
国盾量子 QuantumCTek	May 2023	Launched a quantum computing cloud platform, putting the same 176-qubit (66-qubit, 110-coupling-bit) quantum computer as "Zuchongzhihao" on the cloud.
STRANGE WORKS	April 2023	The new platform adds new classical and quantum heuristic solutions. It also plans to introduce new tools that utilize artificial intelligence technology to the platform.
	June 2023	IBM's 127-qubit Eagle processor is available on the Strangework cloud platform and is available as a pay-as-you-go system.
KAIST Department of Mathematical Sciences	September 2023	An entanglement witness circuit was developed and tested that can prove entanglement even if the cloud-based service only allows limited control of the machine.
中电信量子集团 CHINA TELECOM QUANTUM GROUP	November 2023	Released the "Tianyan" quantum computing cloud platform. The platform integrates the "Tianyi Cloud" supercomputing and 176-qubit superconducting quantum computing capabilities.
IBM **Quantum**	December 2023	Integrating Q-CTRL's error suppression technology into IBM Cloud Quantum Services allows users to reduce error rates with just the flip of a switch

Quantum Computing Cloud Platform Competitive Landscape

Currently, the main users of cloud platforms are universities, research institutions, businesses involved in software algorithm development and validation, developers of peer cloud platforms, students, and trainees aspiring to enter related fields. Potential users include R&D institutions empowered by quantum computing in various industries. For most users, utilizing quantum cloud platforms on a subscription basis is more economical, convenient, and feasible than purchasing and setting up quantum computers.

The competitive advantages of quantum computing cloud platforms include access to advanced hardware, long-term stability, a rich array of software tools, hybrid computing capabilities, user-friendly operations, strong ecosystem support, user privacy and security, and tailored industry application solutions. Additionally, the backend of quantum computing cloud platforms is connected to quantum computing simulators, which simulate quantum properties through classical computer programming, relying on simulated "quantum" for computations. Since computations inevitably consume storage and computing resources, most companies offer quantum computing cloud platforms as simulators for free. Physical hardware computational support often requires payment, as sustaining cloud platform operations necessitates significant financial investment.

The global competition landscape of quantum computing cloud platforms is characterized by intense diversification. Companies in Europe and America, such as IBM, Google, Microsoft, Amazon, and AQT, cover a variety of quantum computing technological approaches, including superconducting, ion trap, neutral atom, and photonic technologies. Chinese companies like Huawei, Origin Quantum, QuantumCTek, and CETC Quantum Group are also emerging, mainly following the superconducting technological approach.

In terms of development trends, the future global quantum computing cloud platforms will evolve towards technological integration, increased computational efficiency, deeper integration with other fields, and standardization. The fusion and interoperability of multiple technological approaches will offer users more choices and flexibility. Seamless integration of quantum and classical computing will improve computational efficiency and reduce costs. Deep integration with artificial intelligence, big data, and cloud computing will expand application scenarios. Standardization will enhance overall security and reliability. This competitive landscape and development trend indicate that the global quantum computing cloud platform is in a rapidly evolving stage, with all parties committed to continuous innovation and strengthening their overall capabilities to vie for global leadership.

Figure: Global Quantum Computing Cloud Platform Distribution Map

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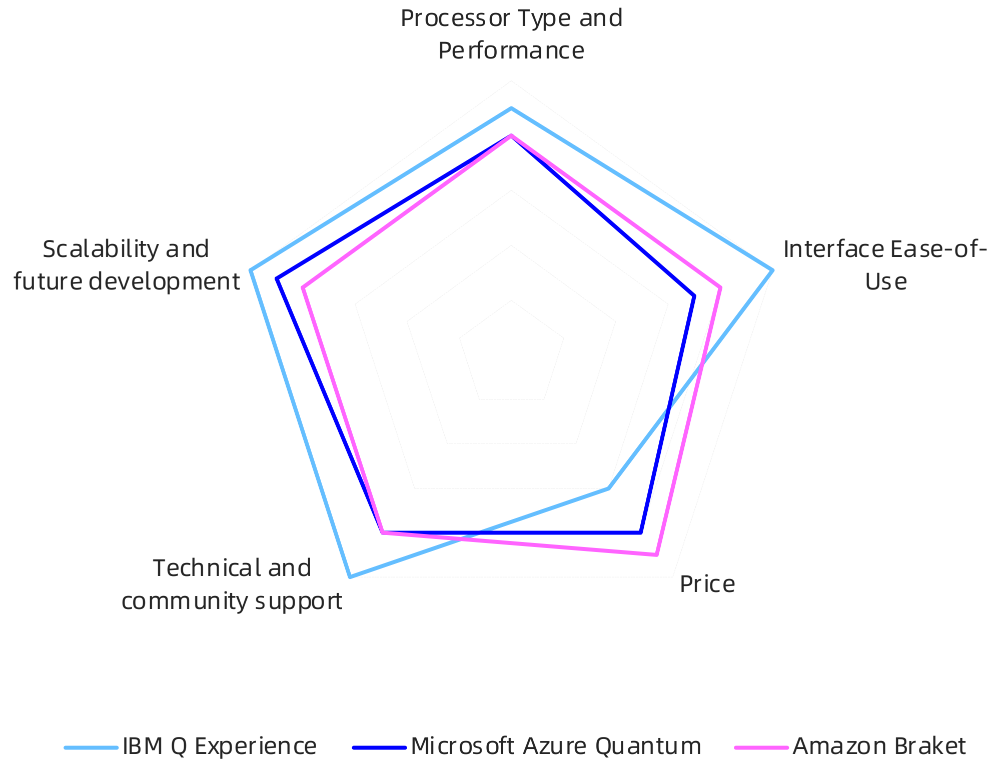
Quantum Computing Cloud Platform Evaluation

This section systematically evaluates the three most common global quantum computing cloud platforms (IBM, Microsoft, Amazon). For each cloud platform, the same circuit operation is selected, and the platforms are evaluated based on the data results returned by the platform and the overall user experience. The evaluation criteria are as follows:

Figure: Evaluation of Global Quantum Computing Cloud Platforms



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Processor Type and Performance: This includes metrics such as the number of quantum bits (qubits), quantum gate error rate, and qubit connectivity. Platforms with higher scores have more qubits, lower error rates, and better qubit connectivity, providing stronger quantum computing capabilities.

- Ease of Use Interface: This evaluates the simplicity and clarity of the platform's user interface and operational processes. Platforms with higher scores offer intuitive user interfaces and clear operational guidelines, allowing users to quickly and efficiently utilize the platform.
- Price: This considers the platform's usage fees and billing models. Platforms with higher scores provide competitive pricing, attracting more users to use the platform.

- Technical and Community Support: This assesses the platform's technical support and community engagement channels. Platforms with higher scores have professional technical teams and active communities, capable of promptly addressing user issues and sharing the latest technological advancements.

- Scalability and Future Development: This includes whether the platform has good scalability and long-term development potential. Platforms with higher scores possess flexible architectures and ongoing technological innovations, capable of adapting to evolving quantum computing needs and maintaining a competitive edge.

IBM Q Experience stands out among many quantum computing cloud platforms, receiving top ratings in processor types and performance, user interface usability, technical and community support, as well as scalability and future development. It boasts the highest number of quantum bits, the most mature ecosystem, cutting-edge error-correction technologies, and an extensive network of partners. IBM Q Experience also offers the most user-friendly interface and comprehensive development frameworks, enabling users to effortlessly design and execute quantum programs. Its only downside is its higher price, which may not be suitable for some budget-constrained users.

Azure Quantum scores highly in price, technical and community support, as well as scalability and future development. Its strength lies in offering multiple hardware vendors for users to choose from, allowing them to select different quantum architectures according to their needs. Azure Quantum also provides a unified development environment and a general-purpose programming language, making it easy for users to write and migrate quantum programs. It integrates with other Microsoft services, enabling users to implement hybrid quantum-classical solutions. However, Azure Quantum's processor types and performance are relatively lower, and the usability of its interface could be improved. It currently only offers a Python-based SDK, lacking a graphical user interface.

Amazon Braket's quantum cloud platform earns high praise for its pricing. Its advantages include offering the most flexible simulators and seamless integration with other cloud services. Amazon Braket uses a Python-based SDK, allowing users to define and execute quantum circuits and algorithms. It also integrates with other AWS services, enabling users to implement quantum-classical hybrid workflows. Amazon Braket provides a variety of hardware vendor choices, including ion trap, superconducting, annealing, and photonic quantum technologies. However, its processor types and performance are lower compared to IBM Q Experience, and it supports fewer quantum bits at the moment.

In summary, IBM Q Experience excels in various performance metrics, albeit with a higher usage cost currently. Azure Quantum and Amazon Braket have advantages in processor types, but they lag slightly behind in processor performance and usage costs.

05

Investment and Financing

Contents

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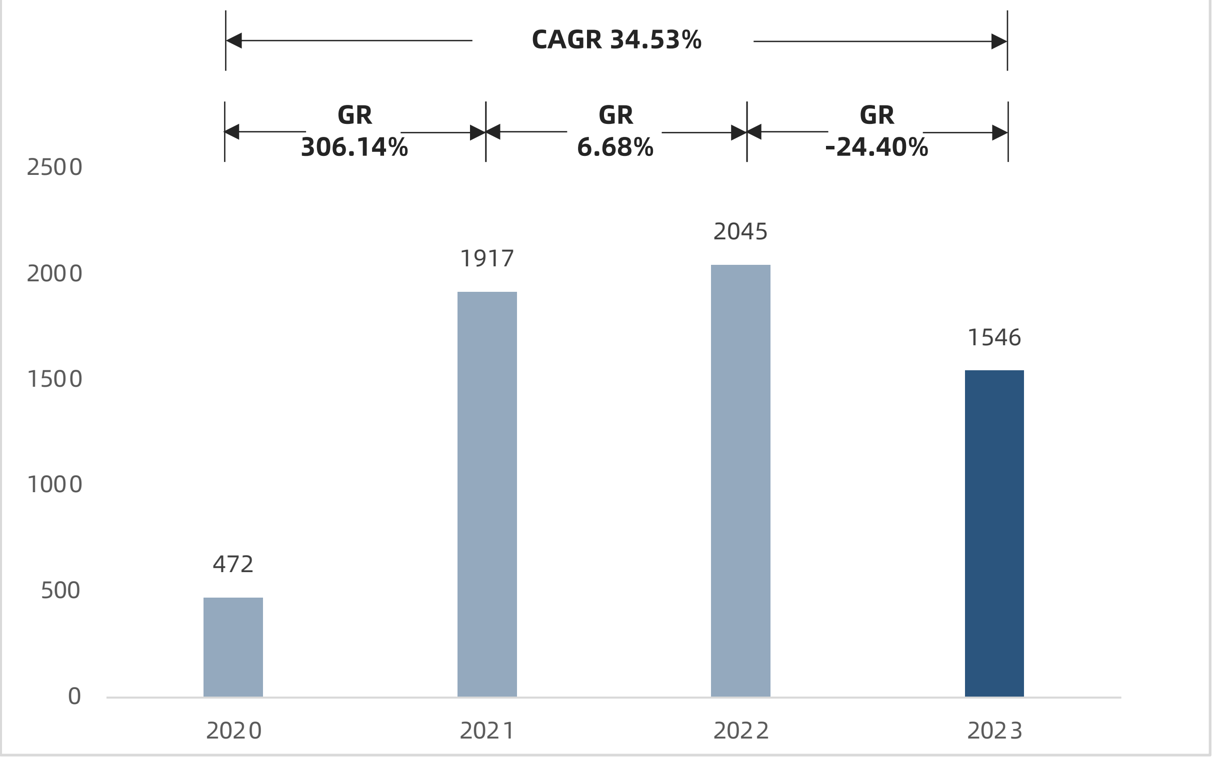
Investment and Financing

01 Financing amount growth slows down

The enthusiasm of investment institutions for quantum computing stems from two key factors: the dual drivers of national support and international competition, and confidence in the expected returns from technological breakthroughs. ICV has compiled the financing situation of major quantum computing enterprises globally from 2020 to 2023, as follows:

Figure: Total global quantum computing financing from 2020 to 2023 (unit: $M)



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The investment scale in the global quantum computing field has shown rapid growth over the past four years. From 2020 to 2023, the total global financing amount for quantum computing reached a staggering $5.98 billion, with a compound annual growth rate (CAGR) of 34.53%. However, there have been some changes in investment trends in 2023. Despite the overall substantial financing amount, there has been a slight decrease compared to the previous year, at around 75% of the previous year's level. This suggests a temporary decline in global enthusiasm for quantum computing investment, failing to sustain the momentum of the previous years.

There are multiple reasons behind this decline in investment. Firstly, external factors such as economic downturns, rising interest rates, or increased market volatility may have led to a reduction in venture capital available for emerging technologies like quantum computing. Secondly, there may have been a shift in investment focus within the quantum computing field itself, such as a move from hardware to software or from broad quantum computing platforms to more specialized applications. This transition may reflect the natural evolution of the industry but could temporarily decrease overall investment levels until new focus areas mature.

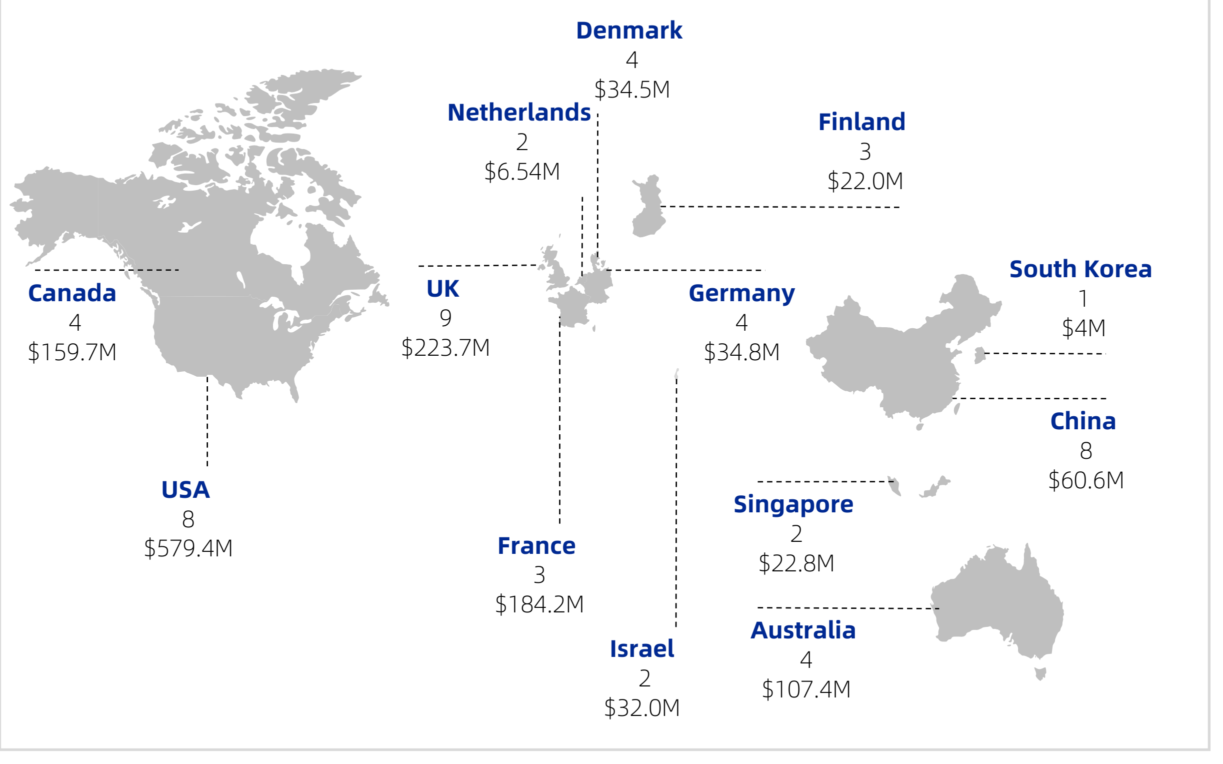
Additionally, the number of quantum computing startups founded in 2023 has decreased compared to 2022. This indicates that entrepreneurs are adopting a more cautious approach amidst the backdrop of a global economic downturn, waiting for clearer evidence of practical, scalable quantum advantages before seeking targeted financing. Investors are placing increasing emphasis on demonstrating commercial viability and clear paths to profitability. Quantum computing companies in the early stages of technical development may find it challenging to secure funding without demonstrating practical applications and potential market demand.

