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2023 Global Quantum Computing Industry Development Prospect

Quantum Annual Series Report

February 2023

Foreword

The quantum computer is a new and next-generation computer that is currently being developed. Due to its powerful parallel computing capability, quantum computing will likely lead a new round of information technology revolution.

Major technological countries worldwide have launched related research and development projects, and actively developed quantum computing industry. Once large-scale quantum computing is achieved, it will pose a significant threat to the current encryption system, making it a matter of strategic importance for national information security. In addition, its broad downstream application prospects are likely to change the rules of industries such as banking, drug development, and logistics in the future.

In 2022, the characteristics of various quantum computing technology routes not yet converging have become increasingly evident. Breakthroughs in various routes have been made to varying degrees, and the pioneers of global quantum computing are rapidly crossing the NISQ era with the main trend of quantum error correction. Among them, the number of superconducting quantum bits is expected to enter the era of thousands of quantum bits in the new year.

2022 is the "neutral atom year." Both in terms of technology and commercial maturity, the neutral atom technology route has shown a leapfrog development. We were surprised to find that in the past three years, we have had a theme each year, such as "superconducting year" in 2019, "ion trap year" in 2020, and "quantum photonics year" in 2021. We can also look forward to whether 2023 will be the "semiconductor year. "

The rapid development of technology has not brought good news for enterprise valuation and financing. The global overall financing growth rate in 2022 has slowed down for the first time since 2018. The investment enthusiasm and confidence of market institutions seem to have had a brief pause, which may not be a bad thing. Some companies, including the media, have inflated the bubble in recent years and need to be squeezed.

Foreword

In 2022, major technological countries continue to strengthen policy support and accelerate the layout of quantum computing, which has become the main theme of global frontier technological development in the past year. The United States and China are the most prominent among them, and their competition and confrontation are accumulating.

Although we cannot accurately predict how many quantum bits quantum computing will achieve in the next few years, how low the computing error rate will be, and what completely overturning applications there will be, we can clearly understand from the development history of classical computers that human demand for computing power is endless. Therefore, we still have great confidence and enthusiasm for the future of the global quantum computing industry, and quantum computing will definitely push humanity's new journey to the stars and the sea! In 2023, ICV will jointly release the "2023 Global Quantum Computing Industry Development Prospect" with China's quantum technology platform company, GUANGZIHE, and we will continue to break through the waves!

ICV Frontier Technology Consulting Director, Senior Vice President

Jude Green

Jude Green

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Global Quantum Computing Report WG

Feb 2023

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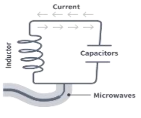
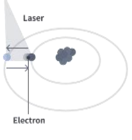
Industry Insight

The Global Industries are Still in the Early Stages of Rapid Development.

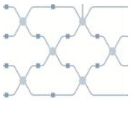
In retrospect of 2022, both hardware technology advancements and the expansion of software development and platforms, the quantum computing industry as a whole remains in the early stages of rapid growth.



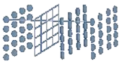
- Superconducting Quantum Computers: Currently, the development of general-purpose superconducting quantum computers is undergoing a crucial stage of transitioning beyond the NISQ era, with a focus on improving both breadth and depth. Breadth refers to the number of quantum bits, with the current highest being 433 quantum bits in IBM's Osprey. Depth refers to the number of continuous high-fidelity multi-qubit logic operations that can be performed.



- Trapped Ion Quantum Computers: One of the two quantum computing research directions that has received the most funding from the US government. In addition to general-purpose quantum computers, ion traps are also widely used in quantum simulation research in fields such as quantum chemistry, relativistic quantum mechanics, and quantum thermodynamics.



- Photonic Quantum Computers: Xanadu successfully demonstrated the superiority of quantum computing in 2022. Neutral



- Atom Quantum Computers: Created in March by the University of Chicago, the neutral atom achieves 512 quantum bits in a laboratory environment. Japanese National Institute of Natural Sciences researchers achieved a 6.5 nanosecond ultrafast dual-qubit gate, breaking the world record.

- Semiconducting, Diamond NV Centers, and Nuclear Magnetic Resonance Quantum Computers: All showed various degrees of technical progress in 2022.

Contrary to the diversity of hardware avenues, the openness of quantum software has emerged as one of the primary trends in current industry development.

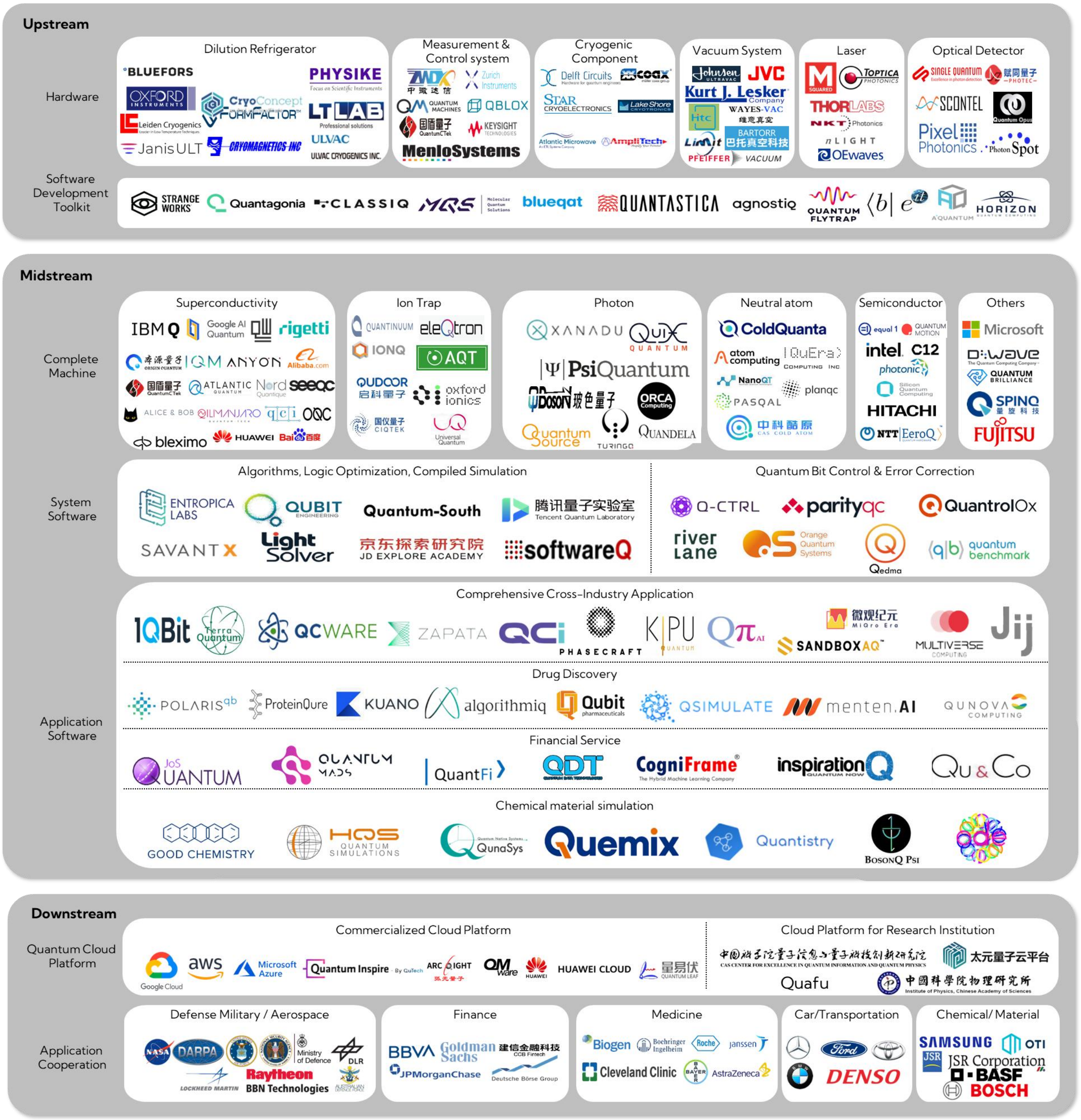
Agnostiq	January	•The release of the open-source workflow orchestration platform, Covalent, designed specifically for quantum computing and HPC technology.
Tencent Quantum Laboratory.	May	•The release of an open-source software product, Tensor Circuit, in the field of quantum computing, designed for the next-generation quantum computing software for noisy intermediate-scale quantum (NISQ) computing.
QuEra Computing	July	•The release of a publicly available test version of the Broqade program, an open-source Julia language package for quantum computing and quantum dynamics based on neutral atom architecture, allowing users to simulate quantum processors in simulation mode.

Currently, the openness and community-based sharing of open-source software frequently result in the presence of numerous vulnerabilities in the source code, significantly increasing the cost of defect resolution and hindering the promotion of open-source software applications. As a result, one of the research hotspots is to effectively and accurately detect software defects and quickly repair them.

The Industrial Chain is Gradually Clarifying and Improving.

As the research and development work for various quantum computing routes advances, the upstream hardware and component selection for the complete machine becomes increasingly clear. At the same time, the software system of quantum computers is also constantly evolving, and the composition of all links in the entire industrial chain is gradually becoming clear and improving, with the number of participants in each link gradually increasing.

Exhibit 1-1 Quantum Computing Industry Landscape



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As the development of quantum computing advances along various routes, the hardware components and devices required for the entire system are becoming clearer. Meanwhile, the software system for quantum computers is also evolving, with a clearer and more complete composition of various stages of the supply chain and an increasing number of participants in each stage.

The upstream of quantum computing mainly consists of hardware and software development tools. Currently, hardware components and devices form the largest part of the upstream due to the efforts of various companies and teams worldwide to develop prototypes of the entire machine. Physically breaking through the development is the current most important task.

The midstream of the quantum computer industry encompasses the quantum computer hardware and software systems, as well as the algorithms and application software. Currently, the most prominent technical avenues in the hardware aspect are superconducting, ion trap, photonic, and neutral atom. For instance, IBM accomplished the fabrication of 433 quantum bit chips in 2022, which marked the achievement of its established roadmap and represented the highest number of quantum bits among all the technical avenues. Meanwhile, ion traps maintain the highest two-bit gate fidelity of 99.99%, and the neutral atom quantum computer surprised the industry by the leapfrog development of its route represented by companies such as Cold Quanta and Pasqal in 2022.

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The downstream of the industrial chain refers to the major application domains of quantum computing, and there are already several representative companies in the segmented industries that collaborate with quantum computing companies to jointly explore application development. With the gradual maturity of quantum computing technology, especially the emergence of dedicated quantum computers, practical downstream applications are expected to be realized within five years.

Actively Exploring Downstream Applications.

Quantum computing is a novel computing paradigm based on the principles of quantum mechanics, offering vastly superior parallel computing power in principle to classical computing. It provides solutions to large-scale computing problems required for artificial intelligence, cryptography, weather forecasting, resource exploration, drug design, and other fields, and can reveal complex physical mechanisms such as quantum phase transitions, high-temperature superconductivity, and the quantum Hall effect. This is the powerful capability that quantum computers can offer us. Currently, limited by the progress of real quantum computers, it is not yet possible to provide the powerful computing power of quantum computers to achieve complete quantum applications. However, various quantum algorithms for vertical industry applications can be developed and verified using the computing power of classical computers, thus laying a solid foundation for future practical applications.

Chemical

- Origin Quantum and Fudan University designed a novel molecular crystal structure prediction algorithm utilizing the parallel computing capabilities of quantum superposition states,
- Sarita University , Using quantum computing ,discovered a new phase of two-dimensional materials, assisting the research of hexagonal boron nitride (h-BN) as a highly promising two-dimensional material at the Gratz Technological University. These studies demonstrate the enormous potential of quantum computing in predicting molecular structures, developing next-generation materials and batteries.

Financial

- CaixaBank and D-Wave Systems have collaborated to develop a quantum hybrid application, reportedly significantly reducing the time to resolve complex financial problems and improving portfolio optimization, resulting in an increase in internal return rates for bond portfolios.
- Origin Quantum has developed the quantum mRMR algorithm to accelerate the identification of debt defaults in the financial risk control domain.
- IBM has introduced quantum computing to the French finance industry, with the National Mutual Credit Bank collaborating with IBM to train teams and explore use cases and concept validation for quantum in financial services. Plans are underway to expand France's quantum ecosystem.

Aerospace

- IonQ announced a collaboration with Airbus to explore the potential and advantages of quantum computing in aviation and passenger experience services. Both parties have jointly launched a 12-month quantum aircraft loading optimization and quantum machine learning project, and will eventually present a prototype of an aircraft loading optimization application, providing guidance for Airbus developers and engineers.

Initial Exploration of Commercial Expansion.

In 2022, the quantum computing machines globally remain primarily in their prototype phase, and we are still in the early stages of the NISQ era with limited progress made in terms of actual applications and problem-solving. Although the emergence of a new technology is bound to attract capital and societal attention, and the occurrence of a bubble is rational to some extent, it is important to clearly communicate that the development of quantum computers is still in its early stages and far from being practical, with the vast majority of verifiable applications being carried out on quantum computing simulators.

We predict that, prior to 2030, the realization of purpose-built quantum computers is most likely, which involve coherent manipulation of hundreds of quantum bits and can be applied to specific problems such as combinatorial optimization, quantum chemistry, machine learning, guiding material design, and drug development.

Global quantum computer companies, including research institutes, are now actively exploring their own profit models, mainly as follows.

Providing Quantum Computing Cloud Services

Due to the high construction costs, high maintenance costs, large footprint, and stringent operating conditions of quantum computers, access to quantum computers via cloud computing is more economical and convenient for the majority of potential quantum computing users. Currently, most companies with quantum computing hardware have developed cloud platforms, with IBM being the first to develop a quantum computing cloud platform and currently a successful case in operation. However, most quantum cloud platforms suffer from low levels of accessibility.

Providing the whole machine of quantum computing

Currently, the purchase behavior of quantum computers as a whole machine is almost dominated by various countries, and the units with the capability to purchase are mainly military forces and national-level research institutions. Although quantum computers are still waiting for practicalization, the emergence of purchasing behavior in the market provides income and support for quantum computer companies on one hand, and on the other hand, it reflects the active involvement of defense and military departments, aiming to accelerate the practicalization process.

Providing quantum solutions for the industry

The future powerful abilities of quantum computers have also attracted downstream industry customers to participate, such as financial customers who have a pressing need to layout technology in advance. Currently, some quantum computer companies can provide suitable service solutions, such as quantum algorithms, model optimization, and Monte Carlo simulations, to such industry customers. These collaborations are mostly strategic, and quantum computer companies and industry customers jointly conduct research on a certain project, which has a good preliminary accumulative effect on the development of future industries.

|02

Quantum Computer

In 2022, the development achievements of quantum computing showed diversified characteristics, with key indices such as the number of quantum bits, gate fidelity, quantum volume, coherence time, and others surpassing previous records, and significant progress was also made in error correction and control. We summarize and analyze the development trends of the main six technical routes, including superconducting, ion traps, photonics, neutral atoms, silicon spins, and topology.

- The Superconducting Quantum Computing : In the past year, it remains the most prominent route, with the most rapid technological breakthroughs, topping all routes. IBM has released its Osprey processor with 433 quantum bits on schedule, strictly following the technology roadmap, and is expected to reach 1000 quantum bits by 2023.
- The Trapped Ion Quantum Computing : There have been advancements in the quality of quantum bits, record-breaking quantum volume, and SPAM fidelity of the world's first. Furthermore, it has created logical quantum bits with higher fidelity than physical quantum bits.
- The Photonic Quantum Computing : Represented by company Xanadu, the latest programmable photonic quantum computer Borealis has successfully completed the Gaussian Boson Sampling experiment, showcasing the superiority of quantum computing.
- The Neutral Atom Quantum Computing : Major companies have all surpassed 100 quantum bits, with companies such as ColdQuanta and Pasqal receiving large amounts of financing, the commercialization process has accelerated, and the advantages in quantum simulation are becoming increasingly obvious.
- The Semiconductor Quantum Computing : Intel's developed semiconductor quantum bit chip has a yield rate of 95%, breaking the record of the number of silicon spin quantum bits at 12.
- The Topological Quantum Computing : Microsoft has eliminated the biggest obstacle to producing topological quantum bits through Majorana zero modes and measurable topological gaps, and has the ability to create and maintain quantum phase.

Exhibit 2-1 Roadmap for Quantum Computing Hardware

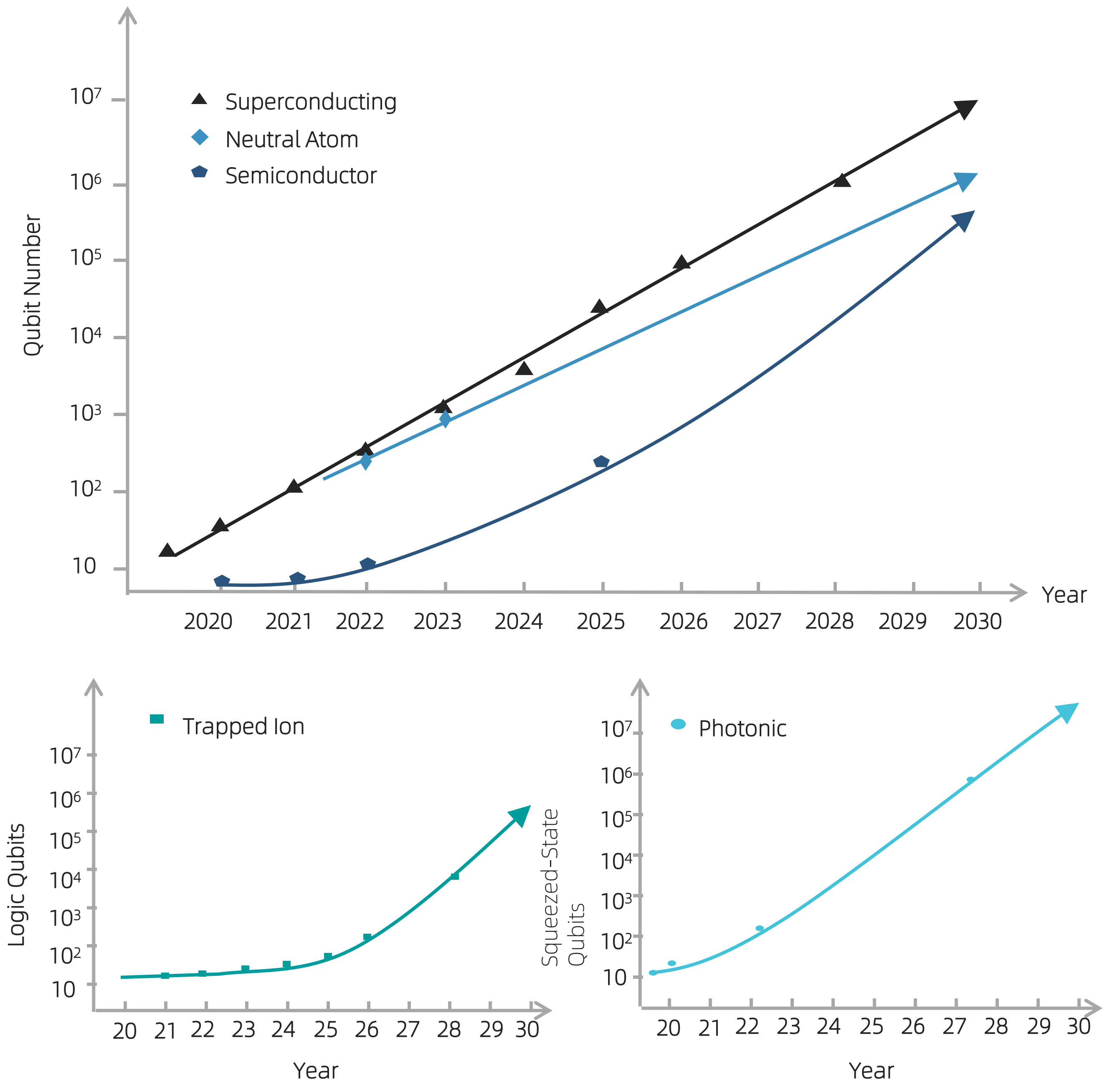
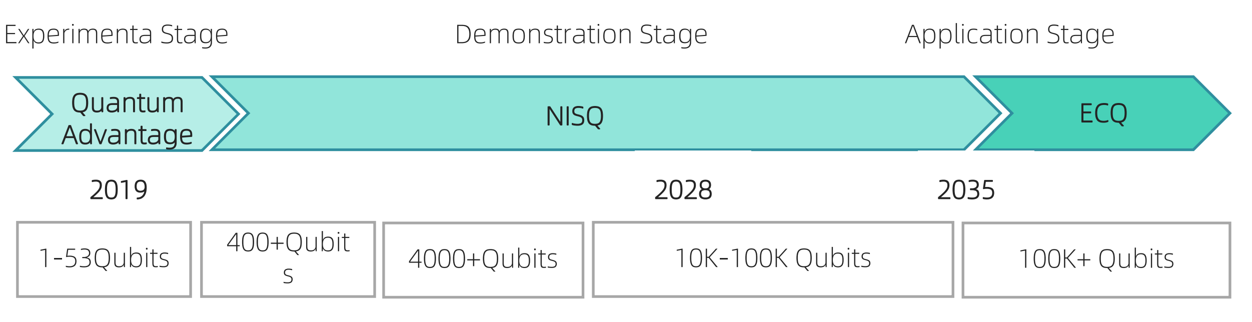


Exhibit 2-2 Quantum Computing Stage



The current primary focus of hardware development in the realm of quantum computing is on increasing the quantity, density, and connectivity of quantum bits, as well as improving their quality by means of better coherence time and gate fidelity. Additionally, there is a drive towards designing and implementing novel architectures, such as 3D settings and innovative assembly techniques, as well as developing large-scale, modular and integratable quantum processing facilities. The demonstration of interconnectivity and information exchange between diverse quantum computers is also a priority. At present, multiple technological avenues for quantum computing are vying for dominance, each showcasing its own advantages, and each with the potential for a remarkable impact.

Superconducting Quantum Computing

IBM is a distant second

IBM Corporation is currently leading the development of superconducting quantum computing technology globally. Based on current trends, it is unlikely that other superconducting quantum computing companies, including Google, will surpass IBM in the short term. IBM represents the United States' international status in the field of superconducting quantum computing.

IBM announced the launch of the 433 qubit Osprey, which not only leads in qubit count but also provides flexibility in signal routing and device layout through its multi-tier wiring. This separation of the wires and components required for readout and control into separate layers helps protect fragile qubits from being damaged and allows the processor to incorporate more qubits.

Compared to the Eagle chip, Osprey has two significant advantages. One advantage is the use of flexible ribbon cables instead of coaxial cables used in IBM's previous quantum processors, as well as the integration of filtering functions to reduce noise and improve stability. The flexible ribbon cable is designed for low-temperature environments with custom resistance and thermal resistance to help microwave signals to be transmitted without conducting too much heat that could interfere with the qubits. This increases the number of chip connections by 77%, almost twice as much as the previous cables, contributing to the expansion of the quantum computer's scale. The other advantage is the new generation of measurement and control systems, which are used to send and receive microwave signals in and out of the quantum processor. The device is more professional and better suited for quantum devices, producing precise signals and frequencies required for computation.

In the future, IBM will focus on two hardware-centered large projects. One involves various types of communication between quantum processors: real-time classical, chip-to-chip quantum gates (quantum entanglement), and quantum communication between multiple quantum processors. The second project involves the development of quantum software, including quantum algorithms, quantum error correction, quantum compilers, and quantum-enhanced optimization algorithms."

Error correction as the core

In 2019, Google achieved quantum superiority for the first time using its "Sycamore" quantum processor, which consisted of 53 quantum bits. By 2022, this had been expanded to 72 quantum bits. Unlike IBM, although Google has fewer quantum bits, they are more focused on the quality of the quantum bits, and have made continual progress in the area of quantum error correction. Google's implementation of error correction uses five-qubit surface codes on its "Sycamore" device, which features 72 transmon quantum bits and 121 tunable couplers. Importantly, previous error correction research has shown that the error rate increases as the number of bits increases, with the adage "the more you correct, the more you err". This time, however, Google achieved "the more you correct, the more you are correct", breaking through the point of balance between the benefits and drawbacks of quantum error correction. This represents a crucial turning point in the long journey of quantum computing and points towards a new path for achieving the low logical error rates required for universal computing.