Furthermore, technical challenges remain significant issues facing quantum computing, such as quantum bit coherence time, error rates, and scalability. These challenges may lead investors to reassess the timeline for achieving commercially viable quantum computers, thereby affecting investment flow. In addition to technical challenges, competition from other technologies, such as advanced classical computing methods and machine learning optimization, is also diverting investors' attention and resources away from quantum computing.

02 Financing subjects are diverse and varied

In 2023, financing for quantum computing across various countries continued to exhibit diversity and geographical dispersion. Overall, the United States remains far ahead in terms of investment scale and level in the quantum computing field. Several European countries show high levels of investment activity and standards in quantum computing, while China still lags behind the United States and European countries in terms of the scale of venture capital investments in quantum computing.

Figure: Financing overview of quantum computing companies in various countries in 2023 (Unit: transactions, $M)



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In terms of total financing volume, the United States leads with a total financing volume of 579.4 million dollars, far surpassing other countries and regions. This demonstrates the United States' enthusiasm and strength in investment in the field of quantum computing, as well as its leading position in quantum computing technology and the market. Following are the United Kingdom with 223.7 million dollars and France with 184.2 million dollars, ranking second and third respectively, showing the overall development level and activity of Europe in the field of quantum computing. Although China's total financing volume of 60.6 million dollars leads in Asian countries, it still lags far behind the United States in terms of magnitude.

Looking at the number of investment transactions, the United Kingdom, the United States, and China are the top three countries, with 9, 8, and 8 deals respectively. This indicates that these countries have a wide range of investment activities in the field of quantum computing, involving multiple types and fields of upstream enabling technologies. European countries as a whole have a higher number of investment transactions, reaching 25, which accounts for about half of the global total.

In recent years, the pressure of macroeconomic downturn has made investors more cautious, preferring to choose relatively mature investment fields with clear short-term revenue prospects, thereby affecting the overall financing volume and activity in the field of quantum computing. As quantum computing technology is still in the development stage with higher risks, investors have become more prudent, leading to more conservative and rational investment trends under such economic conditions.

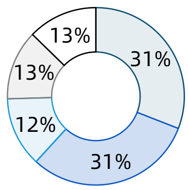
03 The diversification of financing companies

In the post-pandemic era, the economic environment remains sluggish, with the impact of high inflation rates and other factors continuing. This has adversely affected investment in cutting-edge technology fields such as quantum information technology. In the field of quantum computing, the amount of financing has decreased compared to 2022, but the number of financing rounds has slightly increased. In 2023, there were a total of 55 financing events in the field of quantum computing, with the most being transaction A and seed rounds (both are 17 rounds), followed by Series B (7 rounds) and non-equity forms of government funding (7 rounds), with 7 rounds in other categories.

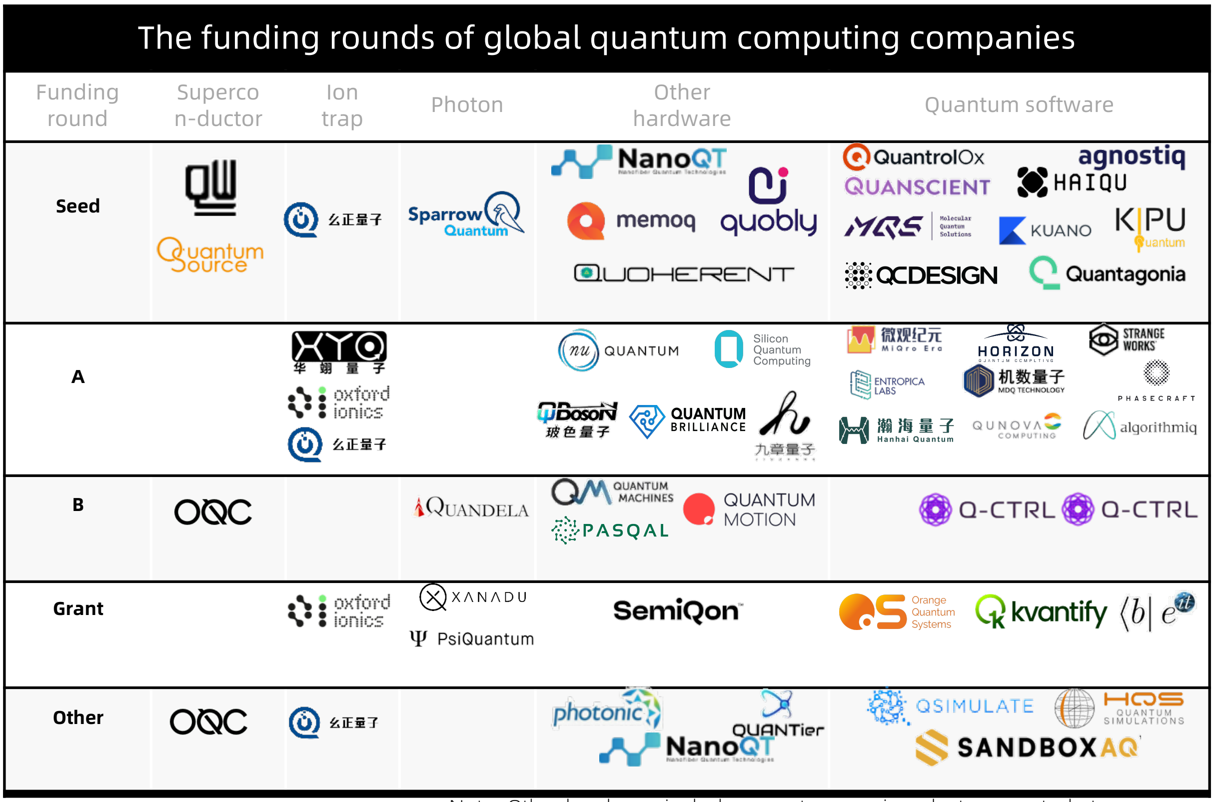
The financed companies are primarily diversified in their core business, encompassing various technological paths, including core hardware and software components. Compared to the financing landscape of 2022, there is a notable increase in hardware ventures that extend beyond the level of complete systems, as well as quantum software enterprises that adhere to a lightweight asset model.

Figure: The comprehensive funding situation of global quantum computing companies in 2023 (Unit: Round, Transaction, Amount)

Funding Rounds & Transactions



	Seed	A	B	Grant	Other
Round/Transaction	17	17	7	7	7
Amount	$148M	$252M	$390M	$133M	$618M



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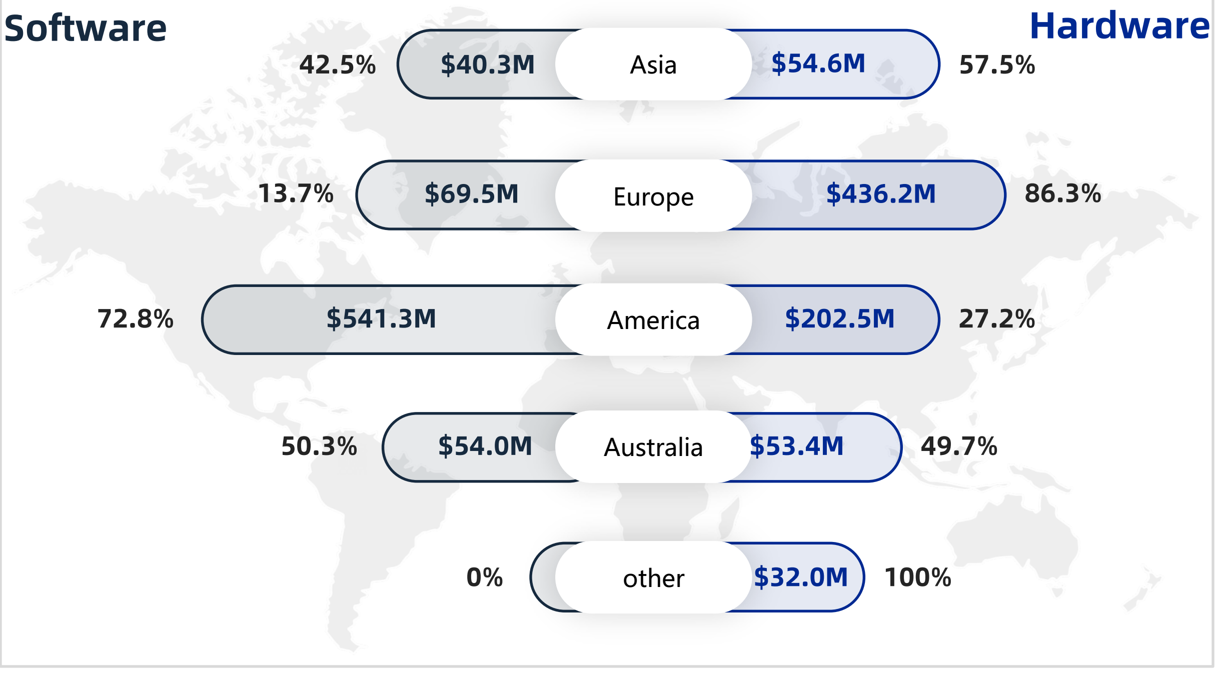
Note: Other hardware includes quantum semiconductors, neutral atoms, computing control systems, quantum memories, etc.

The main research areas of companies participating in the quantum computing industry are diverse, including neutral atom quantum computing, photonic quantum computing, superconducting quantum computing, diamond NV center quantum computing, and quantum software. Compared to the financing rounds and technology routes distribution in 2022, it is evident that hardware companies other than superconducting, ion trap, and photonic quantum technology routes, as well as quantum software companies that comply with asset-light models, are gradually receiving attention from capital.

04 Financing trends shift towards software

In 2023, global venture capital in quantum computing shifted from hardware to software. The development and manufacturing of quantum computing hardware had already attracted significant social capital in previous years, leading to a tightening of investment opportunities and targets for new investors at the current stage. Compared to hardware, software development represents a lighter asset, which may have consequently received financing under the current economic conditions and technological circumstances.

Figure: 2023 Global Quantum Computing Software and Hardware Financing Proportion



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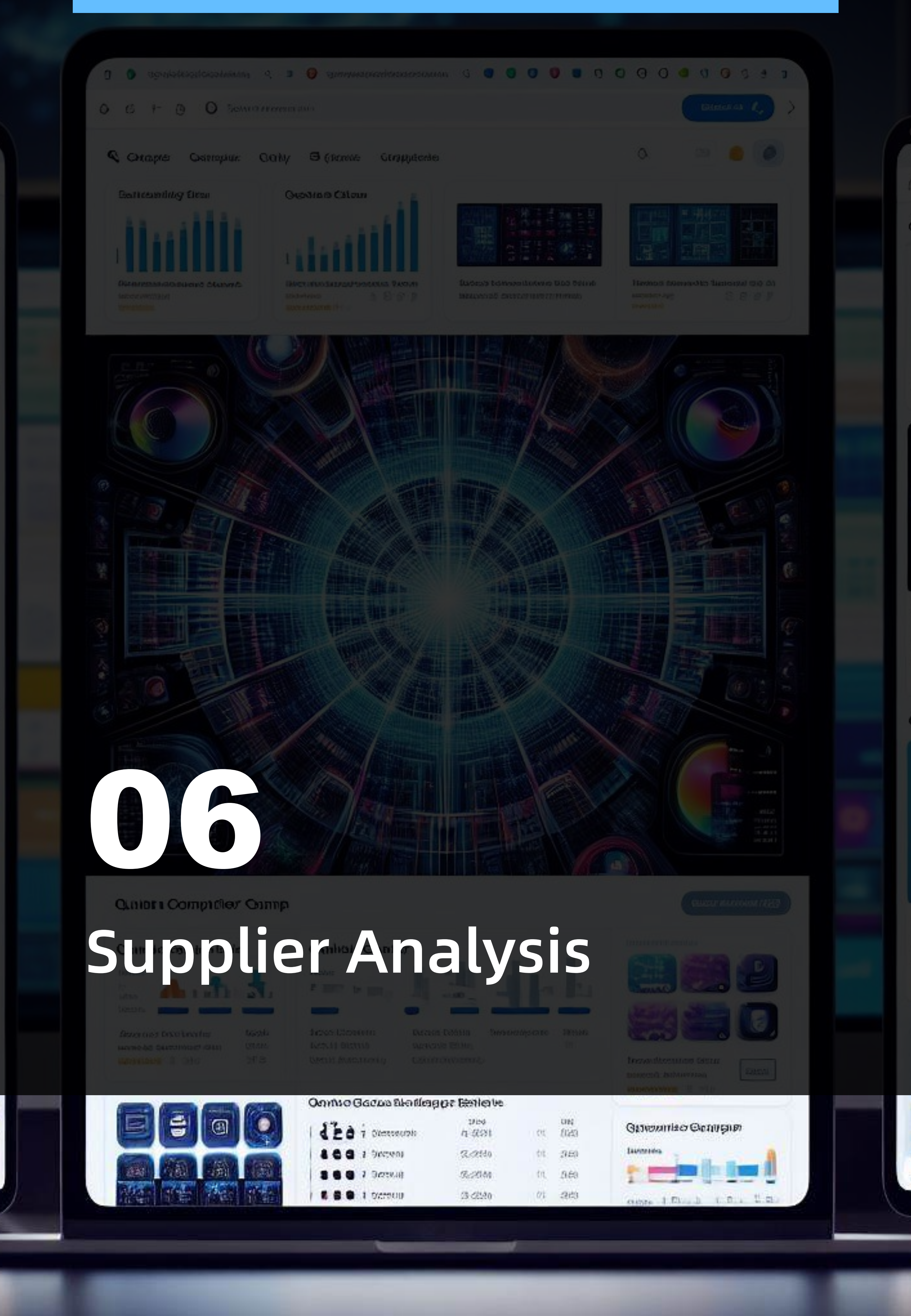
In the field of quantum computing, the Americas demonstrate a clear advantage in software investment. Firstly, with quantum computing hardware technologies maturing in the Americas, investors are increasingly focused on leveraging the full potential of these hardware advancements. The stability and reliability of hardware technologies naturally shift investment focus towards software development. Secondly, as the demand for quantum software grows with the expansion of quantum computing applications, the Americas, particularly Silicon Valley, boast the world's most vibrant innovation ecosystems, providing an ideal environment for quantum software innovation. Investors may perceive this innovative ecosystem as capable of incubating more commercially viable quantum software projects. Additionally, investors in the Americas are generally more inclined to take risks, especially in the technology sector. This risk appetite may prompt them to invest earlier in emerging quantum software fields, seeking opportunities for high-risk, high-return investments.

Conversely, in Europe, the dominance of hardware investment may stem from its deep research and development foundation and technological expertise in the field of quantum computing hardware. The policy environment in Europe and the financial support for technological research and development may also encourage investors to prioritize hardware investments to maintain a leading position in technology.

The investment trends in Asia and Australia are gradually shifting from hardware to software, mainly due to the significant gap in quantum computing hardware technology levels compared to Europe and the Americas, as well as the lack of leading technical talent. Therefore, companies and investors are beginning to seek new growth opportunities. Software companies with lower fixed asset requirements can quickly get their operations up and running with minimal financing, gradually gaining favor in the capital market.