IBM's current heavy hexagonal two-dimensional quantum bit array connects each quantum bit to other nearby quantum bits on the surface of the chip in some repeated pattern. IBM has also begun researching ways to establish connections between quantum bits located far apart on the chip and to cross these connections, which could lay the groundwork for more efficient error-tolerant machines in the future.

In general, the achievements of superconducting quantum computing technology in 2022 were mainly focused on gate speed, gate fidelity, signal readout, coherence time, and number of qubits. It can be expected that the superconducting route, under the leadership of IBM, will continue to lead other technological routes in the next three years. However, there are still many challenges that this technology must overcome, and it is unknown whether it will continue to maintain its leading position in the future.

Trapped Ion Quantum Computing

Towards Fault-Tolerant Quantum Computers

One of the major advantages of ion traps is the natural homogeneity of ions, resulting in long coherence times and high gate fidelity. In this context, one of the key accomplishments of the ion trap quantum computing technology in 2022 was to further improve the state preparation and measurement (SPAM) fidelity. This was achieved by Quantum and IonQ, two quantum computing companies. Both companies raised the SPAM fidelity to 99.9904%, leading the industry, thanks to the ion trap's natural advantage in terms of fidelity compared to other technology lines.

Of even greater significance, Quantum Computing Company, a subsidiary of Honeywell, demonstrated the entangling gate between two logical quantum bits through experiments, and completed real-time error correction in a fully fault-tolerant manner. This demonstrated a logical circuit with higher fidelity than the corresponding physical circuit, marking a milestone achievement that the performance of logical quantum bits surpasses that of physical quantum bits - a crucial step towards fault-tolerant quantum computing.

Exploring ways to extend qubits

Enhancing ion trap interconnectivity and expanding the number of system bits are common goals for ion trap companies. At the beginning of 2022, IonQ announced that it would use barium ions in its new system instead of previously used ytterbium ions, as barium ions are more suitable for photon-ion entanglement. In March, the company released its latest generation of quantum system IonQ Forte, which includes 32 quantum bits and has the ability to handle up to 40 individual ion quantum bits with its AOD system. The ion trap system itself has a problem with scalability, but with IonQ's introduction of a multi-core architecture, the ion trap quantum computer is expected to surpass 100 quantum bits in the next 1-2 years. In January 2023, the Entangled Networks team joined IonQ, mainly engaged in research and development of ion-based quantum computing technology and quantum network solutions.

In addition to quantum bit (qubit) count, other parameters such as coherence time, computation speed, circuit depth, error rate, and connectivity can also effectively represent the performance of a quantum computer.

The superiority of ion trap technology can be reflected in its quantum volume (QV) index, which is currently the largest among all quantum computer technologies with a maximum QV of 8192. The full connectivity between qubits and its long de-coherence time are its two major advantages that compensate for the current limitation in qubit count.

Explore diverse technology routes

IonQ currently uses trapped ion qubits, where the technology involves the stimulation of ions by laser light to emit photons, entanglement of photons and ions, and the transfer of entangled photons to the other side to entangle the two ion traps.

Quantum, on the other hand, uses the QCCD architecture which utilizes segmented ion traps, where internal ions can shuttle back and forth and interact with lasers in different regions. In the IonQ approach, "ions don't move, light moves," meaning that the acoustic optical modulator addresses different ions outside the ion trap.

The advantage of the IonQ approach is that ions can easily interact with each other, while to achieve the same effect in Quantum's technology, the corresponding ions need to be "picked out" to the corresponding region and then interact with the laser. Quantum focuses on solving the problem of accommodating more ions within a single ion trap.

In addition to IonQ and Quantum, the Austrian company AQT has also given a new architecture. AQT's 19-inch rack consists of an optical rack and a "trap" rack, including an optical system, communication and readout system, amplifier and electronic equipment, fiber routing and switch, and other core modules. The optical rack mainly includes optical generation, switching, and routing modules and related electronic equipment, including coherent radio frequency (RF) and digital signal generation modules, while the "trap" rack houses the main trap modules and related drive electronic equipment, as well as communication and remote control hubs. Unlike Quantum's QCCD architecture, AQT's architecture, although with shorter coherence time, is more easily integrated with the optical system.

Furthermore, Qusoul, the cutting-edge quantum computing measurement and control system developed by QUDOOR, boasts domestically developed ARTIQ (Advanced Real-Time Infrastructure for Quantum physics) architecture with independent intellectual property rights in China. This architecture system is at the forefront of quantum information experiments, serving as an advanced control and data acquisition system, and it is currently one of the most advanced and widely used quantum measurement and control systems worldwide. In the future, it is expected that this architecture system will establish a universal platform.

Optical quantum computing

Breakthrough in all indicators

In the realm of quantum computing superiority demonstrations, in June 2022, the photonic quantum computing company Xanadu, using their latest programmable photonic quantum computer Borealis, successfully carried out a Gaussian boson sampling experiment, showcasing the superiority of quantum computing. The company's next goal is to establish a fault-tolerant and error-corrected quantum computer that can scale to one million qubits. Another company with this goal, PsiQuantum, which has accumulated a total of 665 million US dollars in financing, made some breakthroughs in error-corrected quantum computing architecture in 2022, but has not yet launched any products or prototypes.

In terms of photonic quantum processors, the Dutch photonic quantum computing company QuiX Quantum launched their new 20 qumode processor in March 2022. This is a continuous variable (CV) based photonic quantum processor, contrasting with PsiQuantum's route which adopts discrete photonic qubits.

High-dimensional optical quantum computing reveals advantages

In terms of the number of entangled photons, in August the Max Planck Institute for Quantum Optics (MPQ) in the United States succeeded in effectively entangling 14 photons in an unambiguous manner, setting a new world record.

In March 2022, a team from Peking University in China achieved a breakthrough in quantum computing by developing a high-dimensional (quantum dit, qudit) quantum computing chip that enables high-dimensional quantum state initialization, operation, and measurement on a large-scale integrated silicon-based photonic quantum chip. By programming and reconstructing the quantum processor, the team was able to execute over a million high-fidelity quantum operations and perform various important high-dimensional quantum Fourier transform-based algorithms, thus proving that high-dimensional quantum computing has significant advantages over binary quantum bit encoding, such as larger computing capacity, higher computational accuracy, and faster computational speed. This achievement has the potential to accelerate the development of large-scale photonic quantum computers.

The use of high-dimensional quantum states of light for computation is not a new technology. As early as August 2019, a team from the Austrian Academy of Sciences and the University of Vienna

(Anton Zeilinger) successfully transmitted three-dimensional quantum states, demonstrating that high-dimensional quantum systems can transmit more information than quantum bits, which could help connect quantum computers with information capacity beyond quantum bits.

High-dimensional quantum states of light are mainly encoded using the path of light, such as forming a four-dimensional quantum state by encoding it in four paths. This is different from multiple degrees of freedom, such as encoding the angular momentum, polarization, and path of two photons simultaneously.

There are three main advantages of using high-dimensional quantum states of light for quantum computing. Firstly, it can reduce loss. By reducing or maintaining loss, the Hilbert space can be expanded. Secondly, it simplifies the construction and compilation of quantum gates. In quantum computing, to implement a two-dimensional irreversible gate, such as AND, OR, or NOT gate, it can be extended to a three-dimensional quantum bit, using redundant quantum bits to store redundant information during the computation process, making the gate reversible, which can better implement such an operation. Thirdly, it can input higher-dimensional information at once. In phase estimation, using iterative phase estimation, four bits can be obtained after one iteration, which is equivalent to obtaining a result of four bits after the chip runs once. This not only makes the system larger during the computation process, but also increases the number of results that can be obtained each time. Additionally, when combined with classical methods, high-dimensional quantum computing also has some advantages.

Neutral atom quantum computing

One major advantage of this technology is its ability to combine various types of optical tweezers, some of which can be rapidly repositioned, with their accompanying atoms. This approach has been utilized to construct an array of over 200 neutral atoms using optical tweezers technology, and is rapidly integrating new and existing techniques to transform these atoms into fully functional quantum computers. This type of optical tweezers renders the technology more flexible compared to other platforms such as superconductors, as it can interact with a larger range of atoms. In contrast, in superconductors, each qubit can only interact with its direct neighbors on the chip.

The "Year of the Neutral Atom" in 2022

In the past year, various routes of quantum computers have demonstrated impressive performance, but the neutral atom route of quantum computers can be considered the undisputed dark horse of 2022, with main achievements including refreshing the number of atomic qubits, coherent time, the fastest two-qubit gate speed, and the release of large-scale atomic quantum processors. In terms of both technological and commercial maturity, it has shown a breakthrough development.

In March 2022, a team from the University of Chicago in the United States successfully achieved a record-breaking 512 qubits using a neutral atom system in the laboratory. In May, Atom Computing's neutral atom quantum computer Phoenix achieved a coherent time that exceeded the current operating time by 100,000 times, reaching 40±7 seconds, which is the longest coherent time ever achieved on a neutral atom commercial platform. In August, there was a heavyweight achievement when the National Institute of Natural Sciences in Japan successfully executed the world's fastest two-qubit gate, with an operating time of only 6.5 nanoseconds. In September, French neutral atom quantum computing company Pasqal announced the launch of a quantum processor with 324 atoms (qubits), which was the largest quantum processor in terms of qubit scale globally before November 2022 (when it was broken by IBM's 433 qubit superconducting quantum computer chip).

Towards the end of 2022, some commercial progress was made. QuEra launched a 256 qubit simulated quantum processor on AWS. QuEra's QPU is the first device on Amazon Braket that can perform the "analog Hamiltonian simulation (AHS)" quantum computing paradigm. M Squared unveiled the prototype of the UK's first commercial neutral atom quantum computer, the Maxwell system.

Significant advantages on dedicated quantum simulators

The impressive progress made by the neutral atom route in the past year is not coincidental. The fundamental reason is that before universal quantum computing can be achieved with quantum computers, quantum computers with specific purposes may become the main development goal in the field of quantum computing in the near future, given the limitations in the number of quantum bits, fault tolerance, and coherence time of quantum computers. As a universal quantum computing route, the superconducting route can also perform quantum simulation likethe neutral atom route. However, the advantage of the neutral atom route over the superconducting route in quantum simulation lies in the natural interaction between the

Hamiltonians of atoms. For the same problem, the neutral atom route can achieve the same result without requiring a large and expensive dilution refrigerator to provide an ultra-low temperature environment for the chip. Of course, optical quantum computing also has the same advantages in development.

Technical principles common to multiple fields

Neutral atom technology also has a variety of applications. Rydberg atoms in the sub-divisional approach can be used as atomic antennas in quantum communication, as chips in the field of quantum computing, and also have wide applications in the field of quantum precision measurement. In addition, another cold atom approach can also be used for quantum relays and quantum memories.

In conclusion, the wide application prospects of neutral atoms have indirectly driven the process of its scientific research and commercialization, promoting the rapid and leapfrog development of this approach.

Semiconductor Quantum Computing

Breakthrough in fidelity

Currently, the advantage of silicon-based quantum technology lies in the utilization of the semiconductor nanostructure, which is similar to the integration of billions of transistors in a small chip. As a result, the mature semiconductor technology can be utilized. Thanks to the compatibility between the silicon-based spin qubits and mature nanofabrication technology, significant progress has been made in fault-tolerant semiconductor quantum computing in the past year.

In January 2022, three papers on silicon quantum computing were simultaneously published in the journal "Nature" by researchers from the University of New South Wales, Delft University of Technology, and RIKEN. All of them achieved a fidelity of over 99% for two-qubit gates, surpassing the fault-tolerance threshold of quantum error-correcting codes and crossing the threshold for fault-tolerant quantum computing, demonstrating the feasibility of implementing fault-tolerant quantum computing in the silicon-based semiconductor quantum dot system.

In August, researchers from the RIKEN Institute in Japan demonstrated error correction in a three-qubit silicon spin (semiconductor quantum dot) computing system, which was published in the journal Nature under the title "Quantum error correction using silicon spin qubits". This marks the first successful implementation of error correction in semiconductor quantum computing and lays the foundation for the development of large-scale quantum computers.

In September, QuTech, the quantum computing research institute at Delft University of Technology, created a six-qubit silicon chip with observable fidelity in universal operations, state preparation, and qubit measurement. Compared to other architectures, the error rate has also been reduced, representing a valuable step towards creating fault-tolerant quantum computers based on silicon.

Towards Scalability

The scalability of semiconductor quantum chips has been a major challenge for research in this field. In 2022, significant progress was made in this area with advancements in transmission methods, operating temperature range, and number of qubits.

Firstly, in September 2022, researchers from RWTH Aachen University and Forschungszentrum Jülich in Germany successfully transmitted electrons (the carriers of quantum information) over several micrometers on a semiconductor quantum chip. Their "quantum bus" may be a crucial component for future scalability to millions of qubits.

Secondly, in October, Australian company Archer Materials announced a "step change" in the development of their 12CQ chip, which is now capable of detecting quantum information in qubit materials at room temperature. This breakthrough provides a solid foundation for expanding semiconductor quantum computing to room temperature in the future.

Topological Quantum Computing

As a highly promising technology, topological quantum computing has the advantage of hardware-level error correction. In essence, a quantum bit, or qubit, is a single entity that interacts with other qubits, making it susceptible to errors, which can result in lost information, especially as the number of qubits increases. However, in a topological quantum computer, several qubits are combined to form a fixed structure that is impervious to external interference and therefore does not suffer from lost information.

In terms of topological qubits, the most studied particles are the Majorana fermions, which are predicted fermions that are their own antiparticles. However, Majorana fermions have yet to be found in nature, which is why scientists are working to create a type of anyon called a Majorana zero mode, which differs from fundamental particles such as electrons or photons that naturally exist in a vacuum, as Majorana anyons need to be produced in mixed materials.

Continued exploration of new materials

Currently, there are three main types of systems that could potentially form the basis of a topological quantum computer: fractional quantum Hall systems, topological superconductors, and topological insulators. The materials that scientists have experimentally produced to represent each of these types are GaAs/AlGaAs for fractional quantum Hall systems, Fe atom chains on Pb for topological superconductors, and Rebbi-like modes in non-Abelian Jackiw systems (only proposed) for topological insulators.

Intel has achieved a key milestone in the production research of semiconductor quantum chips, with a yield rate of up to 95% and a record-breaking 12 silicon spin qubits, which is an important step towards the commercialization of quantum computers with thousands or even millions of qubits.

However, the main challenge of silicon-based technology is the variability in the quality of each qubit, which scientists are working to address. The next step for silicon quantum computing is to achieve multi-qubit coupling and universal quantum gate manipulation using modern semiconductor industry production techniques, in order to construct large-scale, scalable silicon quantum chips capable of fault-tolerant quantum computing prototypes.

Overall, 2022 was a positive and hopeful year for quantum computing, with research on electronic transport, the development of fault-tolerant spin qubit systems, and the use of traditional electronic techniques to simulate quantum structures, all being key to bringing quantum computers out of the lab and into the real world to solve complex real-world problems while overcoming the limitations imposed by the laws of quantum mechanics

In 2022, researchers from the Swiss National Laboratory used "soft X-ray angle-resolved photoelectron spectroscopy" (SX-ARPES) to compare the electron distribution of two semiconductors and their oxide layers, and found that antimony telluride is more suitable as a carrier material for topological quantum bits than indium arsenide.

In February, researchers at the Paul Scherrer Institute in Switzerland developed a new material called "topological qubits" by creating unique electronic states in thin films of different semiconductors and superconductors.

In June, scientists at the Chinese Academy of Sciences found that stress can induce a large-area, highly ordered, and tunable Majorana zero-energy mode lattice in the iron-based superconductor LiFeAs.

In November, scientists at the University of Chicago discovered a new material, MnBi6Te10, that can be used to create quantum highways that electrons can move along for topological quantum computing.

While topological quantum computing research is still in the basic research phase, it holds great promise for long-term benefits and should be encouraged.

Breakthrough in technical principles

The characteristic of the topological phase is the long-range entanglement of the ground state, which is difficult to obtain using traditional experimental probes. In March 2022, the "Topological Gap Protocol" (TGP) proposed by the Microsoft Azure Quantum team solved this problem as a standard for determining topological phase through quantum transport measurement. If the protocol can be implemented, the existence of a topological gap is demonstrated. To this end, they designed a device: a topological superconducting wire with a Majorana zero mode at its end and a real fermionic operator at both ends of the wire. Finally, the Microsoft team measured a topological gap of over 30μeV on this device, which eliminated the biggest obstacle to creating topological qubits.

These groundbreaking technological advances are key steps in the principle of future topological quantum computer manufacturing. Topological quantum computing relies heavily on the fusion and braiding of anyons (the two primitive operations of topological quasi-particles), and the topological gap controls the fault-tolerant ability provided by these operations to the basic states of matter. Therefore, whether it is Microsoft's ability to create and maintain quantum phase based on the Majorana zero mode and measurable topological gap, which eliminated the biggest obstacle to creating topological qubits, or Princeton University's research on fractional quantum Hall effect, quantum computers based on topological qubits will perform more stably than machines built with other known qubits.

03

Core Equipment & Device

In the hardware systems, mK-level dilution refrigerators (including GM pulse-tube pre-cooling equipment) and microwave control circuit systems (including integrated quantum computing measurement and control systems, RF microwave cables, low-temperature electronic devices, RF microwave instruments, etc.) are the core equipment for superconducting or semiconductor quantum computers. RF microwave cables (coaxial cables, flexible cables, etc.) are the bridge between the quantum chips at low temperatures and the measurement and control system at room temperature, while low-temperature electronic devices include sub-components such as low-temperature couplers, low-pass filters, cryogenic isolators, infrared filters, and low-noise amplifiers.

For the control and measurement of quantum bits, the quantum computing measurement and control system can be broadly divided into two types depending on their technical route: one is the optical system, which includes components such as photon sources, single photon detectors, and lasers. It is mainly responsible for the control and measurement of photonic, ion trap, and neutral atom quantum computing. The other type is the microwave control circuit system, which mainly includes a series of microwave devices such as arbitrary waveform generators, lock-in amplifiers, etc. This system is mainly responsible for the control and measurement of superconducting and semiconductor quantum computing (and also for the control of ion traps, neutral atoms, diamond NV centers, etc.).

Dilution Refrigerator

The core equipment for superconducting or semiconductor quantum computers includes mK-level dilution refrigerators and microwave control circuit systems, which contain integrated quantum computing measurement and control systems, RF microwave cables, low-temperature electronic devices, and RF microwave instruments. RF microwave cables connect the quantum chips at low temperatures to the measurement and control systems at room temperature. Low-temperature electronic devices include low-temperature couplers, low-pass filters, low-temperature isolators, infrared filters, low-temperature amplifiers, and other components. Low-temperature technologies, including adiabatic demagnetization refrigerators and adsorption refrigerators, can achieve extreme temperatures below 1 K, and dilution refrigerators are widely used in various low-temperature fields. Adiabatic demagnetization refrigerators combined with adsorption refrigerators or other pre-cooling methods can achieve temperatures below 250 mK.

Dilution refrigerators are particularly important for superconducting, semiconductor, and topological quantum computers, with the main working temperature range of 5 mK to 4 K.

The only cooling technology currently available for quantum computers

Other types of cryocoolers can achieve temperatures almost as low as dilution refrigerators, but they are not suitable for quantum computing and are instead used for pre-cooling, such as adiabatic demagnetization refrigerators. These methods are not capable of providing a persistent low-temperature environment and are not directly suitable for supporting quantum computing and quantum simulation.

Typically, for topological quantum computing research, dilution refrigerators are used to create temperatures close to 0 K, and even lower temperatures are achieved by pre-cooling with adiabatic nuclear demagnetization refrigerators followed by dilution refrigerators, which is the only way to cool macroscopic objects to microkelvin (μK) temperatures in condensed matter.

Breaking the volume limit is the focus of current R&D

In March 2022, Maybell Quantum, a Denver-based startup company, unveiled the Icebox dilution refrigerator, a low-temperature platform designed to power the next generation of quantum computers. The Icebox supports three times as many qubits in one-tenth the volume compared to previous systems, and includes 4,500 superconducting flexible wires. This is the first gate-enabled system that allows for quantum bit access without disassembling the refrigerator.

In 2021, IBM unveiled its "Goldeneye" project to build an unprecedentedly large dilution refrigerator for quantum computing - with an experimental volume of 1.7 cubic meters, the system can cool a volume larger than three home refrigerators to a temperature colder than outer space, while previous refrigerators were only in the range of 0.4-0.7 cubic meters. In September 2022, the "Goldeneye" was successfully cooled to its operating temperature (~25 mK) and an internal quantum processor was integrated into it.

In December, researchers at the US Department of Energy's Fermilab announced that they are building the Colossus, which will be the largest and most powerful dilution refrigerator at mK temperatures to date, with a volume three times that of Goldeneye. This giant refrigerator will be able to accommodate hundreds to thousands of highly coherent cavities and qubits, and provide ten times the cooling power and fifteen times the volume of a standard commercial dilution refrigerator at this temperature. However, due to its inverted wedding cake structure with a maximum diameter of about 2 meters and containing seven disks of decreasing diameter and temperature that need to be suspended and connected to form the low-temperature structure of the Colossus, this poses a challenge for the construction of the Colossus at present.

China is expected to achieve a technological breakthrough

In 2023, the embargo on dilution refrigerators with temperatures below 10 mK will force China to accelerate its independent research and development process. Currently, the team led by Zhongqing Ji at the Institute of Physics of the Chinese Academy of Sciences has achieved a temperature of 8 mK on a no-liquid-helium dilution refrigerator. The Sixteenth Institute of China Electronics Technology Group Corporation has made a breakthrough in the development of a dilution refrigerator, with a continuous operating temperature of 9.3 millikelvin. The ultra-low temperature dilution refrigerator developed by China Shipbuilding Industry Corporation's Pengli relies on a GM refrigerator as a pre-cooling source, achieving a minimum temperature of 12 mK (during continuous operation).

The current difficulties faced by China in its independent development of dilution refrigerators include heavy reliance on imported isotopes such as ^{3}He, pre-cooling equipment like pulse tubes and cold heads, as well as various technical challenges including welding low-temperature equipment and overcoming issues such as cold leaks, super leaks, and heat exchangers for coils and silver powder. Furthermore, in the key area of dilution refrigerator magnetic resonance cooling technology, it remains unclear whether companies such as China CSIC PRIDE(NANJING)NEW ENERGY TECHNOLOGY, VACREE, Hynhe Technology(GuangZhou), which are capable of achieving temperatures of 4K, can effectively operate at such temperatures.

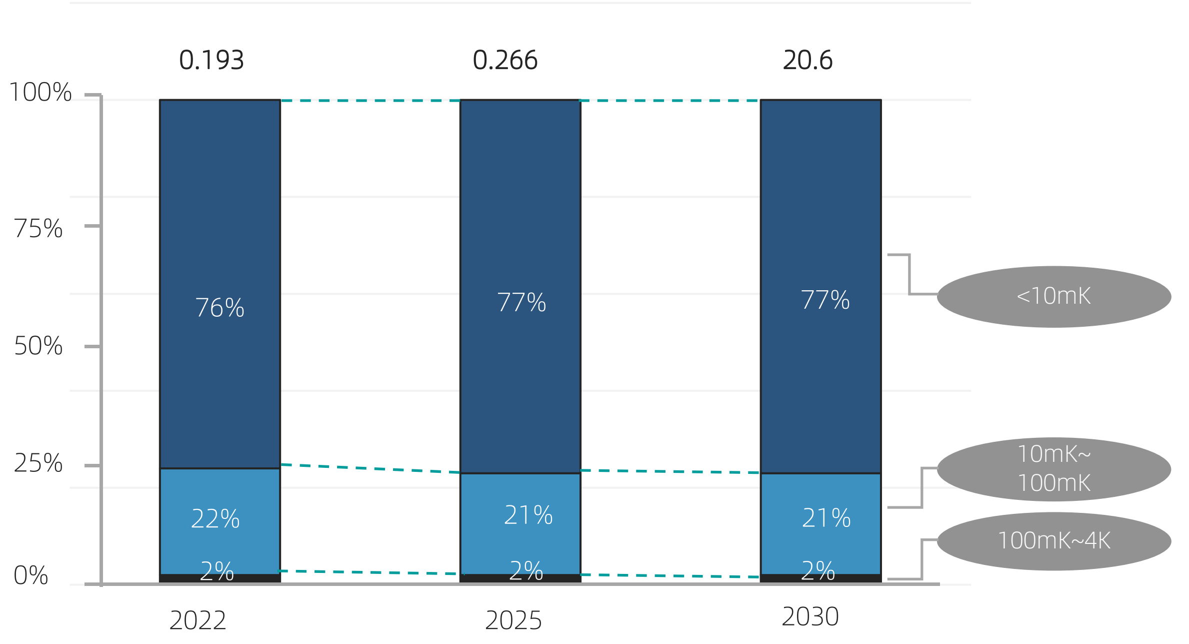
Market Size and Forecast

The development of superconducting and semiconductor quantum computers is expected to drive the growth of the dilution refrigerator market, with the ultra-low temperature range (used for superconducting quantum computers) accounting for approximately 76% of the market share in 2022.