06

Supplier Analysis

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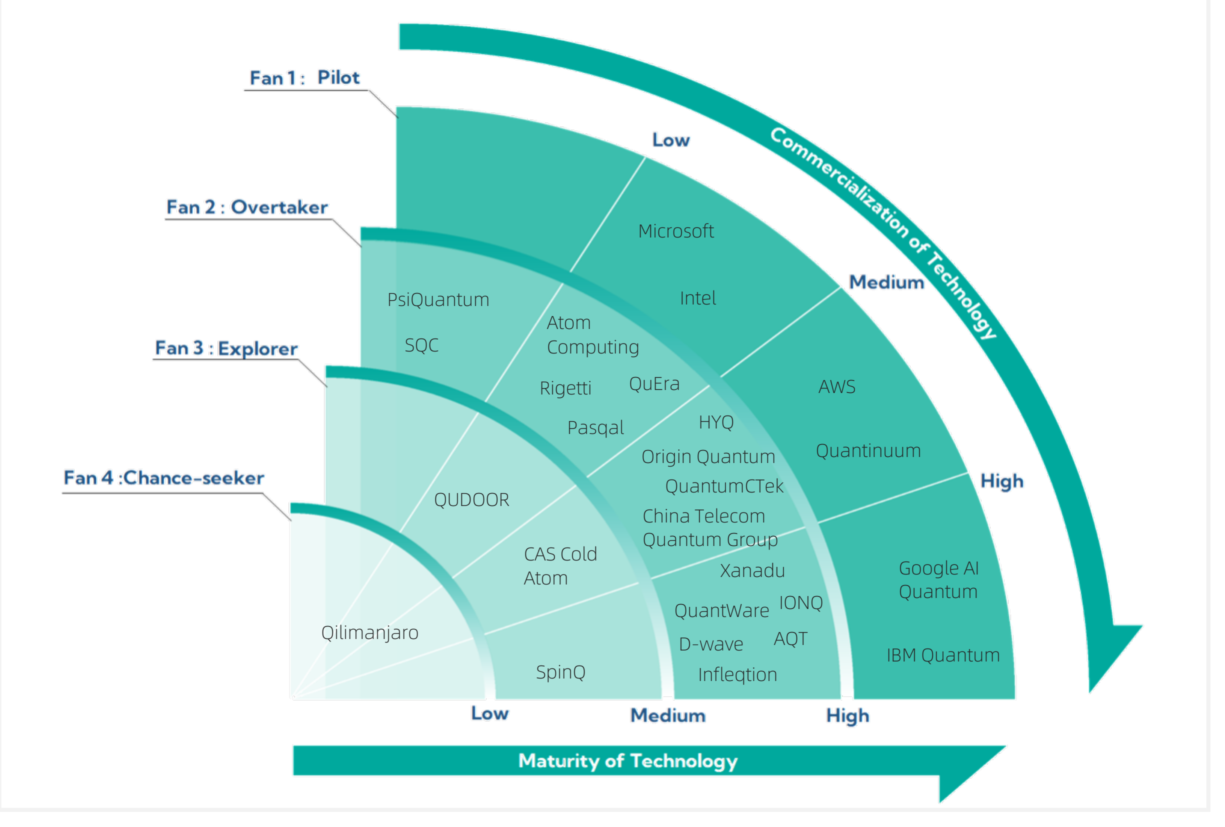
Supplier Analysis

01 Quantum computing computational capability supplier landscape

The CTF model of ICV TA&K helps the public understand the development of cutting-edge technology fields and corresponding companies. Cutting-edge technology has many characteristics such as un-converged technology routes, high uncertainty in technology development, and early stage of commercialization promotion. With the continuous development of technology, a reasonable model is needed to evaluate the company, and form a consensus on the comprehensive evaluation of cutting-edge technology suppliers in specific periods.

The CTF model consists of four differently-sized fan-shaped regions and three-dimensional coordinates. The horizontal coordinate is the Maturity of Technology (i.e. the technology, R&D, team), the lateral coordinate is the Commercialization of Technology (i.e. the revenue, customer, application case), and the vertical coordinate is the Enterprise Heritage (i.e. the elements that the supplier has accumulated over the long-term operation that can help the development of the enterprise). The CTF model divides suppliers into the following four fans according to their comprehensive performance in three dimensions: Pilot, Overtaker, Explorer, and Chance-seeker.

Figure: Global Quantum computational capability Supplier Evaluation System



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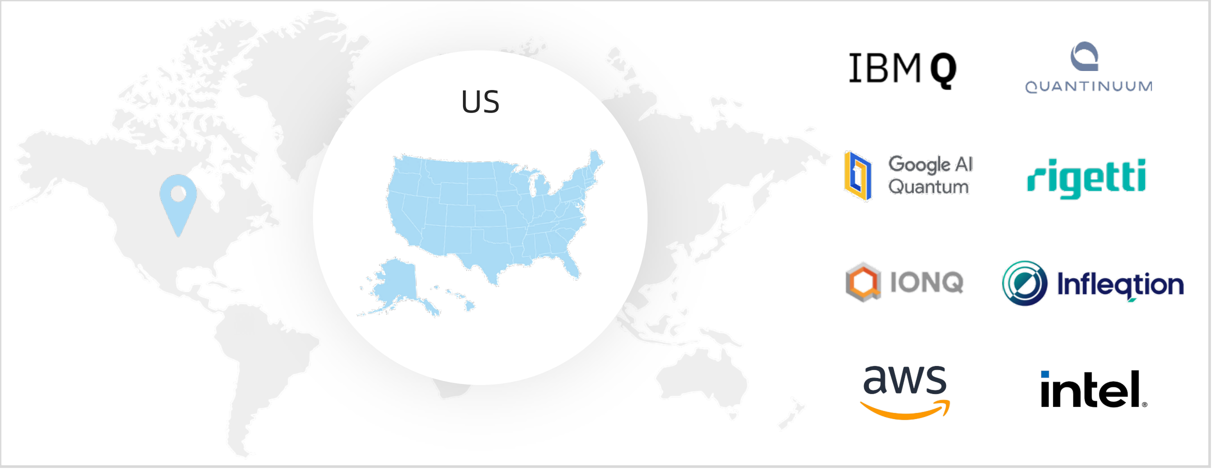
02 Typical Enterprise Analysis

US supplier reviews

Figure: American quantum computational capability supplier



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IBM Q

Key advantages include the Qiskit software framework and quantum runtime, enabling faster and more reliable computation. Quantum serverless offers developers cloud-based services for sampling non-classical probability distributions. They collaborate with industry, academia, and government through the IBM Quantum Network. New technological roadmaps are released, featuring the launch of 1000+ QPU and innovative quantum computer cluster architectures.

QUANTINUUM

A new processor named H2 was launched, featuring 32 fully connected high-fidelity qubits and an innovative architecture that enhances connectivity. H2 utilizes all-to-all connections, qubit reuse, mid-circuit measurement with conditional logic, and industry-leading high-fidelity qubit operations. It also demonstrated scalability potential and set a new record in terms of quantum volume.

Google AI Quantum

A paper was published on reducing quantum errors by expanding logical qubits, showcasing their technical prowess. Furthermore, they successfully implemented non-Abelian braiding on a superconducting processor, demonstrating their capability to explore new quantum computing methods. Their subsidiary, Sandbox AQ, raised $500 million for cybersecurity and other quantum efforts.

The Ankaa-1 system was released in March with outstanding performance, boasting a median fidelity of 96-97% for 2 qubits and fast gate operation speeds. In the future, Rigetti plans to launch the Ankaa-2 system with the goal of narrowing the quantum advantage, achieving a median fidelity of 98% for 2 qubits. Their long-term roadmap includes the development of the Lyra system with 336 qubits. However, as a publicly traded company, Rigetti faces challenges such as financial losses and recent layoffs, which may impact its long-term stability.

The founder is a pioneer in the field of ion trap quantum computing, with extensive research experience. It is the first quantum computing startup to go public, raising hundreds of millions of dollars in funding. The company is actively developing distributed quantum computing capabilities. It has acquired companies to research the next generation of networked quantum computing architectures and full-stack quantum compilers. Additionally, the company provides backend support for AWS with its new Aria system, featuring 25 algorithmic qubits. The company has also signed a $25 million contract with the U.S. Air Force Research Laboratory (AFRL).

Infleqtion is the world's largest quantum computing company in the neutral atom pathway. The company has been dedicated to accelerating the commercialization of quantum computing technology based on neutral atoms and is developing quantum computers based on laser-cooled neutral cesium atoms. In 2023, Infleqtion announced the launch of its first compact vacuum system for neutral atom research and quantum application development, the next-generation miniMOT V2, showcasing a photonic integrated MOT (PICMOT) that utilizes photon chips to deliver laser cooling beams.

The world's largest cloud computing service provider, which offers access to hardware for four types of quantum computing: annealing, superconducting, ion trap, and photonic quantum. The company has made significant progress in fault-tolerant quantum computing research. In 2023, it introduced the new Trainium2 quantum chip, boasting an error rate of just 0.1% and twice the energy efficiency of the previous generation. Additionally, it launched the Graviton4 chip, which offers a 30% performance improvement over its predecessor.

Tunnel Falls, the world's leading semiconductor company, which holds an advantage in integrated technology, is the chosen enterprise for the topological quantum computing route focused on hardware error correction. In 2023, it released the Tunnel Falls quantum chip, featuring 12 quantum bits, built using mainstream CMOS technology.

China supplier evaluation

Figure: Chinese quantum computational capability supplier

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本源量子 ORIGIN QUANTUM

Established in 2017, this company has strategically positioned itself in both the superconducting and semiconductor quantum computing fields, covering chip design and manufacturing, core hardware, and software. They have released a range of products including the Q-EDA quantum chip design software, semiconductor quantum chip circuit boards, quantum chip laser annealers, quantum chip non-destructive probe stations, and high-vacuum storage boxes for quantum chips. Their third-generation 72-qubit superconducting quantum computer, "Source Wukong," is currently operational and available for use via their cloud platform. In terms of industry collaboration, they have partnered extensively with sectors such as finance, healthcare, and chemical engineering. Additionally, the company has published educational materials such as the book "Introduction to Quantum Computing and Programming" and quantum computing teaching aids. They also organize quantum computing competitions, aiming to not only enrich their product offerings and brand promotion but also to cultivate talent within the industry.

Founded in 2009, this company stands as the sole publicly listed quantum information enterprise in China. Collaborating with institutions such as the University of Science and Technology of China and the Shanghai Institute of Technical Physics of the Chinese Academy of Sciences, they have successfully developed the superconducting quantum computing prototypes "Zuchongzhi-1" and "Zuchongzhi-2." In 2021, they unveiled the first-generation quantum computing measurement and control system, with ongoing research into the second-generation system. The company has also expanded its product offerings to include ancillary equipment such as dilution refrigerators, low-temperature signal transmission systems (including low-temperature cables and devices), and software. In 2023, QuantumCTek released the "Zuchongzhi-2," a 176-qubit quantum computing prototype, integrated into a cloud platform.

Established in 2022, the company has developed an ion trap quantum computing system that offers users various internationally leading ion trap architectures. In 2023, the company completed a strategic financing round totaling hundreds of millions of yuan and released the first-generation commercial prototype of the ion trap quantum computer, named HYQ-A37, with a scale of 37 qubits. Its relevant performance indicators have reached the international first-class level. Additionally, the company's HYQ-A37 underwent iterations in May, maintaining a one-dimensional ion crystal containing 92 ytterbium-171 ions without ion loss for several hours, laying a solid foundation for large-scale ion trap quantum computing in the future.

Established in 2018, the company has completed the integration of industrial-grade superconducting quantum computers, including superconducting quantum chips, radio frequency control systems, dilution refrigerators, quantum cloud platforms, quantum operating systems, and application software. In 2023, QuantumSpin's international market expanded to more than 30 countries and regions globally. The company's educational-grade nuclear magnetic resonance quantum computing products were delivered to the Bandung Institute of Technology in Indonesia and the National Autonomous University of Mexico, entering the Southeast Asian and Latin American markets. Additionally, superconducting quantum computing chips were delivered to research institutions in the Middle East.

Established in 2023, it is a wholly-owned subsidiary of China Telecom Corporation Limited. Leveraging China Telecom's expertise in the information field, the company has made rapid progress in the field of quantum computing since its establishment. In November 2023, the company launched the "Tiandyan" Quantum Computing Cloud Platform. This platform integrates the supercomputing capabilities of "Tianyi Cloud" with 176-qubit superconducting quantum computing capabilities, establishing a hybrid computing framework system that supports a series of quantum algorithm and quantum simulation computing applications.

Established in 2020, the company is a leading enterprise in China's neutral atom quantum computing route. Currently, the company has completed the development of products including lasers, optical amplifiers, and desktop magneto-optical traps in the optical system. In 2023, the company demonstrated the first portable atomic quantum computing debugging prototype machine in China, called "Hanyuan-1," capable of performing lossless rearrangement of 16 qubits. The team's prototype machine, under laboratory conditions, can operate with over 300 qubits and also features leading-edge lossless rearrangement algorithms for heterogeneous atomic arrays. Additionally, the company has established internship and practical training bases with the School of Mathematics and Physics at China University of Geosciences (Wuhan) and has won awards in several innovation projects competitions in China.

Established in 2019, the company possesses proprietary modular ion trap quantum computing engineering machine ARTIO architecture quantum computing measurement and control system Qusoil, ion trap cryogenic vacuum system <Aba|Qu|Cryovac>, and ion trap environmental control system <AbalQuENV>. The company has obtained the CMMI Level 3 certification in the software development field and is currently developing a full-stack quantum software system. In 2023, the company relocated its headquarters from Beijing to Hefei, enhancing its research and development capabilities.

Canada supplier evaluation

Figure: Canadian quantum computational capability supplier

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Xanadu leverages squeezed states and silicon photonic devices. In 2023, Xanadu launched the first public cloud-deployed computer with a quantum advantage, capable of solving a problem in 36 microseconds, compared to the 9,000 years required by classical supercomputers. The company collaborated with Rolls-Royce on quantum machine learning, automatic differentiation, and optimizing quantum-classical hybrid computing; established a global partnership with the Pawsey Supercomputing Centre; and worked in collaboration with NVIDIA.

In 2023, Davidson Corporation and Davison Corporation are jointly committed to advancing intelligent technology solutions for the defense and aerospace industries, creating applications that support various mission objectives, including supply chain optimization, logistics management, weapon system optimization, and vehicle routing. These solutions are currently available through the company's Leap™ Quantum Cloud Services and can collaborate with other technologies such as high-performance computing and artificial intelligence/machine learning (AI/ML).

Australia supplier evaluation

Figure: Australian quantum computational capability supplier

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Silicon Quantum Computing

Led by the founders of the Centre for Quantum Computation and Communication Technology (CQC2T) in Australia, SQC is utilizing silicon as a foundational material, achieving several world-first breakthroughs in the field of quantum computing. These achievements include the longest coherence times and the highest fidelity quantum bits in solid-state systems. In 2023, SQC signed a contract with Silex Systems, with the latter providing crucial material, zero-spin silicon (ZS-Si), to support information storage and retrieval for silicon-based quantum processing chips.

QUANTUM BRILLIANCE

Through diamond-based hardware innovation, they aim to reduce the size of quantum computers to the size of modern personal computers, while releasing the Qristal software suite in 2023 to support developers and researchers to integrate quantum systems in real-world applications and test new types of Quantum algorithms.

European supplier evaluation

Figure: European quantum computational capability supplier

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In 2023, Pasqal launched Quantum Discovery, a neutral atom quantum computing exploration platform. The platform includes access to PASQAL's quantum simulator and 100-qubit quantum processing unit, allowing users to experience a real-world quantum computer.

IQM specializes in developing co-designed quantum computers optimized for specific applications. The company plans to collaborate with VTT to launch a 54-qubit superconducting quantum processor in 2024. IQM's proprietary technology combines quantum hardware and software design to achieve optimal performance and scalability. Their quantum cloud services can be accessed through popular programming frameworks, showcasing IQM's innovation in quantum computing. With a focus on customer experience and support, IQM aims to cater to various industries with their jointly developed quantum computers with VTT.

OQC was founded in 2017, specializing in utilizing patented 3D architecture to build superconducting quantum bits and quantum processors. OQC claims that its 3D approach enhances the coherence and connectivity of quantum bits and enables modular scalability of quantum processors. OQC also offers cloud-based quantum computing services called "Quantum Computing as a Service," which is the first platform of its kind in the UK and Europe, allowing users to access its quantum processors and run applications on platforms like Amazon Braket. OQC has been recognized as a technology pioneer by the World Economic Forum in 2023 for its innovation and impact in the field of quantum computing.

AQT is a rapidly growing company in the field of trapped ion quantum computing. In 2021, they launched PINE, the world's first quantum computer that fits into a standard 19-inch rack. They plan to develop more powerful processors with hundreds or thousands of qubits in the coming years. In 2022, AQT launched ROWAN, a laser light control system that supports up to 50 qubits; in 2023, they plan to launch BEECH, an ultra-low drift optical benchmark for quantum applications. AQT's proprietary technology utilizes individual atoms as qubits and provides quantum processor access through major cloud platforms. They have demonstrated market understanding and operational capabilities and participated in the EU flagship project MILLENION to build a quantum internet ecosystem.