The global market size for dilution refrigerators in 2022 was $193 million, with the ultra-low temperature range market accounting for $147 million and the 10mK-100mK temperature range market accounting for $42 million.

The market size for dilution refrigerators is expected to reach $266 million by 2025.

Exhibit 3-1 Global Dilution Chiller Market Size (2022~2030)
Unit: Billion USD



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The major players in the global dilution cooler are Bluefors (Finland), Oxford instruments (UK), Leiden Cryogenics (Netherlands), CryoConcept (France), Form Factor (USA), Maybell Quantum (USA), Quantum Design (USA), Ulvac Cryogenics (Japan), and Zero Point Cryogenics (Canada). Two of them, Bluefors and Oxford instruments, have major global market shares, while Form Factor has become one of the competitive suppliers in North America through the acquisition of Janis ULT.

QCMC (quantum computing measurement and control systems)

The biggest challenge in achieving practical quantum computers is to implement millions of quantum bits or qubits. The development of a quantum computing control and measurement system is essential for this process, regardless of the size or form of the quantum computer. These systems are responsible for real-time control, measurement, reading, feedback, and other processes of quantum bits, and are collectively referred to as quantum computing control and measurement systems, or simply quantum control systems.

The gate operations and measurements of superconducting qubits can be achieved through microwave and radiofrequency pulses, which distinguishes them from other physical systems used to build qubits, such as atoms, ions, and photons.

How to cope with the measurement and control of more qubits

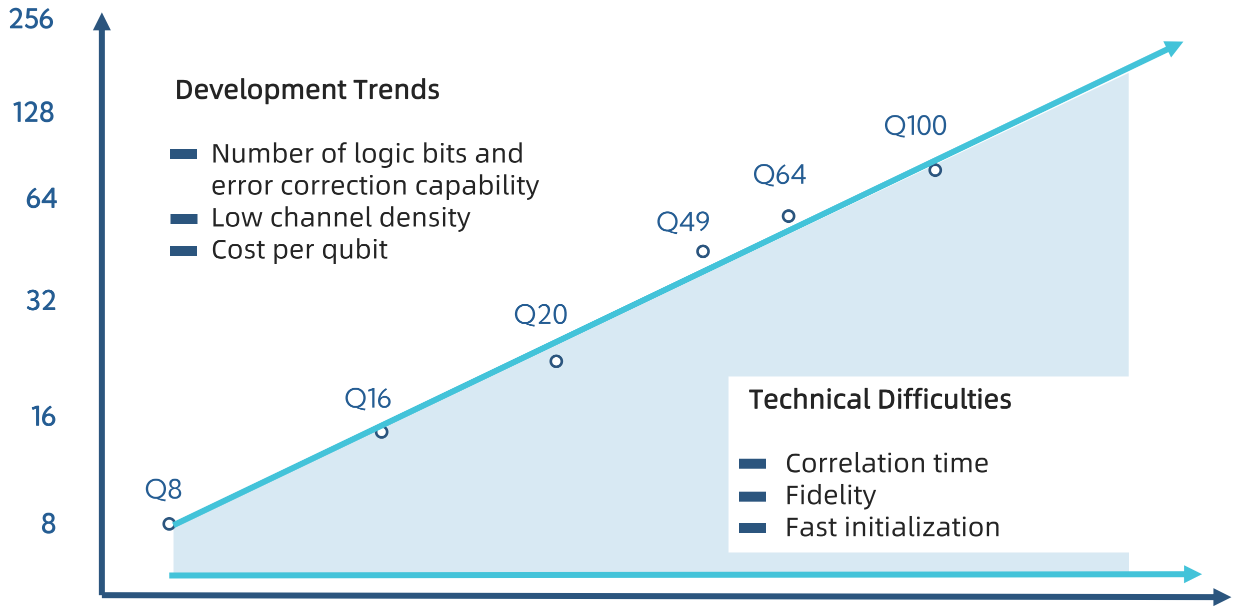
With the increasing number of qubits, the number of measurement and control lines in the measurement and control equipment will also increase correspondingly in theory. Therefore, in addition to improving the hardware performance, future quantum measurement and control systems need to enhance their scalability. Measures to address this challenge include not only enhancing the integration of measurement and control chips but also expanding the system through both intra- and inter-chassis expansion and increasing the system's channel density. Intra-chassis expansion involves inserting corresponding modular measurement and control boards into the chassis, while inter-chassis expansion connects multiple hardware chassis to expand the system to meet more measurement and control needs. Of course, this is a transitional plan currently applicable to systems with several hundred qubits. In the future, with more than a thousand qubits, the chassis plan will be absolutely unable to meet the requirements, so it is necessary to immediately initiate research on low-temperature CMOS control schemes.

Quantum feedback delay time needs to be on the order of 100ns

In order to achieve rapid feedback for readout and control, it is necessary to minimize the delay between uploading and downloading measurement and control data, the control delay between boards and devices, and the output delay of the Arbitrary Waveform Generator (AWG). The entire process of readout, analysis of readout data, and generation of feedback operation for the entire quantum state must be completed before the quantum bit decoherence occurs. Currently, the feedback delay time for quantum systems needs to be in the order of 100 ns.

At present, the technical challenges that limit the measurement and control system correspond to the DiVincenzo criteria. If the future development logic is to be deployed according to fault-tolerant quantum computing, then the current industry evaluation criteria are based on the number of logical qubits, the cost of adding a quantum bit, and whether low channel density can be achieved. With the passage of time, the following figure, which combines the number of qubits and the time scale, presents milestone predictions by Zurich Instruments.

Exhibit 3-2 Development trend of quantum computing measurement and control system



Note: All major hardware manufacturers have given their own Roadmap, and most of them still consider "1000 quantum bits" as the next milestone.

Source: Zurich Instruments

There is still room for improvement in improving synchronization, reducing noise generation and crosstalk

The high synchronicity requirement is a key feature of quantum measurement and control across multiple channels, between different casings, and for control and readout operations. High synchronicity is beneficial for reducing noise caused by relative phase drift between channels, thus minimizing experimental calibration complexity. The reduction of noise is an ever-present focus of discussion, as the stochastic and uncontrollable noise of quantum measurement and control systems, as well as environmental noise around quantum bits, are the primary reasons for decoherence and low fidelity of measurement and control operations.

Currently, noise reduction is generally achieved through improving materials, processes, and internal design of cooling machines. For example, new materials for transmon-type quantum bits can increase the coherence time of thermal relaxation to approximately 300 μs, while the addition of Purcell filters can reduce the impact of the Purcell effect on thermal relaxation coherence time. The addition of infrared filters to the dilution refrigerator can also improve thermal relaxation coherence time to some extent.

In addition to improving the performance of the hardware system to make it highly scalable, synchronous, and low-latency, the design of efficient signal waveform algorithms is also a key focus of quantum measurement and control systems. For example, optimizing the generation logic of DAC waveforms can reduce the delay in controlling quantum bits.

Improving signal crosstalk is also a critical task. Crosstalk is caused by small signals that occur due to poor isolation during the transmission of control signals. Currently, the main way to avoid crosstalk is to isolate quantum bits from their surroundings through vacuum and low-temperature cooling environments. In the future, different isolation methods will be investigated to avoid the impact of crosstalk on measurement and control.

Low-temperature chip-based is the future

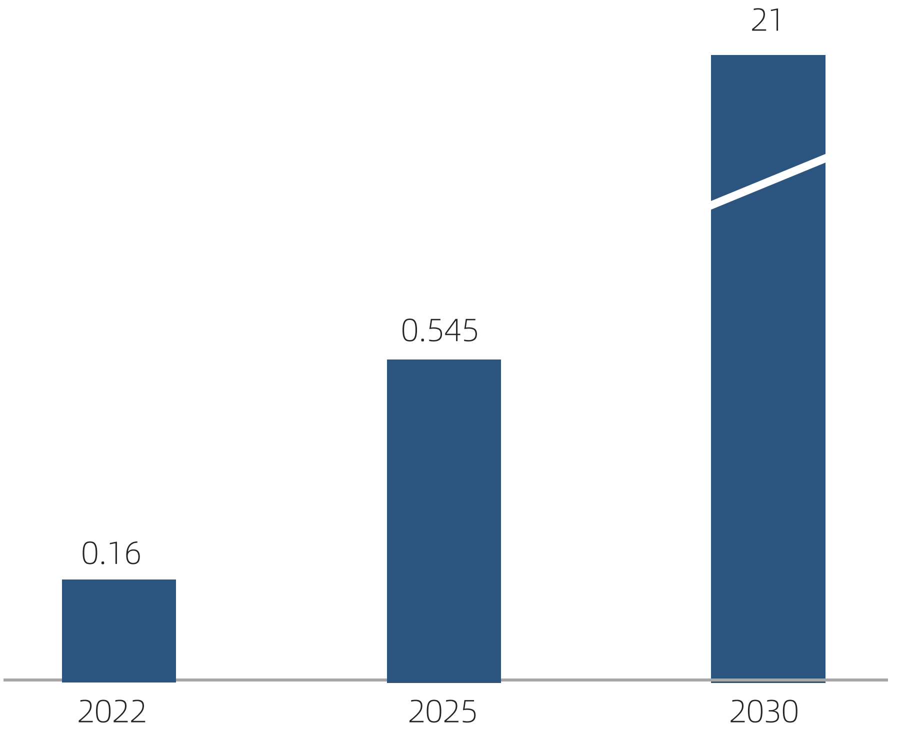
Low-temperature environments can significantly reduce thermal noise caused by temperature and can provide fidelity for quantum gate operations. The trend towards low temperature and chip integration is inseparable because, according to existing quantum bit control methods, a large number of control lines need to be connected from room temperature to quantum chips below 10mK in the quantum measurement and control system..

As the number of quantum bits increases, the existing quantum bit control methods will inevitably bring problems of dilution refrigerator power and volume. Currently, a corresponding control and readout device is needed for each quantum bit in quantum computers with less than 100 quantum bits, but it will be impossible to implement them in the current way for quantum computers with thousands of quantum bits (which are considered practical). To solve these problems, low-temperature integrated control has become a solution, reducing the number of electronic devices and connecting lines required inside the dilution refrigerator through multiplexed readout.

Clear trend of future market growth

The global QCMC (quantum computing measurement and control systems) market size is USD 160 million in 2022. The total market size is expected to reach USD 545 million by 2025.

Exhibit 3-3 Global Quantum Computing Measurement and Control System Market Size (2022~2030)
Unit: Billion USD



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The major global suppliers include Rohde & Schwarz (Germany, acquired Zurich Instruments), Yestech (US), Qblox (Netherlands), SMIT (China), Origin Quantum (China) and QuantumCTek (China). Among them, Rohde & Schwarz and Yestech occupy the majority of the global market share of measurement and control systems.

Laser System

To meet the specific requirements of quantum computers, lasers must have high stability, high precision tuning capability, and low drift to ensure the accuracy and reliability of quantum information. In addition, in quantum computers, lasers also need to be able to generate specific optical signals, such as single-photon pulses or single-mode light, for the manufacture and manipulation of qubits.

The lasers used in quantum computers are mainly all-solid-state lasers with a crystal or glass matrix doped with metal ions as the gain medium, using solid-state (crystal and glass) lasers or semiconductor laser arrays as the pump source. In a sense, all-solid-state lasers integrate the advantages of both semiconductor lasers and solid-state lasers, with a small size, light weight, long life, stable performance, high reliability, good beam quality, and high conversion efficiency, and have huge development potential. They can also obtain wideband visible, infrared, ultraviolet, and even deep ultraviolet laser output through frequency conversion, and are easy to modularize using electrical excitation.

Among various all-solid-state lasers (rod lasers, slab lasers), we are particularly interested in fiber lasers, which use optical fibers as laser media and are mainly used in optical quantum computing, neutral atoms, and ion trap quantum computing.

Single Photon Detector

The lasers used in quantum computers are mainly all-solid-state lasers with a crystal or glass matrix doped with metal ions as the gain medium, using solid-state (crystal and glass) lasers or semiconductor laser arrays as the pump source. In a sense, all-solid-state lasers integrate the advantages of both semiconductor lasers and solid-state lasers, with a small size, light weight, long life, stable performance, high reliability, good beam quality, and high conversion efficiency, and have huge development potential. They can also obtain wideband visible, infrared, ultraviolet, and even deep ultraviolet laser output through frequency conversion, and are easy to modularize using electrical excitation.

Among various all-solid-state lasers (rod lasers, slab lasers), we are particularly interested in fiber lasers, which use optical fibers as laser media and are mainly used in optical quantum computing, neutral atoms, and ion trap quantum computing.

Single Photon Detector

Single-photon detectors must possess several key qualities, including high-performance detection, low cost, and the potential for integration into existing systems. However, these detectors also face an important challenge, which is how to integrate other optical components on silicon photonics.

Single-photon detectors used in quantum computing can be divided into several types, including single-photon avalanche diodes (SPADs), superconducting nanowire single-photon detectors (SNSPDs), and electron-multiplying charge-coupled device (EMCCD) detectors. The first two types are mainly used in photonic quantum information technology, while EMCCDs have broad applications in ion trap and neutral atom quantum computers.

Taking the example of superconducting nanowire single-photon detectors (SNSPDs), they have played an indispensable role in China's "Jiuzhang" photonic quantum computer, which used 100 high-performance SNSPDs with an average system detection efficiency of 0.81. In October 2021, the photon number of "Jiuzhang 2.0" increased from 76 in version 1.0 to 113, marking the first time that the number of quantum information processing units has exceeded 100 in all physical systems.

A typical SNSPD is a switch-type device with single-photon detection capability, but its response waveform does not have a clear resolution to photon energy or photon number. This is because the characteristics of the response waveform are mainly determined by the material, bias current, and dynamic inductance of the SNSPD.

Photon sources and other optical components

In the field of entangled photon sources, the production of polarization-entangled photons is predominantly achieved through the process of spontaneous parametric down-conversion (SPDC). SPDC is a typical nonlinear process that occurs when a laser beam, or pump light, is incident on a crystal. Under certain conditions, incident photons are converted into two photons that are strongly correlated in frequency, polarization, propagation path, and time. This process is often referred to as pump-probe interaction in nonlinear optics.

Currently, there are two main issues facing entangled photon sources: decoherence and low brightness. Decoherence refers to changes in the relative phases of the overlapping parts of the generated photons, which disrupts their coherence and affects the entanglement effect. In experiments, the contrast is a measure of the strength of the entanglement between photons, and the more severe the decoherence, the lower the contrast.

In terms of single-photon sources, purity has long been a major challenge for scientists. Basic methods involve quasi-coherent technologies, such as spontaneous parametric down-conversion (SPDC), and single-crystal materials that produce single-photon sources. By using these techniques, it is possible to generate single-photon sources with higher purity, which meets the needs of quantum information science research.

In 2022, the University of Science and Technology of China proposed the best current solution. The research team used the interaction between Rydberg atoms to achieve high-precision excitation and manipulation of the superatomic quantum state and based on this, prepared a high-quality single-photon source with a purity of 99.95% and an indistinguishability of 99.94%. Subsequently, they applied it to the experiment of the optical quantum logic gate based on the KLM scheme, and successfully improved the fidelity of the truth table to 99.84%. Using this high-fidelity optical quantum logic gate, they finally performed quantum entanglement measurements through quantum tomography and Bell inequality, and achieved an entanglement gate fidelity of 99.69%.


Getty Images

04

Software, Algorithms, Cloud Platform

The ecosystem of classical computers revolves around the operating system, and the same is true for quantum computers. Similarly, compiling software, software development tools, and industry-specific algorithms and software are indispensable.

In terms of the development level of quantum computer system software, quantum algorithms, and quantum software technology in various countries, the United States is at the forefront in 2022 in terms of quantum algorithms, software, and development toolkits, as well as error correction software. China, Canada, Japan, and France closely follow, each with outstanding performance in various subfields. Other countries such as Germany, Spain, and the United Kingdom have also made significant contributions to some specific subfields.

Progress in system software is mainly reflected in error correction. Most hardware manufacturers have released their own quantum computing programming languages for compiling software. For software development work, the future community open source development will become a mainstream mode. For the development of application software, the focus is mainly on continuously expanding contacts with downstream industries, deeply exploring the enterprise needs in different downstream fields, and identifying the advantages of quantum parallel computing.

Quantum cloud platforms can be broadly classified into three application scenarios. In quantum research, scientists can use quantum cloud platforms to test quantum information theory, conduct experiments, and compare architectures. In quantum education, teachers can use quantum cloud platforms to help students better understand quantum mechanics and implement and test quantum algorithms. In quantum development, programmers can use quantum cloud platforms to create quantum educational games to introduce people to quantum concepts, or develop quantum programming software to enrich quantum development tools.

Quantum Software

At present, the main development direction of software is still focused on the development of quantum compilers with automatic scheduling functions and distributed programming capabilities that demonstrate multiple hardware control backends. Additionally, there is a need for standardized intermediate representation frameworks that can work across multiple technologies, as well as the development of hybrid classical/quantum software stacks based on APIs and compiler instructions (pragma).

This section mainly lists the technical advances in important subfields such as system software, compiling software, software development tools, and application software in 2022, and summarizes some possible future trends in overall software development.

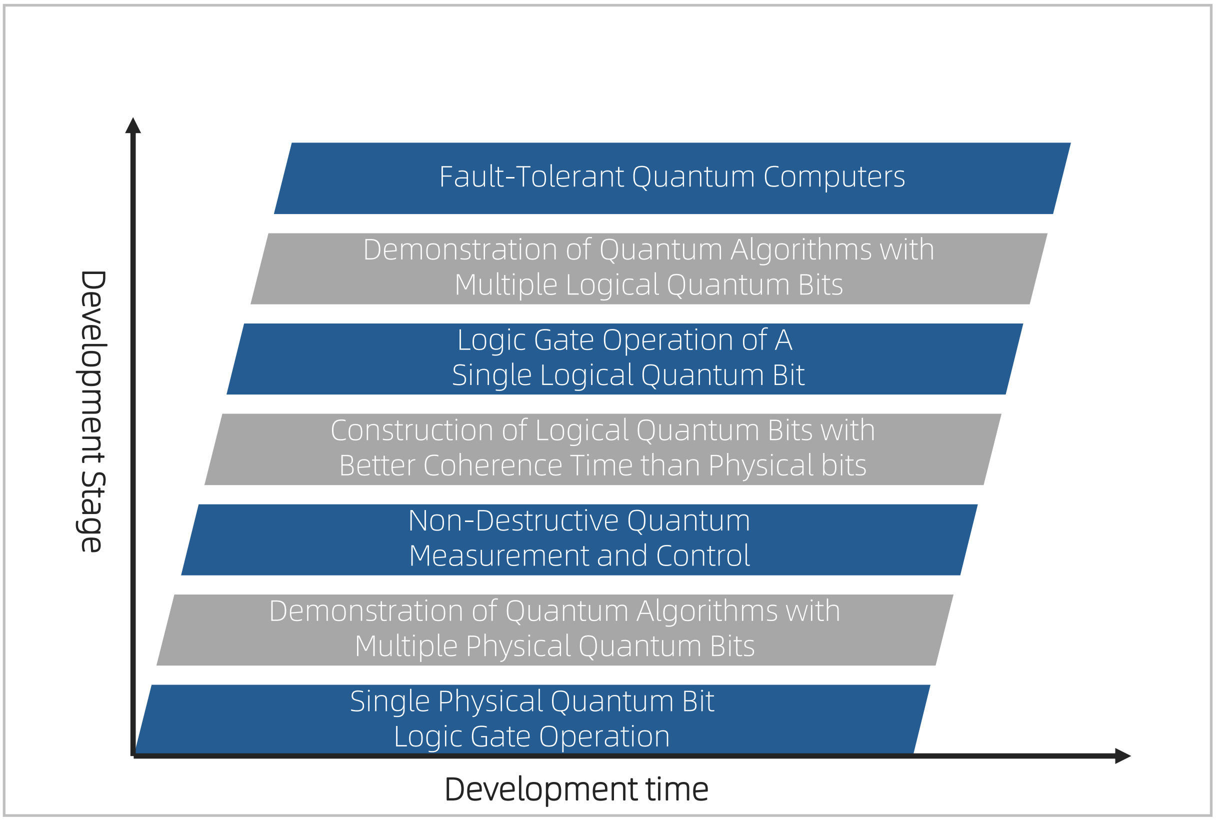
System Software

Software error correction of the attention of the elevated

Looking at the overall picture in 2022, the surface code remains the leader in error correction. However, it has two significant drawbacks. On the one hand, in this mode, most of the physical qubits will be used for error correction. As the distance of the surface code increases, the number of physical qubits required to encode one qubit must increase, just like the square of the distance. For example, a surface code with a distance of 10 will require about 200 physical qubits to encode one logical qubit. On the other hand, it is challenging to implement a set of computationally universal logical gates. It requires additional resources and is not simply encoding quantum information as error-correcting codes. The spatiotemporal cost of these additional resources may be too expensive for small and medium-scale computing.

As the number of quantum bits continues to increase year by year, the field of fault-tolerant quantum computing is continuously advancing, and the demand for quantum computer error correction is also increasing year by year. In addition to the hardware-based error correction route of topological quantum computing, other routes require urgent and necessary software-based error correction. It can be foreseen that in the near future, companies dedicated to developing error correction software will play a pivotal role in the entire system software field. Several software companies have already made good progress in this area.

Exhibit 4-1 Stages of Quantum Computing Development



Source: "Quantum Computing Technology Industry Development Status and Application Analysis

For example, Q-CTRL announced the results of their hardware benchmarking experiment at the American Physical Society (APS) March Meeting, the largest physics conference in the world, held in Chicago in March Developers can obtain hardware-stable, error-reducing, and automated underlying software tools through Q-CTRL's technology, including its flagship product, Boulder Opal.

Furthermore, there has been some progress in setting standards for software error correction. In 2022, the US Quantum Economic Development Consortium (QED-C) expressed interest to IEEE in developing standards suitable for emerging quantum information markets. Quantum information standards may evolve over time from informal to formal specifications. Currently, there are four active quantum standardization projects, one of which is the P3120 standard that defines the technical architecture of quantum computers, including hardware components and low-level software, such as quantum error correction.

Measurement and control system software receives attention

As a derivative of quantum computing software, measurement and control system software is showing a rising trend as the demand for error correction continues to increase. From the perspective of the proportion of technological updates in 2022, the future development of this sub-segment is not to be underestimated.

In January 2022, Zurich Instruments launched its new generation 8.5 GHz quantum measurement and control integrated machine SHFQC and supporting control software, LabOne®, LabOne QCCS, and Python APIs. The machine has low phase noise, low spurious signals, and a large output power range, which can meet fast and high-fidelity gate operations. The real-time signal processing chain has a matched filter and multiple-pulse discrimination function. Feedback measurement and control can be completed within the instrument with a delay of 300 ns, which reduces the error correction burden on the entire quantum computing system.

In October of the same year, the company released the latest generation of measurement and control software, LabOne Q, which can be used as an intuitive software framework for scalable quantum computing. LabOne Q is based on a Python-based high-level programming interface that allows users to focus on intuitive and efficient experimental design while automatically considering instrument details and maximizing useful computing time. Tight system integration between software and hardware ensures a seamless user experience from single quantum bits to 100 or more quantum bits.

The requirements for the measurement and control software are basically the following.