Oxford Ionics is developing high-performance quantum computers using trapped ion technology and noiseless electronic qubit control. In 2023, Oxford Ionics secured £30 million in Series A funding from leading quantum and technology investors. Oxford Ions also demonstrated a trapped ion processor with high-fidelity gates and long coherence times. Oxford Ionics' unique advantage is its use of a proprietary, patented Electronic Cupid Control (EQC) system, which eliminates the need for expensive and complex lasers typically used in trapped ion systems. Oxford Ionics' distinctive feature is the integration of its quantum processors with standard semiconductor production lines, enabling the scalability and reliability of quantum chips.

ORCA Computing uses fiber optics to connect modular quantum processors and operates at room temperature. In 2023, they launched the PT series of rack-mounted, air-cooled, photonic quantum computers based on standard optical fiber components, which can be integrated with classical computing equipment and workflows and are suitable for quantum-classical hybrid machine learning applications; launched the PT series of software development tools Package (SDK); works with government and enterprise customers to explore and develop quantum computing applications across industries and across domains, such as generative machine learning and optimization. Their strength lies in their ability to provide high performance, high scalability, high availability, and low-cost solutions.

Quandela's technology is the result of groundbreaking research in nanotechnology and photonics for over 20 years. In 2023, they introduced Prometheus, a high-quality single-photon source crucial for modern quantum technologies, enabling quantum-secure communication networks and scalable quantum processors. They launched Quandela Cloud, a photon quantum computing service that allows users to send tasks to Quandela's quantum processing units (QPUs) and monitor them in real-time. They also unveiled MOSAIQ, a modular, reconfigurable, interconnected, and scalable photonic quantum computing platform. Additionally, they released a Python-based photon quantum machine learning programming framework compatible with PyTorch.

07

Industry Analysis and Forecast

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Industry Analysis and Forecast

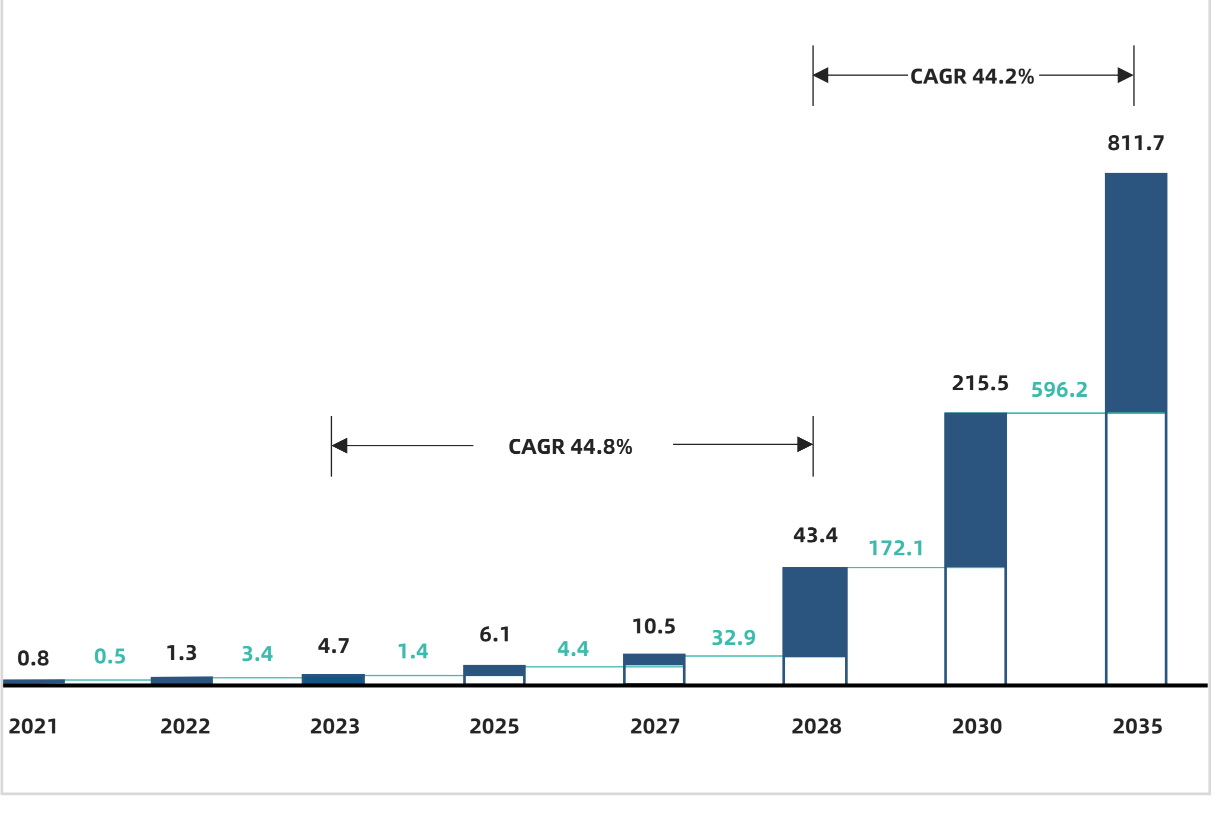
01 Forecast of Industry Scale

ICV still believes that the end of 2027 to early 2028 will be an important milestone for the entire industry. Specialized quantum computers will gradually solve specific problems such as combinatorial optimization, quantum chemistry, and machine learning, guiding material design and drug development.

Compared to last year, there are two main reasons for the upward adjustment of the quantum computing market size forecast in this report. First, referring to IBM's latest technology roadmap, it is expected that by 2028, the number of quantum gates and error correction and other computing technologies will reach a relatively mature stage, laying a solid foundation for practical commercial applications.

Second, with the continuous evolution of quantum computing technology and the rapid development of artificial intelligence (AI) technology, large-scale models, machine learning, and other fields, the application boundaries of quantum computing are constantly expanding, making the commercial potential of quantum computing more extensive and profound.

Figure: Global Quantum Computing Industry Scale (2021-2035) (Unit: $B)



In 2023, the global quantum industry reached a scale of $4.7 billion USD, with a Compound Annual Growth Rate (CAGR) of 44.8% from 2023 to 2028, which essentially complies with the industry's development trend. By 2027, specialized quantum computers are expected to achieve performance breakthroughs, driving the overall market size to reach $10.54 billion USD. From 2028 to 2035, the market size is projected to continue expanding rapidly, benefiting from the technological advancements of general-purpose quantum computers and the widespread application of specialized quantum computers in specific fields. By 2035, the total market size is expected to reach $811.7 billion USD. This nearly trillion-dollar market scale marks a crucial stage for quantum computing, indicating that quantum computing will enter a comprehensive stage of maturity and commercialization, foreshadowing profound and lasting impacts across various domains in the future.

02 Forecast of Industry Scale in Various Regions

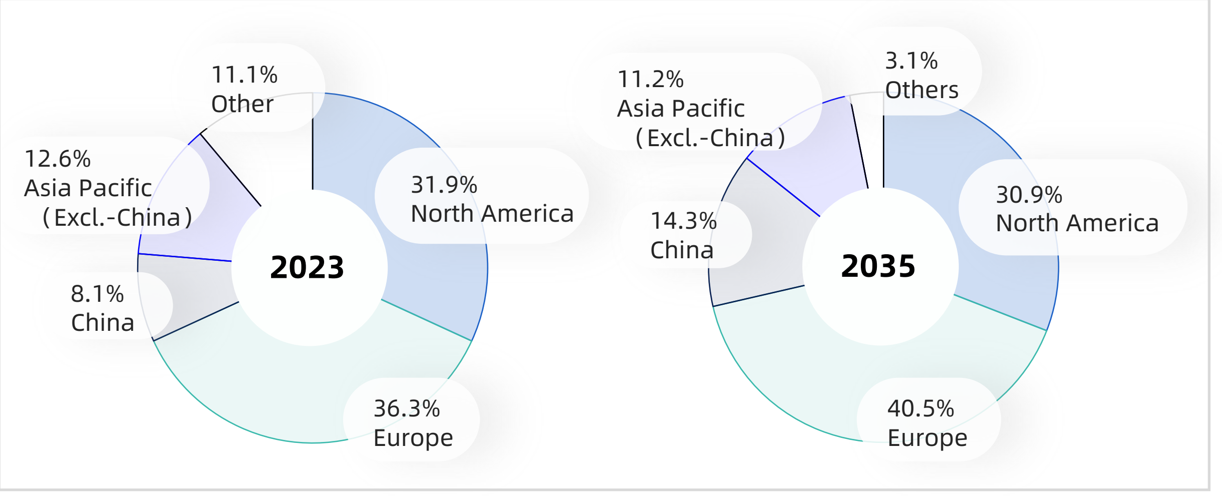
The global quantum computing market is experiencing dynamic changes. In 2023, the global quantum computing market reached $23.8 billion, with China accounting for 8.1%, the Asia-Pacific region (excluding China) 12.6%, other regions 11.1%, and North America 31.9%. Benefiting from its strong research and development foundation, active scientific institutions, and policy support, Europe had the largest share at 36.3%, reflecting its significant influence in the field of quantum computing. Additionally, North America, with innovation centers like Silicon Valley, also plays a crucial role in quantum computing development.

By 2035, as the quantum computing market continues to mature and develop, the global market size will soar to $811.71 billion. During this period, China's market share will significantly increase to 14.3%, showcasing China's rise in the global market. The Asia-Pacific region (excluding China) will slightly decrease to 11.2%, other regions will account for 2.1%, North America will maintain its position at 31.9%, while Europe's market share will further rise to 40.5%.

The increase in China's market size can be attributed to its strong capabilities in technological innovation and research and development. The Chinese government has been actively promoting technological innovation, striving to enhance the country's research level in the field of quantum computing through funding, policy support, and research institution construction. This support has fostered a collaborative innovation ecosystem among universities, research institutions, and enterprises, driving technological breakthroughs in the field of quantum computing.

Although the market share of the Asia-Pacific region (excluding China) is decreasing, the overall market size is still growing rapidly, indicating that the region maintains a strong development momentum in the field of quantum computing. This may be attributed to the proactive efforts of other countries in the Asia-Pacific region to promote technological innovation and develop emerging technologies, albeit slightly lagging behind China.

Figure: Global Quantum Computing Industry Scale by Region (2023 & 2035) (Unit: %)



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North America has always been a center of global technological innovation, and it will continue to have a significant market share in 2035, reflecting its leading position in the field of quantum computing. The United States has numerous world-class research institutions, companies, and innovation centers, continuously investing substantial funds in quantum computing research and development to ensure its competitiveness in the market.

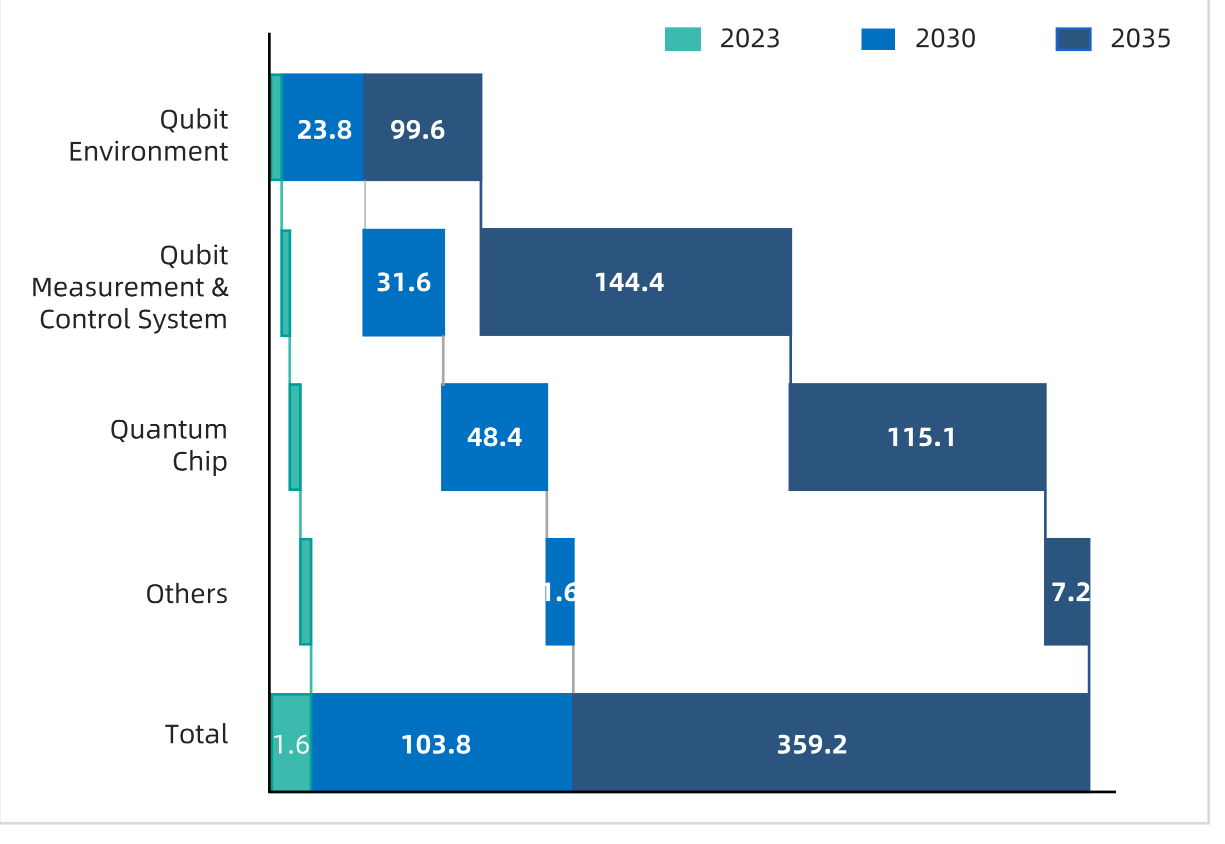
The rise in Europe's market share is due to its continuous research and development investment, policy support, and the prosperity of its innovation ecosystem. European countries are actively building research cooperation networks, promoting international cooperation and knowledge sharing, enabling Europe to form a strong united force in the field of quantum computing.

03 Forecast of Upstream Hardware Segmented Market Scale

The development of the upstream market in the field of quantum computing is crucial, mainly divided into quantum bit environment, quantum bit measurement and control systems, quantum chips and others. Technological advancements, expanding application areas, policy support, increased investments, and challenges and opportunities in commercialization have collectively driven the rapid development of the quantum computing market. From 2023 to 2035, the upstream market size shows a significant growth trend, with the total market size increasing from less than $2 billion in 2023 to hundreds of billions of dollars in 2035.

The rapid growth of the quantum bit environment market size indicates that providing a stable and controllable environment is crucial in the evolution of quantum computing. The continuous advancement of technology has driven the increasing demand for quantum bit environments, reflecting the trend of high requirements for quantum bits, including low-temperature environments and low noise. In this process, investment in creating suitable quantum bit environments continues to increase.

Figure: Global Quantum Computing Upstream Industry Scale (2030, 2030, 2035, Unit: $ B)



At the same time, the market size of quantum bit measurement and control systems has grown most rapidly, from a few hundred million dollars in 2023 to $31.6 billion in 2030, and finally to $144.4 billion in 2035, spanning three orders of magnitude. Measurement and control systems are crucial for maintaining the coherence of quantum bits and achieving quantum computing tasks. The development of technology has driven the increasing demand for more precise and efficient measurement and control systems, thereby driving the significant growth of the market size.

The rapid growth in the market size of quantum bit environments underscores the crucial importance of providing stable and controllable environments in the evolution of quantum computing. The continuous advancement of technology drives the increasing demand for quantum bit environments, reflecting a trend towards high requirements for quantum bits, including low-temperature environments and low noise. In this process, investment in creating suitable quantum bit environments continues to grow.

Meanwhile, the market size of quantum bit measurement and control systems experiences the most rapid growth, escalating from a few hundred million USD in 2023 to 31.6 billion USD in 2030, and ultimately reaching 144.4 billion USD in 2035, spanning three orders of magnitude. Measurement and control systems are crucial for maintaining the coherence of quantum bits and achieving quantum computing tasks. The development of technology drives the continuous demand for more precise and efficient measurement and control systems, thereby propelling significant growth in the market size.