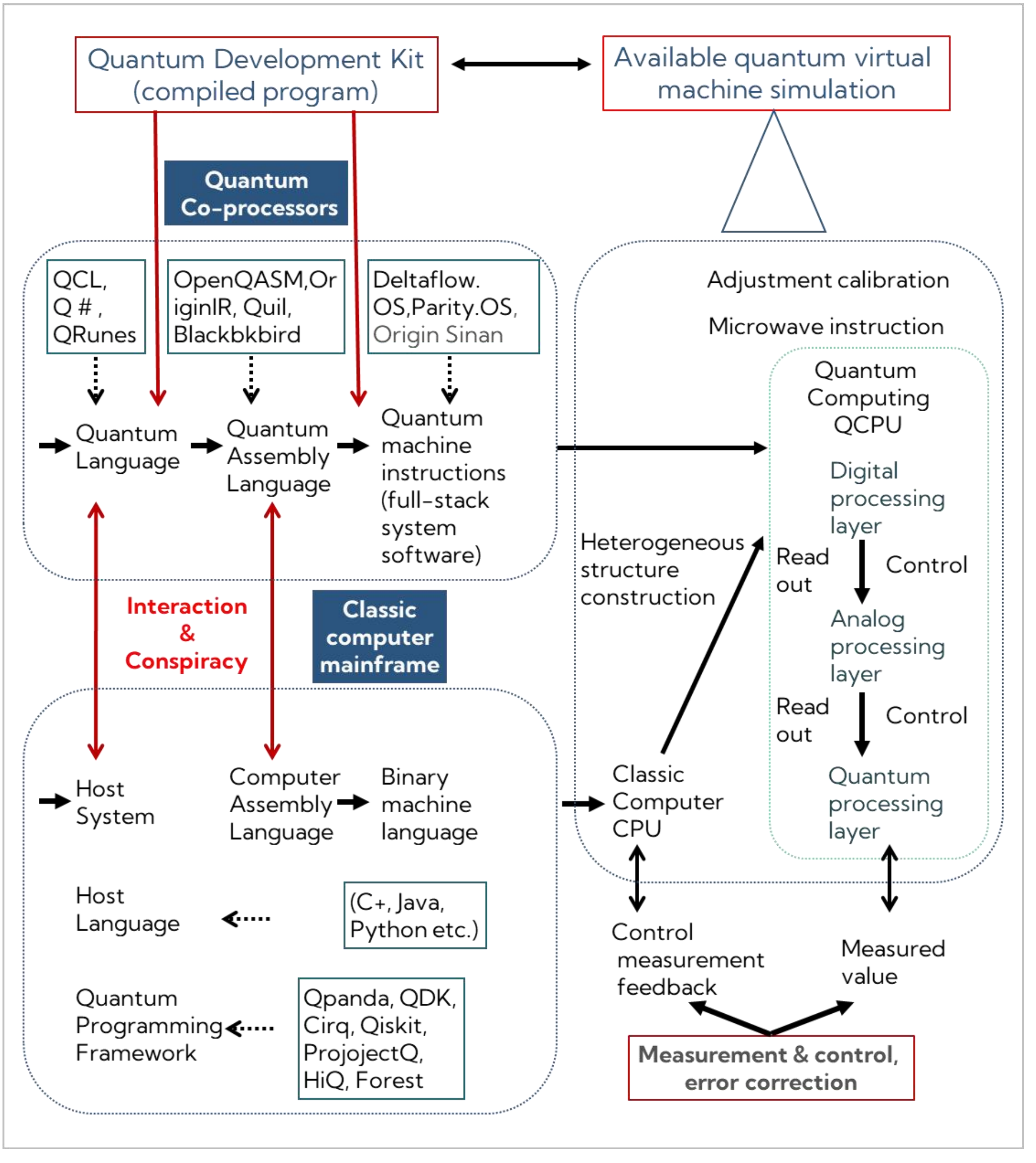
- Accuracy: The measurement and control software should have a clear structure for timing arrangement, waveform control, and device connection, and be able to correctly execute commands issued at a higher level.
- Practicality: The program should include all procedures in a normal experiment as much as possible, and all situations should be taken into consideration to make the call more convenient and the experiment more efficient.
- Conciseness: The function of each program file should be clear, and different functional files and different levels of files should be distinguished, avoiding the mixing of programs as much as possible.
- Device independence: The program should be easy to change the corresponding values of various hardware and different hardware, and avoid excessive communication with the hardware. There should be an intermediate layer to isolate software and hardware.
- Abstraction: The program should maintain a higher level of abstraction to facilitate the execution of various operations. For example, by corresponding the parameters of various bit gates with the gate symbols, it can perform functions described in gate operation language, which is much more convenient than controlling many parameters at a lower level.
- Flexibility: This includes the ability to add various specific function codes more easily and to adapt to various input parameters more easily. This requires considering many experimental factors when writing low-level programs, leaving more freedom to add function parameters for some special experiments in the future.
- Simulation of classical algorithms: Use Qutip (a quantum simulation Python library) to add some simple quantum bit simulation parameters and gate manipulations. This can make it more flexible to compare with experiments and easier to simulate various experimental parameters.

An effective measurement and control software should not only perform its measurement and control functions with high quality, but also minimize the interference with the fragile quantum system as a whole. In the future, with the continuous development of error correction software and the increasing demand for fault tolerance, there is a potential for significant profit growth in the relatively mature subfield of measurement and control software.

Compilation Software

Every quantum computing research and development company or institution has its own quantum development tools, leading to confusion for users when choosing their development tools. Generally, these tools can be divided into three categories: quantum languages, quantum programming frameworks, and quantum intermediate representations (QIR). Although these tools can generally be referred to as "quantum programming languages", they are actually three different levels of development tools.

Exhibit 4-2 Heterogeneous Programming Model for Quantum Computers



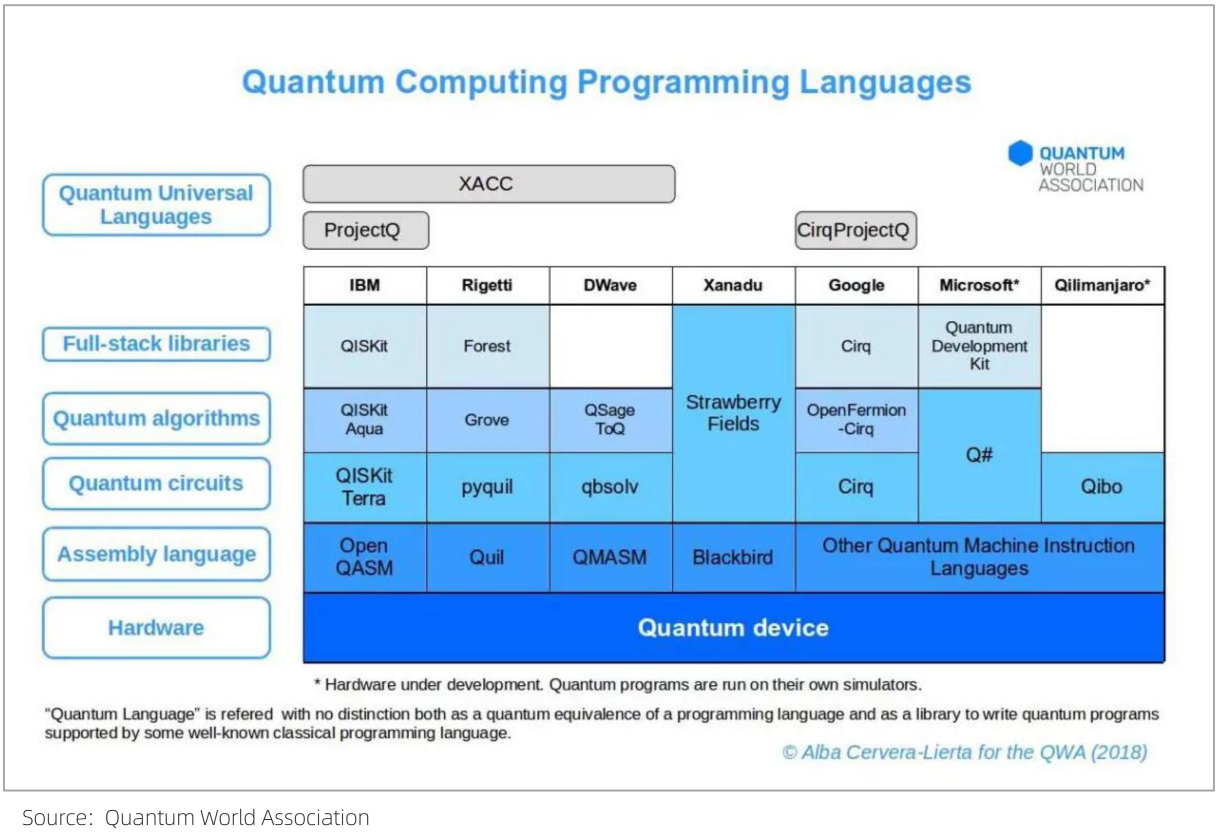
Quantum Language

The quantum language is an independent and novel programming language that implements a syntax specifically designed for quantum computing. It is utilized for writing quantum algorithms and programs that run on quantum computers. Popular examples of quantum languages include QCL, Q#, and QRunes. The quantum language directly embodies the unique quantum features of quantum computing technology and natively supports common quantum algorithm operations. Furthermore, it can support mixed quantum and classical programming, a feature not found in classical programming languages.

Naturally, as a new programming language, the quantum language typically presents a high learning curve for developers. However, since its inception, the quantum language has emphasized fully utilizing and leveraging the advantages of quantum computing, which is advantageous for the future development of large-scale quantum applications and a long-term trend for quantum computing development tools. Currently, quantum languages are often compiled onto a quantum programming framework for processing, enabling mixed quantum and classical computing tasks.

Quantum Programming Framework

Exhibit 4-3 Quantum Programming Framework



Source: Quantum World Association

Quantum programming frameworks focus on the fast development of quantum programs under current technological conditions. They usually take traditional programming languages as host languages and add elements such as variables, functions, and objects that describe the quantum computing system. By processing these elements, quantum algorithms can be implemented and quantum software can be developed.

Due to the existence of host languages, quantum programming framework technologies can easily achieve hybrid programming of quantum and classical computing. Common quantum programming frameworks include QPanda, QDK, Cirq, Qiskit, ProjectQ, HiQ, and Forest. Since quantum programming frameworks introduce quantum computing elements and concepts under classical host programming languages, and regard quantum chips as a special device or object, this is a relatively familiar development paradigm for developers.

In July 2022, the Google Quantum AI team announced the release of the first complete version of their open-source quantum programming framework, Cirq. It is a Python framework designed for writing, running, and analyzing program results for recent quantum computers. The significance of version 1.0 lies in supporting the vast majority of workflows for these systems, and it is considered a stable application programming interface (API) for program exchange.

Programs developed using quantum programming frameworks are compiled, with the classical program code part being translated into machine instructions and subsequently executed on classical processors, while the quantum circuit code part that describes the quantum algorithm is usually converted into quantum intermediate representation and subsequently sent to the quantum chip control system for processing.

Quantum intermediate representation

The quantum intermediate representation includes only the quantum circuit code portion of the quantum-classical hybrid code after separation. It provides a unified way of representing the data of quantum algorithm programs, describing the underlying operations such as quantum logic gates and their timing, and is directly connected to quantum hardware. The quantum intermediate representation is derived from higher-level languages that describe quantum algorithms but is more hardware-oriented and easier for compilers to analyze and optimize. It is similar to assembly language or instruction set architecture in classical computers, but it is not usually machine instructions. Currently, commonly used quantum intermediate representations include OriginIR, Quil, and Blackbird.

Recently, new programming languages have been created, such as Twist, a quantum computing programming language developed by MIT in January 2022. Twist can describe and verify the entangled data in quantum programs, write programs for quantum algorithms, and identify errors in their implementation. In February, the Shanghai-based Institute of Quantum Information and Quantum Technology Innovation of the Chinese Academy of Sciences launched the "Quingo" quantum programming language on the quantum computing cloud platform. Based on this language, the comprehensive quantum-classical heterogeneous programming framework was designed and implemented, which innovatively proposed a series of advanced technologies such as quantum operation timing control and quantum runtime system at the level of advanced quantum programming languages.

In addition, IBM and AWS jointly launched Open QASM in March 2022. For the entire quantum computing assembly language, there are multiple competing but generally complementary quantum bit technologies. Customers can choose from a series of open-source end-user libraries, but they all need to send a set of instructions, i.e., quantum programs, to the quantum processor to execute. The quantum intermediate representation processing process needs to map the quantum bits in the program to the actual positions of the quantum bits in the quantum chip and generate a sequence of quantum logic gate control based on the quantum program, and finally drive the operation of the quantum chip through the quantum measurement and control hardware.