Similarly, the market size of quantum chips experiences exponential growth by 2030 and 2035. As the core components of quantum computing, quantum chips play a crucial role in realizing quantum computing tasks. With increasing requirements for quantum computing performance, the demand for more advanced and scalable quantum chips continues to rise, driving significant growth in the market size.

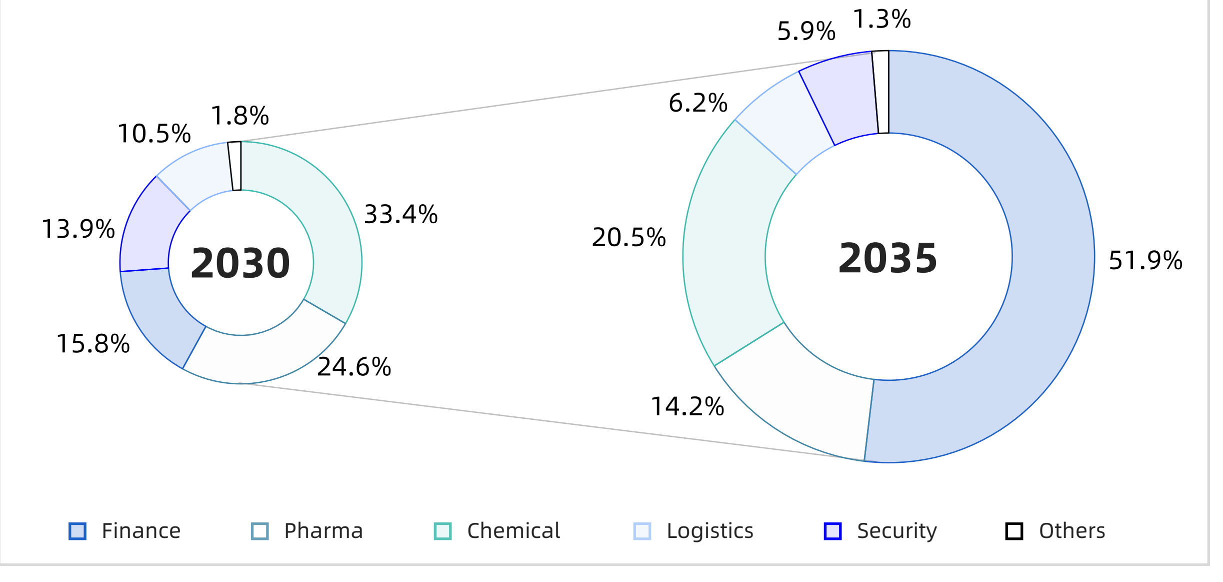
04 Forecast of Downstream Application Market Scale

The industry application collaborations of quantum computing encompass various sectors such as defense, finance, healthcare, automotive, and chemical industries. In these domains, large enterprises or industry giants with years of experience have partnered with quantum computing software and hardware companies to address current practical problems and challenges.

It is noteworthy that these partners are not specialized quantum software companies but rather experienced giants in their respective fields accumulated over many years. They have a deep understanding of the development direction and needs of their industries. By collaborating with quantum computing software and hardware companies, they can address practical problems that require large-scale computing capabilities and engage in collaborative exploration. These partners have an in-depth understanding of the development direction and pain points of their respective industries. Through collaboration with quantum computing software and hardware companies, they can jointly explore and develop quantum computing solutions applicable to their industries.

Through inter-industry collaborations, users and enterprises can fully leverage the capabilities of quantum computing to solve complex problems and optimize various business processes. This collaborative model drives the application of quantum computing technology and brings significant potential and opportunities to different industries.

Figure: Global Quantum Computing Downstream Application Scale (2030, 2035) (Unit: %)



In 2035, the market share of the finance sector reached 51.90%, a significant increase from 15.8% in 2030. This change primarily stems from the profound recognition of quantum computing technology in the finance industry, particularly in areas such as risk management and portfolio optimization. The powerful computational capabilities of quantum computing give it superior performance in addressing financial challenges, leading to a rapid increase in demand for quantum computing in the finance sector and the rapid expansion of market share.

Although the market share of the pharmaceutical sector declined to 14.20% in 2035, considering the significant overall market growth, and the pharmaceutical industry's early active investment in quantum computing, particularly in enhancing research and development efficiency through collaborative applications with AI large models, the relative share has decreased. However, the pharmaceutical sector still maintains a significant market size in research and development and other areas.

The market share of the chemical industry decreased to 20.47% in 2035, but the market size continued to grow significantly. This indicates that despite the decrease in proportion, the chemical industry still has a strong demand for quantum computing in materials and efficiency improvement, leading to a significant expansion of the market size. Meanwhile, the logistics and security sectors saw an increase in market share in 2035, reflecting the gradual increase in new demands for quantum computing technology in these two areas. The logistics sector improved supply chain efficiency and resource scheduling accuracy through the widespread application of offline clusters.

Additionally, factors such as artificial intelligence, quantum-computing integration, and cluster architecture also had a profound impact on the market. Industries such as finance and pharmaceuticals seek stronger computational capabilities in the development of artificial intelligence algorithms, and the rise of quantum computing provides them with more powerful computing tools, partially replacing traditional computing solutions, thereby bringing about profound changes in the market landscape. The comprehensive impact of these diverse factors has led to a multi-level development pattern in the global quantum computing market in 2035.

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Industry Outlook

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Industry Outlook

The Power of Clusters: Cluster technology may break through the performance bottleneck of quantum computers

As quantum computers evolve, the number and quality of quantum bits (qubits) on a single quantum chip have become performance bottlenecks. To overcome this limitation, cluster technology has been introduced, which connects multiple quantum processors via network to form a larger quantum system. This not only enhances the performance of quantum computers but also creates new possibilities for the fusion of quantum computing and supercomputing. By integrating quantum computers into supercomputers, the advantages of supercomputers in large-scale data processing and traditional computing can be fully utilized, complementing the advantages of quantum computers. For example, IBM's recently released modular Heron chip has 133 qubits and has improved performance by 3 to 5 times, while almost eliminating crosstalk issues. Additionally, IBM's Quantum System 2 is the first modular quantum computer, combining scalable low-temperature infrastructure, third-generation control electronics, and classical computers. This modular design not only improves the performance of quantum computers but also makes the system more flexible. Depending on computational needs, the number of modules can be easily increased or decreased, allowing for flexible resource allocation.

Furthermore, offline cluster-based quantum computers bring a range of other advantages. Firstly, they effectively address the limitation of the number of qubits on a single processor by integrating multiple processors, significantly increasing the overall number of qubits. Secondly, modular design improves the maintainability and upgradability of quantum computers, reducing overall costs. With the continuous development and improvement of technology, offline cluster-based quantum computers are expected to become the mainstream trend in the future. This will drive further development in the field of quantum computing, providing more powerful computing capabilities for solving complex and important problems. This trend will also inspire more innovative applications and solutions, promoting the widespread use of quantum computing technology in various fields.

A New Era of Cloud
Cloud platforms help quantum computing continue to expand its influence and application boundaries

Several companies and research institutions have launched their own quantum cloud computing platforms, providing convenient and fast quantum computing services, reducing the threshold and cost of quantum computing, and expanding the scope and influence of quantum computing. Cloud platform technology allows users to access quantum computing services via the internet without the need for their own quantum hardware and software. Users can design quantum algorithms, compile quantum circuits, and run quantum programs remotely. Cloud platform technology can effectively address the high cost, high threshold, and low popularity of quantum computing, providing convenience and support for the development and application of quantum computing. It is expected that in the future, with the development of internet technology and the growth of user demand, cloud platform technology will undergo more innovation and optimization, providing more features and services to meet more scenarios and problems.

Additionally, integrating quantum computers into supercomputer clusters currently requires remote links via cloud platforms. This integration method not only reduces the deployment costs and maintenance difficulties of quantum computers but also expands user access, forming a flexible and efficient computing resource sharing architecture. For example, several supercomputing centers in Europe have connected quantum computers to supercomputers via cloud services, providing users with comprehensive quantum computing capabilities. Similarly, quantum computers presented in cluster form can achieve powerful and stable computing capabilities, enabling closer and more efficient quantum-classical cooperative computing.

China's proposed collaborative operation scheme for quantum computers and supercomputers fully demonstrates the advantages of this integration method. By using quantum computers as accelerators for supercomputers, the computational scope of classical computers on specific problems has been successfully narrowed, greatly enhancing the processing speed of the entire system. This trend is expected to drive deeper and broader development in the field of quantum computing in the future, providing more advanced computing tools for solving more complex and important problems.

Quantum Superconvergence The fusion of classical supercomputing and quantum computing in the field of artificial intelligence will show great potential

In 2023, the innovative cross-fusion of supercomputing and quantum computing in the field of artificial intelligence (AI) has attracted widespread attention and exploration. This fusion includes leveraging the advantages of quantum computing to accelerate and optimize traditional AI/ML models, providing computational support for problems that supercomputers cannot solve, and using AI/ML technologies to assist and improve the efficiency and performance of quantum computing. These two aspects complement each other, jointly driving the development and improvement of large models and quantum computing technologies.

On one hand, with the continuous development of the AI/ML field, an increasing number of large models have achieved significant results in natural language processing, computer vision, recommendation systems, and other fields. However, this has also brought enormous computational costs and resource consumption. To address this challenge, some companies and institutions have begun to explore using the advantages of quantum computing to accelerate and optimize these large models. Quantum computing features such as parallelism, reversibility, and randomness can be advantageous in specific areas, such as quantum Fourier transforms, quantum machine learning, and quantum optimization algorithms. These quantum algorithms can improve the training speed of large models, reduce computational complexity, and enhance the generalization and robustness of models. For example, NVIDIA has introduced the DGX Quantum platform, which combines traditional AI/ML models with quantum computing modules, enabling hybrid computing to improve model performance and efficiency.

On the other hand, quantum computing also faces many challenges, such as designing effective quantum algorithms, optimizing quantum circuits, and controlling quantum systems. To address these issues, some companies and institutions have begun to explore using AI/ML technologies from classical computing to assist and improve the efficiency and performance of quantum computing. AI/ML technologies can help in various stages of quantum computing, such as automated quantum algorithm design, intelligent quantum circuit optimization, and adaptive quantum system control. These AI/ML technologies can improve the accuracy, stability, and scalability of quantum computing. For example, Microsoft Azure Quantum has developed a quantum simulation algorithm based on product formulas, which uses AI/ML technology to improve the efficiency and accuracy of quantum simulation.

Tendency towards Rationality
The quantum computing industry is entering a stage of rational development

Due to factors such as the risk of economic recession in the United States, the resurgence of the epidemic in Europe, and the conflict between Russia and Ukraine, the global economic growth rate is expected to be 3.2% in 2023, a decrease of 1.3 percentage points from the previous year. At the same time, constrained by factors such as the Federal Reserve's interest rate hikes, the return of cross-border capital, and market volatility, the global venture capital investment scale is expected to be $1.2 trillion, a decrease of 18.6% from the previous year. Against this macroeconomic background, the global quantum computing industry saw 23 financing transactions in 2023, with a total financing amount of $1.53 billion. Although the number of financing rounds and the amount have declined compared to the previous year, the overall trend remains relatively stable. With various uncertainties stacking up and the overall risk resistance of institutions decreasing, investors will pay more attention to the quality rather than the quantity of investments, and will focus more on the actual potential and innovative capabilities of various sectors within the industry.

In the future, the financing growth rate in the field of quantum computing will trend upwards in fluctuations, and the overall financing amount will continue to show a gradual increase. Although current investors remain cautious about the overall market risks, their confidence in the quantum computing industry remains strong, with a certain degree of optimism about its potential value and future development prospects. With the continuous advancement of technology and the improvement of market awareness, more financing opportunities may arise for the quantum computing industry.

Policy Guidance
Countries' support is continuously strengthening, providing a solid backing for innovation and development

Policy formulation has become a key driver for advancing global quantum technology development. Countries' strong focus on and active support for quantum technology are reflected in their extensive strategic plans and policy measures. These policies aim to establish the long-term development direction and goals of quantum technology and provide necessary resources and funding support.

In 2023, several countries globally issued comprehensive quantum technology plans, demonstrating consensus in this field and laying a solid foundation for the advancement of global quantum technology. The European Commission's "2030 Digital Compass: the European way for the Digital Decade" plan aims to have the first quantum-accelerated computer by 2025, paving the way for being at the forefront of quantum capabilities by 2030. The Canadian federal government invested $40 million to support Canadian quantum computing company Xanadu, enabling it to build and commercialize the world's first fault-tolerant quantum computer based on photons, pioneering the commercialization of quantum computing. The UK's Department for Science, Innovation and Technology provided over £370 million in new government funding, covering various fields such as artificial intelligence, quantum technology, and bioengineering, providing strong financial support for technological innovation and development. The Japanese Ministry of Economy, Trade and Industry decided to support the University of Tokyo in providing cloud services using the next-generation high-speed computer "quantum computer," providing about 4.2 billion yen in subsidies, which is crucial support for the application of quantum computing in the cloud services field. The construction of the Extreme Computing facility by the US Air Force Research Laboratory (AFRL) and the injection of $44 million in new federal funding further promote research and innovation in the United States in the field of quantum technology. Among them, the investment of $10 million for the distributed quantum network testing platform and quantum cloud computing environment, and the investment of $4 million for the development of photonic quantum computing, provide crucial support for the development of next-generation quantum computers and networks.

In the future, as countries' understanding of quantum technology deepens and demand for it continues to grow, support for this field will be further strengthened to ensure its long-term prosperity and innovative development. Government strong support will provide more solid guarantees and motivation for research institutions and enterprises, helping to significantly advance innovation and application of quantum technology worldwide.

Deepening Cooperation
The Quantum Alliance worldwide is fostering a new era of in-depth research cooperation

Multiple countries and regions have established their own quantum alliances and organizations, promoting the exchange and cooperation of quantum technology and providing a platform and opportunities for the innovation and application of quantum technology. Collaboration is one of the important factors driving quantum technology innovation, as it can provide diversified and complementary knowledge, resources, and capabilities for quantum technology. In 2023, several countries and regions established their own quantum alliances and organizations, such as:

Japan established the Japan Quantum Science and Technology Association (JQSTA), aiming to promote coordination and cooperation in research, education, and industrialization of quantum science and technology in Japan, and to propel Japan to a leading position in global quantum competition. Germany established the German Quantum Alliance (DQV), aiming to promote coordination and cooperation in research, development, and application of quantum information and communication, quantum computing and simulation, quantum sensing and measurement, and other fields in Germany, and to propel Germany to a leading position in European quantum competition. Australia established the Australia-Pacific Regional Quantum Alliance (APRQ), consisting of 11 countries or regions including Australia, New Zealand, the United States, the United Kingdom, Canada, India, Japan, South Korea, Singapore, Israel, and the United Arab Emirates. The alliance aims to promote coordination and cooperation in research, education, and industrialization of quantum technology in Australia and the Pacific region, and to propel Australia and the Pacific region to a leading position in global quantum competition.

These quantum alliances and organizations demonstrate the high importance and strong support of various countries and regions for the exchange and cooperation of quantum technology, providing a platform and opportunities for the innovation and application of quantum technology. It is expected that in the future, with the deepening and enhancement of the understanding and demand for quantum technology in various countries and regions, industry-academia-research cooperation will further deepen, providing more resources and impetus for the innovation and application of quantum technology.

Ecological Barriers
Quantum Cloud Platforms Will Accelerate the Construction of Industry Ecosystems

Currently, although the formulation and release of industry standards for quantum computing are still in the early stages, potential industry barriers and standards led by tech giants such as IBM and NVIDIA are gradually taking shape. Leveraging their long-term technical accumulation and market influence in the classical computing domain, these companies are creating a unique and closed application environment for users of quantum computing cloud platforms. This not only accelerates the application and commercialization pace of quantum computing technology but also establishes formidable ecological barriers for these companies in the future quantum computing industry.

The specificity of quantum computing technology, including the need for high technical professionalism and complex hardware, makes the setting of related industry standards a complicated and time-consuming task. In this process, companies with technical, resource, and market advantages naturally take a leading position. IBM's early exploration in the commercialization of quantum computing, along with the inseparable link between quantum and classical computing, has facilitated this situation. Therefore, companies like IBM and NVIDIA, with deep accumulations in the classical computing field, naturally occupy advantageous positions in the quantum computing domain. They not only provide necessary technical and resource support but also promote innovative applications and services that combine quantum with classical computing.

The investments and development efforts of these tech giants in quantum computing cloud platforms further solidify their positions in the quantum computing industry ecosystem. Quantum computing cloud platforms not only lower the barrier to entry for the application of quantum computing technology, enabling a broader range of researchers and developers to access and utilize quantum computing resources but also promote the commercialization process of quantum computing technology. Through these platforms, these companies have collected a vast amount of user data, providing valuable references for the further optimization and application of quantum computing technology.

Looking ahead, the roles and influence of some tech giants in the quantum computing industry ecosystem are expected to become even more prominent. Their efforts in promoting the commercialization pathways and the establishment of industry standards for quantum computing technology will have a profound impact on the development of the entire quantum computing industry. In this process, the role of quantum computing cloud platforms cannot be underestimated; they serve not only as a bridge for technological applications but also as a key force in shaping the future ecosystem of the quantum computing industry.

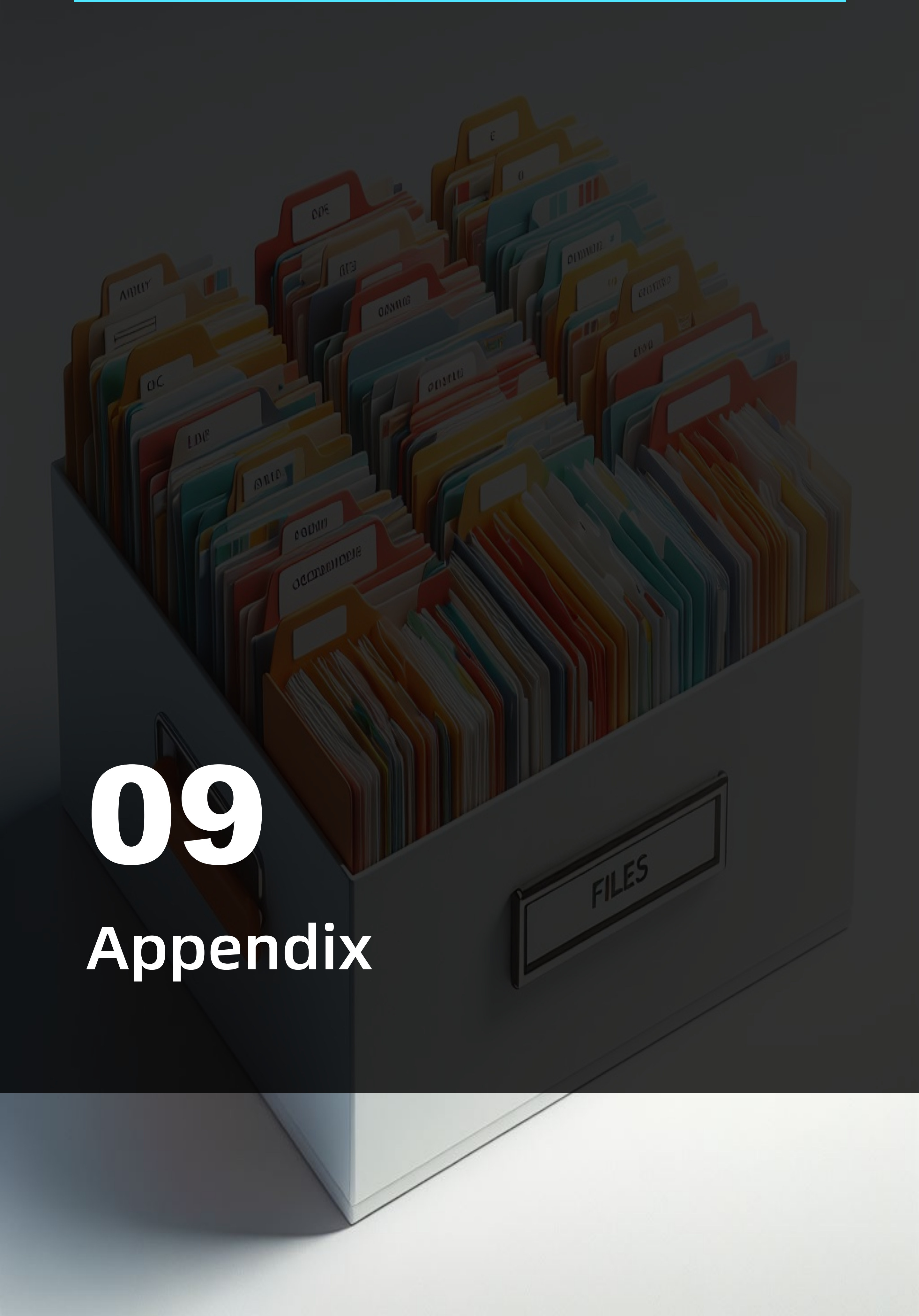
The three pillars stand firm: the United States, China, and Europe each demonstrate their capabilities, intensifying international competition

From a policy perspective, the United States, China, and Europe have continuously released favorable policies to promote the development of quantum computing technology and industry. In China, in addition to quantum information being identified as an important direction for scientific research and development in the highest-level "14th Five-Year Plan", relevant policies encouraging the development of the quantum industry were also released in 2023. For example, the State-owned Assets Supervision and Administration Commission of the State Council (SASAC) clarified the acceleration of the development of strategic emerging industries and future industries, with quantum information being one of the major fields of future industries. The Ministry of Industry and Information Technology and five other departments jointly released the "Action Plan for the High-Quality Development of computational capability Infrastructure." In the United States, support from organizations such as the National Institute of Standards and Technology (NIST), the Department of Energy (DOE), and the Air Force Research Laboratory (AFRL) is inseparable from the Quantum Initiative Act, which continues to be implemented after some revisions in 2023. The number of members of the Quantum Economic Development Consortium (QED-C), supported by NIST, continues to increase, extending U.S. cooperation and influence globally. The DOE invests funds to support basic research, exploring scientifically impactful scientific computing and large-scale scientific methods. The AFRL opens new laboratories to research the military applications of quantum computing. In Europe, initiatives such as Digital and EuroHPC JU are driving the development of quantum computing in Europe. In the UK, the new ten-year "National Quantum Strategy" (2024-2034) was released, providing £2.5 billion in government investment and attracting at least an additional £1 billion in private investment to promote various aspects of quantum technology development.

From a technical perspective, the United States, China, and Europe each have their own areas of expertise and are actively exploring various cutting-edge technologies in quantum computing. Companies such as IBM, Microsoft, and NVIDIA in the United States vie to demonstrate their leading positions in the field of quantum computing. IBM has released the Condor processor with over 1000 quantum bits and launched a cluster-based quantum computing architecture built with a 133-qubit processor (Heron), making it the only company currently to disclose such an innovative architecture. Microsoft has also made key progress in its six-step roadmap towards quantum supercomputing. NVIDIA's DGX Quantum and CUDA Quantum provide solutions for quantum cloud platforms and quantum-superfusion and are adopted by numerous quantum computing institutions worldwide. In China, research institutions such as the University of Science and Technology of China, Tsinghua University, the Beijing Quantum Institute, and the Shenzhen Quantum Research Institute have made multiple advancements in superconducting, ion trap, and photonic quantum computing. In particular, the team at the University of Science and Technology of China successfully constructed the "Nine Chapters III" photonic quantum computing prototype with 255 photons, placing China at the forefront of the international community in the field of photonic quantum computing. In Europe, companies such as PASQAL, AQT, QUANDELA, and OQC have made progress in quantum computing hardware, cloud platforms, and quantum-superfusion.

Currently, each of the three parties has its own strengths in technology and continues to invest in quantum computing. The competition and development of quantum computing technology are bound to accelerate further, laying the foundation for their respective positions in the quantum era.

From a market perspective, there is a continuous growth in demand for computational capability, and quantum computing, as a new paradigm, presents significant market space and opportunities. Competition for market share among China, the United States, and Europe will become more intense. Currently, the United States, as a traditional powerhouse, maintains unique advantages in the market. However, China, as an emerging technological powerhouse, will see an increase in market share in the ongoing process of international openness and cooperation. European countries such as the United Kingdom, Germany, and France have already identified quantum computing as a new point of economic growth. In the future, fierce competition will force countries to further increase investment in technology research and development, talent cultivation, and business expansion in order to consolidate their industry positions and attempt to expand their commercial footprint.



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01 Global Quantum Computing Ecological Construction Evaluation Model

Governmental Support

— If the government has a national quantum plan or strategy, or has established a dedicated agency/office to coordinate the development of the quantum industry, with clear goals and a large budget, then the country can be given a score of 1.

— If the government has some departments or agencies to support research and development in the quantum industry but does not have a unified plan or strategy, then the country can be given a score of 0.8.

— If the government only occasionally or indirectly supports the research and development of the quantum industry without a dedicated department or agency responsible for it, then the country can be given a score of 0.6.

— If the government has little support for research and development in the quantum industry, has no relevant plans or strategies, and does not have any relevant departments or agencies responsible for it, then the country can be given a score of less than 0.4.

Number of Companies

— If a country has more than 50 quantum computing-related companies, then the country can be given a score of 1.

— If a country has 10 to 50 quantum computing-related companies, then the country can be given a score of 0.8.

— If a country has less than 10 quantum computing-related companies, it can give the country a score of less than 0.6.

Type of Enterprise

— If a country has all types of quantum computing companies (hardware and software for each technology line) and has some innovative and leading companies, then the country can be given a score of 1.

— If a country covers most types of quantum enterprises and has some excellent and dedicated enterprises, then the country can be given a score of 0.8.

— If a country only covers a few types of quantum enterprises and does not have some outstanding and leading enterprises, then the country can be given a score of less than 0.6.

Scientific Research

— If a country publishes more than 50 quantum computing-related papers in the first half of 2023 and the average impact factor of the papers exceeds 7, then the country can be given a score of 1.

— If a country publishes 10 to 50 quantum computing-related papers in the first half of 2023 and the average impact factor of the papers is between 5 and 7, then the country can be given a score of 0.8.

— If a country publishes less than 10 quantum computing-related papers in the first half of 2023 and the average impact factor of the papers is less than 5, then the country can be given a score of less than 0.6.

Global Cooperation

— If a country participates in international programs or projects (such as the European Quantum Flagship Program) and international dialogues or initiatives (such as the Quantum Policy Dialogue between the United States and Japan), and has some leading or outstanding performance, then the country can be given a score of 1 point.

— If a country participates in part of it and has some excellent or outstanding performance, it can be given a score of 0.8.

— If a country does not participate in any form of international cooperation and does not have some special or leading performance, then the country can be given a score of less than 0.6.

02 Published Articles in Top Journals Related to Quantum Computing in 2023

Organization	Country of Author	Article Title	Journal
Tsinghua University, Hyqubit	China	Probing critical behavior of long-range transverse-field Ising model through quantum Kibble-Zurek mechanism	PRX Quantum
Tsinghua University, Hyqubit	China	Probing Complex-energy Topology via Non-Hermitian Absorption Spectroscopy in a Trapped Ion Simulator	Physical Review Letters
Tsinghua University, Hyqubit	China	Observation of Non-Markovian Spin Dynamics in a Jaynes-Cummings-Hubbard Model Using a Trapped-Ion Quantum Simulator	Physical Review Letters
The Quantum Nanostructures and Photonics Group (QNPG) of the Quantum Electronics and Optical Division (QEOD) at the Physical Measurement Laboratory (PML) of the National Institute of Standards and Technology (NIST)	US	Chip circuit for light could be applied to quantum computations	Optics & Photonics
Shanghai Jiaotong University	China	Sliding ferroelectricity in van der Waals layered γ-InSe semiconductor	Nature
Department of Physics (HKU), MIT Department of Physics	Hong Kong (China), US	Innovation strengthens electron-triggered light emissions for quantum-based computational and communications systems	Optics & Photonics
University of Bristol Quantum Engineering Technology Labs （QETLabs） and Centre for Quantum Photonics （CQP）	UK	New quantum computing architecture could be used to connect large-scale devices	Nature
University of Basel Department of Physics and Swiss Nanoscience Institute （SNI）	Switzerland	Quantum computers threaten our whole cybersecurity infrastructure: Here's how scientists can bulletproof it	Nature Reviews Physics
University of Basel Department of Physics and Swiss Nanoscience Institute （SNI）	Switzerland	A new qubit approach for more stable states for quantum computers	Nature Communications
The Australian National University （ANU） Research School of Physics and Centre for Quantum Computation and Communication Technology （CQC2T）	Australia	New techniques for accurate measurements of tiny quantum objects	Nature Physics
University of Glasgow	UK	Observation of spin-momentum locked surface states in amorphous BiSe	Nature
Massachusetts Institute of Technology （MIT） Department of Physics and Research Laboratory of Electronics （RLE）	US	Can you trust your quantum simulator? New technique helps verify accuracy of experiments	Nature
Joint Quantum Institute （JQI） and the NSF Quantum Leap Challenge Institute for Robust Quantum Simulation （RQS） at the University of Maryland （UMD）	US	Twisting up atoms through space and time	Physical Review Letters
University of California, Berkeley	US	A three-terminal magnetic thermal transistor	Nature
Shanghai Jiaotong University	China	Pressure driven rotational isomerism in D hybrid perovskites	Nature
University of Copenhagen Niels Bohr Institute	Denmark	Quantum physicists determine how to control two quantum light sources rather than one	Science
University College Dublin School of Physics and Centre for Quantum Engineering， Science， and Technology （C-QuEST）	Ireland	New analog quantum computers to solve previously unsolvable problems	Nature Physics
Princeton University Department of Physics	US	Researchers reveal microscopic quantum correlations of ultracold molecules	Nature Physics
School of Chemistry and Molecular Engineering, Peking University	China	Universal epitaxy of non-centrosymmetric two-dimensional single-crystal metal dichalcogenides	Nature
Department of Physics and Astronomy, Seoul National University	South Korea	Monolayer Kagome metals AVSb	Nature
Lawrence Berkeley National Laboratory （Berkeley Lab） Molecular Foundry	US	Microscopy images could lead to new ways to control excitons for quantum computing	Nature Physics
University of Sussex, Universal Quantum	UK	Another step towards practical quantum computers	npj Quantum Information

Organization	Country of Author	Article Title	Journal
Pennsylvania State University	US	Proximity-induced superconductivity in epitaxial topological insulator/graphene/gallium heterostructures	Nature
QuEra Computing	US	Encoding breakthrough allows for solving wider set of applications using neutral-atom quantum computers	Quantum Physics
Qudoor, Sun Yat-sen University	China	Distributed exact Grover's algorithm	Frontiers of Physics
Google	US	Google hails 'key milestone' in quantum computing	Nature
Rice University, Oxford	US, UK	Theory can sort order from chaos in complex quantum systems	Physical Review X
Nanjing University	China	Bright Tm±based downshifting luminescence nanoprobe operating around 00 nm for NIR-IIb and c bioimaging	Nature
Pennsylvania State University, University of Manchester, Max Planck Institute for Solid State Physics in Germany, et al.	US, UK, Germany, et al.	New material may offer key to solving quantum computing issue	Nature Nanotechnology
University of Rochester	US	Evidence of near-ambient superconductivity in a N-doped lutetium hydride	Nature
University of Bristol	UK	'Counterportation': Quantum breakthrough paves way for world-first experimental wormhole	Quantum Science and Technology
University of California, San Diego	US	Cleaning up the atmosphere with quantum computing	Analytical Chemistry
Oxford, University of California (Santa Barbara)	UK, US	Quantum chemistry simulations on a quantum computer	Science Advances
Purdue University, Northwestern University	US	Qubits put new spin on magnetism: Boosting applications of quantum computers	Physical Review Letters
Yale University	US	Doubling a qubit's life， researchers prove a key theory of quantum physics	Nature
University of California	US	New experiment translates quantum information between technologies in an important step for the quantum internet	Nature
Oxford	UK	A robust quantum memory that stores information in a trapped-ion quantum network	Physical Review Letters
University of Massachusetts Amherst	US	'QBism': Quantum mechanics is not a description of objective reality—it reveals a world of genuine free will	Quantum Physics
RIKEN Center for Emergent Matter Science	Japan	Connecting distant silicon qubits for scaling up quantum computers	Nature Communications
University of Tokyo	Japan	Absolute zero in the quantum computer: Formulation for the third law of thermodynamics	PRX Quantum
Institute of Crystallography of the Russian Academy of Sciences	Russia	Dzyaloshinskii-Moriya-Interaction allows magnon-magnon coupling in hybrid perovskites	Physical Review Letters
Ghent University—Interuniversity Microelectronics Center， Technical University of Denmark and Politecnico & Università di Bari	Denmark	Using quantum fluctuations to generate random numbers faster	Physical Review Letters
Amsterdam Quantum Software Center (QuSoft)	Netherlands	How to overcome noise in quantum computations	Physical Review X Quantum
University of California, Davis and University of California, Berkeley	US	A new quantum approach to solve electronic structures of complex materials.	Journal of Chemical Theory and Computation
ETH Zurich	Switzerland	A universal protocol that inverts the evolution of a qubit with a high probability of success	Physical Review Letters
Lawrence Berkeley National Laboratory	US	Innovating quantum computers with fluxonium processors	PRX Quantum
NIST	US	Manipulating multiple lasers on a single chip for a new generation of quantum devices	Light: Science & Applications
University of California， Berkeley	US	Physicists take step toward fault-tolerant quantum computing	Annals of Physics

Organization	Country of Author	Article Title	Journal
Pennsylvania State University	US	Proximity-induced superconductivity in epitaxial topological insulator/graphene/gallium heterostructures	Nature
University of Portsmouth	UK	Scientists increase efficiency of enzyme that breaks down PET plastic	Nature Communications
University of Twente	Netherlands	Backscattering protection in integrated photonics is impossible with existing technologies， says study	Optics & Photonics
KIST	South Korea	Scientists increase efficiency of enzyme that breaks down PET plastic	Biochemistry
Radboud University Nijmegen	Netherlands	New kind of quantum transport discovered in a device combining high-temperature superconductors and graphene	Physical Review Letters
RIKEN	Japan	Quantum 'magic' could help explain the origin of spacetime	Nature Communications
University of Cambridge	UK	Breakthrough in magnetic quantum material paves way for ultra-fast sustainable computers	Nature Communications
University of California， Berkeley	US	Team develops the world's smallest and fastest nano-excitonic transistor	ACS Nano
KAIST	South Korea	Team develops the world's smallest and fastest nano-excitonic transistor	Nano Letters
Brookhaven National Laboratory	US	X-rays reveal electronic details of nickel-based superconductors	Physical Review Letters
Helmholtz Superconductivity Research Center, Dresden University of Technology, Fraunhofer Institute for Photonic Microsystems in Dresden, et al.	Germany	Deepfreeze electronics for supercomputers—technology prepares quantum computing for industrial use	Superconductivity
School of Physics and Astronomy, Shanghai Jiao Tong University	China	Evidence of high-temperature exciton condensation in a two-dimensional semimetal	Nature
Oak Ridge National Laboratory	US	Deep-learning-based data analysis software promises to accelerate materials research	Physical Review X
Brookhaven National Laboratory	US	X-rays reveal electronic details of nickel-based superconductors	Condensed Matter
University of California, Berkeley	US	The comprehensive characterization of hydrogen at ultra-high pressures	Nature Physics
Oak Ridge National Laboratory	US	Deep-learning-based data analysis software promises to accelerate materials research	Analytical Chemistry
University of Twente	Germany	Quantum light source goes fully on-chip， bringing scalability to the quantum cloud.	Nature Photonics
University of Stuttgart	Germany	The quantum spin liquid that isn't one	Nature Physics
National Institute for Materials Science (Japan)	Japan	Embracing variations: Physicists first to analyze noise in Lambda-type quantum memory	Physical Review A
University of California, San Diego	US	Lossless light: Revisiting Raman gain and amplification in a silicon photonic platform	Optica
University of California， Riverside.	US	Team creates 'quantum composites' for electrical and optical innovations.	Advanced Materials
Rice University, University of Texas at Austin, et al.	US	A particular 'sandwich' of graphene and boron nitride may lead to next-gen microelectronics	Nature Nanotechnology
Technical University of Denmark; Boston University; etc.	Denmark	Scaling information pathways in optical fibers by topological confinement	Science
University of Vienna	Austria	Study proves compatibility of two fundamental principles of quantum theory	Physical Review Letters
Max Planck Institute for Microstructure Physics	Germany	Two qudits fully entangled	Physical Review Letters
University of California, Los Angeles	US	Molding of nanowires spurs unanticipated phases	Matter
University of California, Los Angeles	US	Quantum entanglement could make accelerometers and dark matter sensors more accurate	Nature Photonics
The University of Tokyo	Japan	Ultra-miniaturized non-classical light sources for quantum devices	IEEE Journal of Selected Topics in Quantum Electronics

Organization	Country of Author	Article Title	Journal
Tilburg University	Netherlands	Communication about quantum technology offers many opportunities （but there are risks too）	Quantum Science and Technology
he Chinese University of Hong Kong	China	Enhanced osmotic transport in individual double-walled carbon nanotube	Nature
University of California, San Diego	US	Simulations with a machine learning model predict a new phase of solid hydrogen	Physical Review Letters
University of California	US	Building better superconductors with palladium	Superconductivity
Bar-Ilan University	Israel	A quantum leap in computational performance of quantum processors	Nature Communications
South China University of Technology	China	Solution epitaxy of polarization-gradient ferroelectric oxide films with colossal photovoltaic current	Nature
Stanford University	USA	Scientists reconstruct full state of a quantum liquid	Nature Physics
Nagoya University	Japan	Fluorescent aromatic nanobelts with unique size-dependent properties	ACS Nano
National Institute of Standards and Technology (NIST)	USA	Scientists create a longer-lasting exciton that may open new possibilities in quantum information science	Physical Review Letters
Nagoya University	Japan	Fluorescent aromatic nanobelts with unique size-dependent properties	Nature Communications
Hefei Institutes of Physical Science, CAS	China	Monolayer hexagonal boron nitride can extend plasmonic enhancement limit	Nano Letters
University of California, Riverside	USA	Could quantum fluctuations in the early universe enhance the creation of massive galaxy clusters?	Physical Review D
University of California, San Diego (UCSD)	USA	Highly multicolored， light-emitting arrays for compressive spectroscopy on a chip	Optics & Photonics
University of Texas at Austin	USA	Tunable electron–flexural phonon interaction in graphene heterostructures	Nature
University of California, San Diego	USA	Counting photons for quantum computing	Nature Photonics
University of Rochester	USA	Newly observed effect makes atoms transparent to certain frequencies of light	Nature
University of California, Berkeley	USA	No need for a super computer: Describing electron interactions efficiently and accurately	Physical Review B
Northeastern University	Japan	Research on light emission from black phosphorus hints at new applications	ACS Nano
Tokyo Institute of Technology	Japan	A model system of topological superconductivity mediated by skyrmionic magnons	Physical Review B
National University of Singapore	Singapore	Controllable dimensionality conversion between D and D CrCl magnetic nanostructures	Nature
University of Illinois at Urbana-Champaign	USA	Zeroing in on a fundamental property of the proton's internal dynamics	Physical Review Letters
National Institute of Standards and Technology (NIST)	USA	Zeroing in on a fundamental property of the proton's internal dynamics	Physical Review Letters
California Institute of Technology	USA	Quantum entanglement of photons doubles microscope resolution	Nature Photonics
UC Santa Barbara	USA	Beyond Moore's Law: Innovations in solid-state physics include ultra-thin D materials and more	Advanced Materials

Institution	Country of Author	Article Title	Journal
National University of Singapore	Singapore	Technology enables conversion of mobile phone cameras into high-resolution microscopes	Optics & Photonics
Pennsylvania State University; Argonne National Laboratory; etc.	USA	Topological kinetic crossover in a nanomagnet array	Science
CNRS,CEA,ENSTA, École Polytechnique (Polytechnique), IOGS	France	A highly performing device for polariton-based coherent microwave emission and amplification	Nature Communications
Max Planck Institute for Solid State Research	Germany	Scale separation: Breaking down unsolvable problems into solvable ones	Physical Review Letters
University of California, Berkeley	USA	The exciting possibilities of tiny, twisted superconductors	Physical Review Letters and Physical Review B
ETH Zurich	Switzerland	Engineering graphene-based quantum circuits with atomic precision	Journal of the American Chemical Society
University of Illinois at Urbana-Champaign and NIST	USA	A graph neural network for fast evaluation of the adsorption energy in heterogeneous catalysis	Nature Communications
University of Bristol	UK	Scientists find link between photosynthesis and 'fifth state of matter'	Physical Review Letters
Massachusetts Institute of Technology (MIT)	USA	Scientists find link between photosynthesis and 'fifth state of matter'	Nature Physics
National Institute of Standards and Technology (NIST)	USA	Magnetic energy strings flex, wiggle and reconnect in a nanomagnetic array	Nanophysics
Intelligent Computing	South Korea	Researchers use quantum computer to identify molecular candidate for development of more efficient solar cells	Analytical Chemistry
Department of Energy's Oak Ridge National Laboratory	USA	Can cloud-based quantum computing really offer a quantum advantage?	Nature Physics
The University of Texas at El Paso	USA	Researchers advance topological superconductors for quantum computing	Nature Nanotechnology
RIKEN Center for Quantum Computing	Japan	Physicists create powerful magnets to de-freeze quantum computing	Physical Review Applied
NIST/University of Maryland, UC Berkeley, Caltech and other institutes in the United States	USA	Machine learning contributes to better quantum error correction	Nature Physics
Delft	Netherlands	A new protocol to reliably demonstrate quantum computational advantage	Nature Physics
Department of Energy Lawrence Berkeley National Laboratory	USA	Chessboard-like method enables the operation of largest gate-defined quantum dot system	Nature Nanotechnology
Oak Ridge National Laboratory	USA	Advances in quantum emitters mark progress toward a quantum internet	Physical Review Applied
RIKEN	Japan	A superconducting junction made from a single 2D material promises to harness strange new physics3	Advanced Materials
Institute for Basic Science	South Korea	Discovery of magnetic liquid crystal: First direct observation of spin quadrupole moments in a spin-nematic phase4	Nature Communications
State University of Campinas	Brazil	Study paves way for development of advanced quantum networks5	Nature Communications

Organization	Country of Author	Article Title	Journal
Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS)	US	Engineers develop first-of-its-kind integrated optical isolator	Nature Photonics
North Carolina State University	US	Quantum computing could get boost from discovery of Q-silicon	Physical Review Letters
Physikalisch-Technische Bundesanstalt (PTB) Quantum Metrology Group	Germany	Electron collider on a chip verified by three independent research teams	Nature Nanotechnology
Chinese Academy of Sciences	China	Application of two-photon lithography in photonics packaging: A promising solution	Light: Advanced Manufacturing
Eötvös Loránd University (ELTE)	Hungary	Revealing the spacetime geometry of quark matter using the world's most powerful particle accelerators	Phys.org
University of Colorado at Boulder	US	Revealing the secrets of spin with high harmonic generation probes	Science Advances
Intelligent Computing	China	Can cloud-based quantum computing really deliver quantum advantage?	Intelligent Computing
Universität Konstanz	Germany	Discover a novel ultrafast magnetic switch during noise interference studies	Physical Review B
Leiden University	Netherlands	Magnetic fusion plasma engines: A potential journey beyond the solar system into interstellar space	Universe Today
Purdue University	US	Is graphene the ultimate thermal conductor? Investigating through four-phonon scattering	Physical Review B
Ohio State University	US	A novel method for observing the orbital hall effect may improve spintronics applications	Physical Review Letters
Trinity College Dublin	Ireland	Late not great—imperfect timekeeping places significant limit on quantum computers	Physical Review Letters
University of California, Santa Barbara	US	From supersolid to microemulsion: Exploring spin-orbit coupled Bose-Einstein condensates	Physical Review Letters
Hong Kong University, The Hong Kong University of Science & Technology	Hong Kong, China	Physicists unlock controllable nonlinear Hall effect in twisted bilayer graphene	Physical Review Letters
University of Science and Technology of China	China	Elevating neuromorphic computing using laser-controlled filaments in vanadium dioxide	Science Advances
RIKEN Center for Emergent Matter Science	Japan	Simulating spins， spirals and shrinking devices for new classes of energy-efficient materials	Physical Review Letters
Vienna University of Technology	Austria	Limits for quantum computers: Perfect clocks are impossible， research finds	Physical Review Letters
Oak Ridge National Laboratory	US	Three-pronged approach discerns qualities of quantum spin liquids	Physical Review Letters
Max Planck Institute for the Structure and Dynamics of Matter	Germany	Vacuum in optical cavity can change material’s magnetic state without laser excitation	npj Computational Materials
Rice University	US	Study leverages chiral phonons for transformative quantum effect	The Journal of Chemical Physics
exas A&M International University	US	Researchers use quantum computing to predict gene relationships	npj Quantum Information
Technische Universiteit Delft	Netherlands	Controlling waves in magnets with superconductors for the first time	Science
Tokyo University of Science, RIKEN	Japan	Study observes strong noise correlations between silicon qubits1	Nature Physics
University of Duisburg-Essen	Germany	Eavesdropping on the electron: A new method for extracting data from noise3	Physical Review
ICFO	Spain	Optical fiber-based， single-photon light source at room temperature for next-generation quantum processing5	Optics & Photonics
IBS Quantum Nanoscience Center	South Korea	A new qubit platform is created atom by atom6	Science
ICFO	Spain	Single ions in nano-sized particles: A new platform for quantum information processing8	Optica
Columbia University	US	Q&A: A new Nobel laureate describes the development of quantum dots from basic research to industry application9	Analytical Chemistry
Rice University	US	Physicists find evidence of exotic charge transport in quantum material10	Science

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QuTech	Netherlands	Stable qubit is a prime candidate for universal quantum computer	Nature Physics
University of Minnesota, Twin Cities	US	Stretching metals at the atomic level allows researchers to create important materials for quantum applications	Nature Materials
Tokyo Institute of Technology	Japan	Toward the realization of chiral spin liquids and non-Abelian anyons in quantum simulators	PRX Quantum
University of California, San Diego	US	Using nuclear spins neighboring a lanthanide atom to create Greenberger-Horne-Zeilinger quantum states	Optica
Leibniz University Hannover	Germany	Progressive quantum leaps—high-speed， thin-film lithium niobate quantum processors driven by quantum emitters	Science Advances
École Polytechnique Fédérale de Lausanne	Switzerland	Quantum matter breakthrough: Tuning density waves	Physical Review Letters
Aalto University	Finland	Quantum scientists accurately measure power levels trillion times lower than usual	Review of Scientific Instruments
Peking University, Chinese Academy of Sciences, etc.	China	Proximate deconfined quantum critical point in SrCu（BO）	Science
Peking University, Chinese Academy of Sciences, etc.	China	Mid-circuit correction of correlated phase errors using an array of spectator qubits	Science
University of Toronto	Canada	Researchers develop ‘noise-canceling’ qubits to minimize errors in quantum computers	Science
Korea Integrated Energy Research Institute	South Korea	Scientists propose revolution in complex systems modeling with quantum technologies	Nature Communications
Technische Universität München	Germany	Study presents a new， highly efficient converter of quantum information carriers	Nature Photonics
Superconducting Technology Center (SCT)	Spain	Chip-based quantum key distribution achieves higher transmission speeds	Optica
Department of Energy’s SLAC National Accelerator Laboratory， Stanford University， University of California， Berkeley and others	US	In a first， researchers capture fleeting ‘transition state’ in ring-shaped molecules excited by light	Science Advances
University of Basel	Switzerland	Skepticism about Microsoft results regarding robust quantum bits	Physical Review Letters
Japan's Institute of Physical and Chemical Research	Japan	Forging a dream material with semiconductor quantum dots	Nature Communications
University of Illinois at Urbana-Champaign, NIST	US	Absolute vs. relative efficiency: How efficient are blue LEDs， actually?	Applied Physics Letters
Moscow Institute of Physics and Technology	Russia	From self-driving cars to military surveillance: Quantum computing can help secure the future of AI systems	Nature Machine Intelligence
Flinders University	Australia	New-look infrared lens shines a light on future technology and manufacturing	Polymers
Columbia Engineering	US	Examining a nanocrystal that shines on and off indefinitely	Nanophysics
NIST	US	Understanding the tantalizing benefits of tantalum for improved quantum processors	Advanced Science
Ohio University， Argonne National Laboratory， University of Illinois-Chicago and others	US	Scientists’ report world’s first X-ray of a single atom	Nature Communications
University of California, Berkeley	US	Indefinite and bidirectional near-infrared nanocrystal photoswitching	Nature
University of Science and Technology of China	China	New scheme for qubit control in a multilevel system	Physical Review A
Brookhaven National laboratory	US	Tiny quantum electronic vortexes can circulate in superconductors in ways not seen before	Physical Review Letters
Technische Universität Darmstadt	Germany	Optical effect advances quantum computing with atomic qubits to a new dimension	Optics & Photonics
Osaka Metropolitan University	Japan	New study explains interaction between quantized vortices and normal fluids	Soft Matter
University of Washington	US	The ‘breath’ between atoms—a new building block for quantum technology	Nature Nanotechnology
City University of Hong Kong （CityU）	China	An optical method to polarize free electrons in a laboratory setting	Physical Review Letters

Organization	Country of Author	Article Title	Journal
Rice University	US	Quantum visualization technique gives insight into photosynthesis	The Journal of Physical Chemistry Letters
University of Pennsylvania	US	A new twist on chirality: Researchers extend the concept of directionality and propose a new class of materials	Condensed Matter
Juelich Research Centre	Germany	Symmetric graphene quantum dots for future qubits	Nature
University of Zurich	Switzerland	Modeling electron dynamics in real time	Analytical Chemistry
ETH Zurich	Switzerland	Entangled quantum circuits further disprove Einstein's concept of local causality	Nature
University of Cambridge , University of Oxford and others	UK	Physicists discover 'stacked pancakes of liquid magnetism'	Nature Physics
Barcelona Superconducting Technology Center	Spain	New technology developed for quantum cryptography applications	PRX Quantum
Google Quantum AI Lab	US	Google Quantum AI braids non-Abelian anyons for the first time	Nature
Rensselaer Polytechnic Institute	US	Researcher uses artificial intelligence to discover new materials for advanced computing	Advanced Theory and Simulations
University of California , Riverside and the Institute of Magnetism in Kyiv	US	Researchers develop manual for engineering spin dynamics in nanomagnets	Matter
University of Cambridge	UK	Researchers find new approach to explore earliest universe dynamics with gravitational waves	Physical Review Letters
University of Colorado Boulder	US	Correlated insulator of excitons in WSe/WS moiré superlattices	Science
University of Queensland	Australia	Jellybeans: A sweet solution for overcrowded circuitry in quantum computer chips	Advanced Materials
Ecole Normale Superieure	France	Researchers find new approach to explore earliest universe dynamics with gravitational waves	Physical Review Letters
Rice University， University of Texas at Austin and others	US	Researchers discover superconductive images are actually D and disorder-driven fractals	Nature Communications
MIT	US	Proposed perovskite-based device combines aspects of electronics and photonics	Nature Communications
Ames Laboratory	US	Ultralow temperature terahertz microscope capabilities could enable better quantum technology	Review of Scientific Instruments
Harvard University	US	Forming and sensing optical emitters in real time	Optics & Photonics
Moscow Institute of Physics and Technology	Russia	New tool to guide efficient energy extraction from quantum sources	Journal of the American Chemical Society
Los Alamos National Laboratory , D-Wave	US	Team demonstrates quantum advantage on optimization problems with a ， 000-qubit programmable spin glass	Nature
National University of Singapore	Singapore	Quantum random number generator operates securely and independently of source devices	Advanced Photonics
Rice University	US	Using nanofaceting to manipulate quantum dots into nanocrystals	Nano Letters
University of Innsbruck	Austria	Curved spacetime in a quantum simulator	Proceedings of the National Academy of Sciences
ETH Zurich	Switzerland	Wiring up quantum circuits with light	Science
Flinders University	Australia	'Electrifying' achievement for making more sustainable polymers	Journal of the American Chemical Society
Insilico Medicine	Hong Kong, China	Study combines quantum computing and generative AI for drug discovery	Nature Communications
Flinders University	Australia	'Electrifying' achievement for making more sustainable polymers	Polymers
Duke University	US	Machine learning approach opens insights into an entire class of materials being pursued for solid-state batteries	Materials Science

Organization	Country of Author	Article Title	Journal
Oak Ridge National Laboratory	USA	New way to charge batteries harnesses the power of 'indefinite causal order'4	Condensed Matter
University of Chicago	USA	New technique could make modeling molecules much easier5	Condensed Matter
RIKEN, Japan	Japan	Researchers take a different approach with measurement-based quantum computing1	Quantum Physics
Kyoto University and Hiroshima University	Japan	Let there be light: Many photons are better than one for advancing quantum technologies	Science Advances
Shanghai Jiao Tong University	China	Geometric origin of intrinsic dark counts in superconducting nanowire single-photon detectors	Nanomaterials
University of Science and Technology of China	China	A logical magic state with fidelity beyond distillation threshold realized on superconducting quantum processor	Physical Review Letters
University of São Paulo	Brazil	Embedding nanodiamonds in polymer can advance quantum computing and biological studies	Nanomaterials
Princeton University	USA	Physicists 'entangle' individual molecules for the first time， hastening possibilities for quantum computing	Science
University of Chicago Pritzker School of Molecular Engineering	USA	An advanced computational tool for understanding quantum materials	Journal of Chemical Theory and Computation
CERN, DESY, IBM Quantum	Multiple	Preparing for a quantum leap: Researchers figure future for use of quantum computing in particle physics	Nature Communications
Michigan State University	USA	Physicists work to prevent information loss in quantum computing	Nature Communications
U.S. Department of Energy's Ames National Laboratory	USA	New tool helps improve quantum computing circuit component	IEEE Microwave and Wireless Technology Letters
École Polytechnique Fédérale de Lausanne (EPFL)	Switzerlan d	Quantum neural networks: An easier way to learn quantum processes	Nature Communications
National Astronomical Observatory of Japan (NAOJ)	Japan	Novel microwave isolator points the way to new radio cameras and quantum computers	IEEE Microwave and Wireless Technology Letters
Trinity College Dublin	Ireland	Research team simulates super diffusion on a quantum computer	Quantum Physics
Los Alamos National Laboratory	USA	Revolutionary hardware unveils new quantum computing model	General Physics
Sandia National Laboratories	USA	Bigger and better quantum computers are possible with new ion trap dubbed the Enchilada	Quantum Physics
University of Sydney	Australia	Scientists observe first evidence of 'quantum superchemistry' in the laboratory	General Physics
Osaka University	Japan	Who's afraid of quantum computing?	Quantum Physics
Oak Ridge National Laboratory	USA	Researchers use quantum circuit to identify single nucleotides	Biochemistry
Harvard University, QuEra Computing Inc., University of Maryland, and Massachusetts Institute of Technology (MIT)	USA	Using logical qubits to make a quantum computer that can correct its errors1	Quantum Physics

Organization	Country of Corresponding Author	Article Title	Journal
Nanjing University	China	Researchers achieve quantum storage of entangled photons at telecom wavelengths in a crystal1	Nature Communications
University of Chicago, Argonne National Laboratory, and University of Cambridge	USA, UK	Researchers invent new way to stretch diamond for better quantum bits3	Physical Review X
Northeastern University	Japan	Exploring parameter shift for quantum Fisher information4	EPJ Quantum Technology
University of Washington	USA	Speeding up creation of quantum entanglement5	Physical Review Letters
AMOLF	Netherlands	Research claims novel algorithm can exactly compute information rate for any system6	Physical Review X
University of Southern California	USA	A scientist explains an approaching milestone marking the arrival of quantum computers7	The Conversation
University of Illinois	USA	Nondestructive measurement realized in ytterbium qubits， aiding scalable neutral atom quantum computing8	/
University of Michigan	USA	Next-gen computing: Hard-to-move quasiparticles glide up pyramid edges	Phys.org
National Institute of Information and Communications Technology	Japan	Successful development of the world's first superconducting wide-strip photon detector	Phys.org
Oak Ridge National Laboratory	USA	Scientists use quantum biology， AI to sharpen genome editing tool	ScienceDaily
IQOQ,ÖAW	Austria	Quantum tool opens door to unfigureed phenomena	Phys.org
European Space Agency	Europe	Europe's quantum decade extends into space	European Space Agency
Technical University of Munich (TUM)	Germany	Q&A: Professor discusses new approaches for the implementation of the quantum internet	Lifeboat Foundation
Massachusetts Institute of Technology (MIT)	USA	Study finds more stable clocks could measure quantum phenomena， including the presence of dark matter	Tech Explorist
Argonne National Laboratory	USA	New quantum computing architecture achieves electron charge qubit with 0.1 millisecond coherence time	Nature Physics
California Institute of Technology	USA	A new way to erase quantum computer errors	Quantum Physics
Harvard University	USA	Self-correcting quantum computers within reach?	Nature Materials
Princeton University	USA	Illuminating errors creates a new paradigm for quantum computing	Nature Materials
University of Warsaw	Poland	Discovery may enable network interface for quantum computers	Optics & Photonics
Pennsylvania State University	USA	Electrical control of quantum phenomenon could improve future electronic devices	Nature Materials
University of Cambridge	UK	Diamonds and rust help unveil 'impossible' quasi-particles1	Nature Materials
University of Rochester	USA	New strategy reveals 'full chemical complexity' of quantum decoherence2	Proceedings of the National Academy of Sciences
U.S. Department of Energy's Oak Ridge National Laboratory	USA	Computational scientists generate molecular datasets at extreme scale3	Analytical Chemistry

03 Classification of Quantum Computing Algorithms

Classification of Quantum Computing Algorithms

Category	Algorithm	Function	Application
Algebra and number theory	Shor	Fourier transform of periodic functions	Solution to Ground State Problem
Algebra and number theory	Euler	Inverse operation of modular exponentiation	Cryptography, used to solve elliptic curve cryptography, etc.
Algebra and number theory	HHL	Solving systems of modular linear equations	Linear algebra for solving large-scale sparse systems of linear equations
Algebra and number theory	Hallgren	Pell equation and solutions to principal ideal problems	Number theory, used to solve problems such as Pell's equation, principal ideals, unit groups, etc.
Based on black box	Grover	Acceleration of unordered search problems	Database search to find target elements in an unordered list
Based on black box	Grover（Flip H）	Acceleration of ordered search problems	Database search to find the target element in an ordered list
Based on black box	QAOA	Acceleration of optimization problems	Combinatorial optimization, used to solve NP-hard problems such as the maximum cut problem
Based on black box	QPEA	Acceleration of optimization problems	Continuous optimization, used to solve problems such as the minimum value of convex functions
Machine learning	QKmeans	Acceleration of operations related to cluster analysis	Machine learning is used for tasks such as data analysis and visualization
Machine learning	QHMM	Acceleration of operations related to hidden Markov models	Machine learning for tasks such as speech recognition and bioinformatics
Machine learning	QSVM	Acceleration of support vector machine related operations	Machine learning is used for tasks such as data classification and regression
Machine learning	QNN	Acceleration of artificial neural network related operations	Deep learning for tasks such as image recognition and natural language processing
Machine learning	QNGD	Acceleration of gradient descent related operations	Deep learning, used to train models such as neural networks
Machine learning	QGD	Acceleration of gradient descent related operations	Deep learning, used to train models such as neural networks
Machine learning	QSVD	Acceleration of linear algebra related operations	Matrix decomposition, used for matrix compression, noise reduction, feature extraction, etc.
Machine learning	QPCA	Acceleration of linear algebra related operations	Data dimensionality reduction, used to extract data features and compress data storage
Quantum simulation	QLindblad	Solving Open System Evolution Problems	Physics simulation, used to simulate systems interacting with their environment
Quantum simulation	QITE	Solving thermal problems	Physical simulation for simulating equilibrium states at finite temperatures
Quantum simulation	Trotter-Suzuki	Solution to Dynamic Evolution Problems	Physical simulation for simulating complex phenomena such as spin systems or optical systems
Quantum simulation	VQE	Solution to Ground State Problem	Quantum chemistry, used to solve for the ground state energy of the Hamiltonian of a molecule
Quantum simulation	QPE	Solution to Ground State Problem	Quantum chemistry, used to solve for the ground state energy of the Hamiltonian of a molecule

04 Development Status of Global Quantum Computing Standards

Figure: Global Quantum Computing Standards Development In 2023

Release time	Implementation time	Publishing Organization	Standard Title	Standard Number
2021.06	/	C/S2ESC - Software & Systems Engineering Standards Committee	Trial-Use Standard for a Quantum Algorithm Design and Development	IEEE SA - P2995
2021.09	/	IEEE Computer Society/Standards Activities Board Standards Committee （C/SABSC）	Standard for Quantum Computing Performance Metrics & Performance Benchmarking	IEEE SA - P7131
2023.02	/	C/SABSC - Standards Activities Board Standards Committee	Standard for Quantum Computing	IEEE SA - P3329
2023.05	2023.12	State Administration for Market Regulation, Standardization Administration of China	Quantum computing—Terminology and definition	GB/T 42565—2023
2023.09	/	C/MSC - Microprocessor Standards Committee	Standard for Quantum Computing Architecture	IEEE SA - P3120

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Figure: Research Standards in the Quantum Computing Field

Release time	Implementation time	Publishing Organization	Standard Title	Project Number
2020.06	/	/	Quantum computing Terminology and vocabulary	ISO/IEC FDIS 4879

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05 Supplier Evaluation System (CTF Model)

The CTF (Capability, Traction, Future) model is an evaluation and analysis framework for future industry participants. ICV TA&K's CTF model serves to help the public understand the development status of cutting-edge technology fields and corresponding companies. Cutting-edge technologies exhibit characteristics such as non-convergent technological paths, high uncertainty in technology development, and early-stage commercialization efforts. With continuous technological advancements, it becomes necessary to have a rational model for evaluating companies and forming a "consensus" on specific periods of cutting-edge technology suppliers.

The CTF model consists of four sectors presented in depth, with different-sized fan-shaped regions, and is constructed using three-dimensional coordinates. The horizontal axis represents the Maturity of Technology (the technological aspects, including the supplier's technology, research and development, and team), the vertical axis represents the Commercialization of Technology (the business aspects, including the supplier's revenue, customers, and use cases), and the implicit variable represents the underlying factors (the long-term operational elements accumulated by the supplier that can drive enterprise development). Based on the supplier's comprehensive performance in different dimensions, the CTF model classifies them into the following four sectors: Pilot, Overtaker, Explorer, and Chance-seeker.

Due to the rapid growth and high uncertainty inherent in emerging technologies, CTF diagrams for various subfields need to be updated periodically.

- Fan1—Pilot: The characteristic of companies in this sector is that they have relatively large enterprise scales and have accumulated considerable experience during the previous technology development cycles. This solid foundation enables them to enter new frontiers of technology confidently. These companies possess the capability and resources to become leaders in the new wave of cutting-edge technologies, potentially exerting a profound influence on the future direction of the industry.
- Fan2—Overtaker: Companies in this sector, after a period of development, have begun to establish a certain scale. One of their major advantages is their robust capability in new technology research and development. Leveraging their accumulated expertise in specific technological domains, these companies are poised to "overtake" and emerge as industry leaders in the future.

- Fan3—Explorer: This sector comprises smaller-sized companies, yet they have ventured into the path of emerging technologies relatively early. The development of specific technologies is still in its early stages, and compared to Pilots and Overtakers, they often have a gap in overall technological prowess.
- Fan4—Chance-seeker: The companies in this sector possess keen business acumen and are emerging players in the industry. They are not large in scale but have founding team members with some resources, enabling the company to seize opportunities for growth in new domains. These companies currently have few product engineering prototypes and limited market exposure opportunities.

The CTF model can assist clients in the forefront of technology in evaluating procurement and investment in a particular technology vendor. It's crucial to note that suppliers in the Pilot quadrant aren't always the best choice. Depending on the specific needs of the enterprise, companies in the Overtaker or Explorer quadrants might be the better option.

06 Reference Link

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