Quantum Virtual Machine

For the development of current quantum programs, a quantum virtual machine is also an important tool. It uses classical computers to simulate the operation of quantum computers, execute quantum programs, and provide the corresponding results. The quantum virtual machine offers a convenient tool for analyzing and debugging quantum algorithms and programs, as well as verifying the correctness of quantum hardware. It is highly beneficial for the development of software and hardware of current quantum computing technology. A quantum virtual machine is typically included in a quantum programming framework, but it can also exist independently and is widely used in quantum cloud systems. In addition, Origin Quantum and Atos have developed quantum learning machine products, which are essentially quantum virtual machines with additional features such as quantum computing education and training.

In summary, although competition among software vendors is inevitable, the future development of quantum computing will undoubtedly be open, interconnected, and integrated. This is particularly true for quantum computing software systems. Companies such as IBM, Google, Microsoft, and Rigetti are highly active in the research and application of quantum computing, leading the direction of technology and industry, which is inseparable from their long-term technological accumulation and strong financial investment.

For full-stack quantum computing enterprises, the progress of their software largely depends on their achievements in the hardware roadmap. As the number of quantum bits has not yet reached a level where practical applications are possible, the company that first breaks through this bottleneck in its corresponding roadmap for quantum computing hardware will undoubtedly usher in a larger-scale use of its quantum computer software.

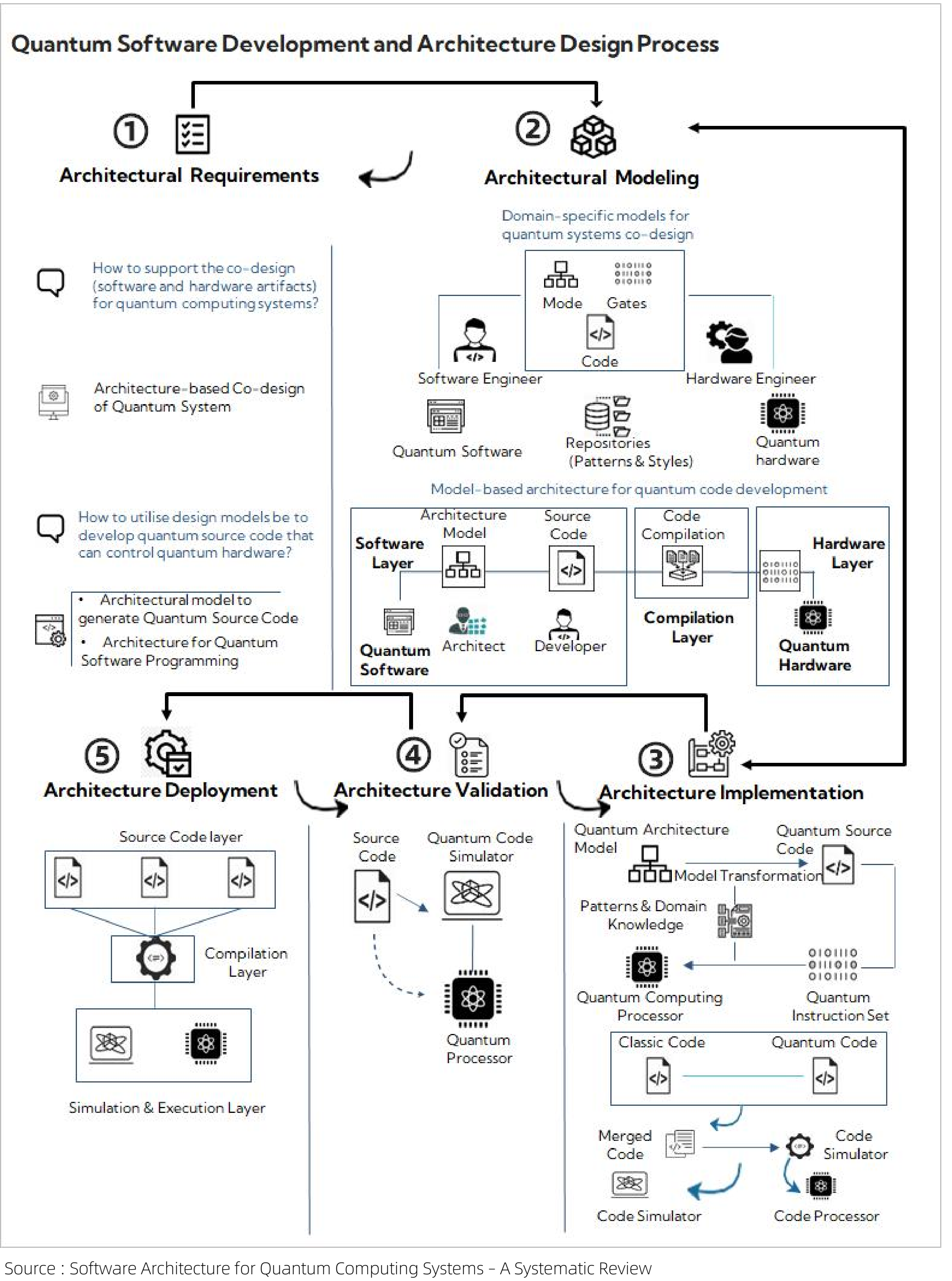
Software Development Tools

Quantum software comprises quantum algorithms, but it is formed by a combination of code, structure, algorithms, and data, among other things. If only an algorithm is considered, it can at best be regarded as a rule, and not a software. On the other hand, a quantum software development toolkit broadly refers to a collection of relevant documentation, examples, and tools that assist in developing a particular type of quantum software.

Software development and architecture design is getting better and better

In July 2022, Nvidia announced the launch of a new platform called QODA (Quantum Optimized Device Architecture), which supports the development and compilation of hybrid environment quantum-classical programs. This platform includes a central processing unit (CPU), a graphics processing unit (GPU), and a quantum processing unit (QPU) that are interconnected. The basic programming interface for the QODA platform is currently in C++, with plans to add Python in the future.

Exhibit 4-4 Quantum Software Development and Architecture Design Process



Source : Software Architecture for Quantum Computing Systems - A Systematic Review

The development of quantum software is currently a complex and tedious process, in which architecture requirements are the initial activities of the development process. The purpose of this activity is to analyze, clarify, and/or re-define the focus of architecture in order to obtain a set of architectural requirements, also known as architecture requirements, and to identify the problems that the architecture needs to address.

Development tools code open source

The creation and use of open-source development tools will allow a wider range of personnel to participate in quantum software development. As a result, quantum algorithm designers can explore new algorithms in a more realistic environment with actual noise and physical resource limitations.

In September 2022, Intel joined the ranks of IBM and Google as a full-stack quantum computing company with the release of a test version of their Quantum Software Development Kit (SDK) at their Innovation Conference. Customers can use the Quantum SDK test version through the Intel Developer Cloud platform Dev Cloud. Intel is expected to release version 1.0 in the first quarter of 2023.

From a technical perspective, having a layered software architecture with a clear open interface has many benefits. First, using a layered architecture facilitates tool interoperability, making it easier to add new tools to existing toolkits and to maintain and improve existing tools. As the current understanding of how best to optimize quantum circuits to avoid noise is limited across various fields, researchers can use a layered architecture to experiment with new algorithms and simulate their advantages in quantum technology. Additionally, the significant software development costs can be shared among various software development groups, providing an economic benefit.

Application Software

The practical commercial application of quantum computing depends on two main prerequisites: having a processor with enough quantum bits to run quantum simulations and quantum algorithms capable of solving the underlying mathematical problems of the applications. Currently, the development strategy of most quantum enterprises is a combination of production and research, with a focus on gradual and continuous progress.

Quantum simulation software is developing rapidly

It seems that in 2022, there were many positive attempts to use quantum simulation in various fields, such as chemistry, biology, and finance. Quantum simulation software can be used to model chemical molecules, which has the potential to greatly advance the development of pharmaceuticals, drug approval, and the research of new materials in the material industry. In the field of biology, quantum simulation can be used to simulate the biological structure of molecules, as well as simulate neural networks, and even simulate artificial life in the future. Due to the high complexity of financial markets, and the fact that they, like quantum systems, have randomness, using quantum software to simulate financial markets has significant advantages, such as Monte Carlo simulations.

In March of 2022, the Google Quantum AI team published a paper in the journal "Nature" indicating that they had completed a 16-qubit chemical simulation on their "Sycamore" quantum computer, which was the largest-scale chemical simulation at the time. In December, Qubit Pharmaceuticals significantly reduced the time and investment required for promising treatments in oncology, inflammatory diseases, and antiviral drugs by using a hybrid quantum classical computer and its Atlas software suite to accelerate drug molecule simulation and modeling. The company used NVIDIA's QODA programming model to build a drug discovery platform that created detailed simulations of physical molecules. Compared to traditional research methods, the calculation speed was increased by 100,000 times.

Collaborating with established technology giants in the field

Such as IBM and Microsoft, holds tremendous appeal for leading companies in downstream industries. For large technology firms, they are constructing a comprehensive quantum computing ecosystem around their own technology solutions, gathering academic research, innovative quantum start-ups, and large potential customer companies together.

In September 2022, JSR Corporation stated that it has established a close partnership with Quantinuum since early on and participated in the beta testing of In Quanto. This platform is mainly used for new materials research and performance prediction and is remarkably user-friendly. Besides JSR, Quantinuum has also announced partnerships with Samsung, Nippon Steel, and BMW, to explore solutions to problems in material science, supply chain, and logistics optimization.

Collaborating with quantum start-up companies

That companis tend to focus on the development of quantum software and algorithms is crucial. In the financial industry, quantum computing applications include portfolio optimization, high-frequency trading, quantitative trading, trading, and fraud detection. These applications involve a significant amount of simulation and algorithm development, and a good source of high-quality quantum algorithms is not limited to top-tier companies.

For example, in March 2022, two leading computational chemistry software companies, Open Eye Scientific and Gaussian, announced that Open Eye's Orion® molecular design platform now supports Gaussian's electronic structure modeling software with an automated scientific workflow to facilitate faster and more comprehensive quantum chemical calculations. In August, the Spanish quantum computing start-up Multiverse Computing applied quantum computer vision for the first time in the automotive manufacturing industry, detecting defects in the manufactured car parts through image classification using a quantum artificial vision system, which outperformed classical methods. In October, the quantum computing company QCI launched the Path to Quantum consultation, Qatalyst™ software, and quantum photonics system hardware to determine the optimal flight path for drones, among other applications.

Collaboration with academia and government agencies

This type of collaboration aims primarily to gain first-hand, potentially exclusive or semi-exclusive knowledge and technology, as seen in examples such as China's Hefei Quantum Industry Park. However, most of these partnerships are regional in nature. Typical progress can be seen in the example of Multiverse Computing, which joined the Spanish industry alliance project led by Renault in September 2022. The goal of the project is to promote electric, autonomous, and connected vehicles. The project, named "Innovative Industrial Ecosystem for Electric and Connected Vehicles in Spain," has been approved by the Spanish government and aims to make the country a leader in sustainable transportation in Europe.

It is foreseeable that in the near future, various types of quantum computing application software will also be able to fully leverage the unique advantage of high-speed parallel computing of hardware, and prioritize their role in specific scenarios with extremely high computing demands. These scenarios include scientific computing, artificial intelligence, big data, space exploration, and other fields, which will bring disruptive impacts to various aspects of technological innovation, industrial development, and economic and social progress.

Expanded application scenarios

Artificial Intelligence

In recent times, artificial intelligence has become ingrained in various aspects of human society and continues to evolve. In the future, with the maturation and improvement of quantum computing hardware, as well as the development of quantum artificial intelligence algorithms, quantum computing is expected to contribute to the realization of deep artificial intelligence scenarios in fields such as machine learning and image recognition. Quantum computing has the potential to become a significant driving force for the growth of the artificial intelligence market.

Chemical

In the field of chemical engineering, quantum computing can be utilized to improve the manufacturing process of ammonia fertilizer in agriculture. Ammonia fertilizer is the most widely used agricultural fertilizer in the world, but it is not a natural product, rather it is an artificially synthesized compound of nitrogen and hydrogen. The "Haber-Bosch process," invented in the 20th century, greatly improved the production efficiency of ammonia fertilizer, but its high-temperature and high-pressure synthetic process unavoidably results in extremely high energy consumption. Effective nitrogenase molecules in nitrogen-fixing bacteria can convert nitrogen gas to ammonia gas through a complex catalytic process without requiring high-temperature and high-pressure conditions, greatly reducing energy costs. However, the number of possible nitrogenase catalytic combinations is too large for supercomputers to process.

Google used a quantum computing error correction device to simulate the catalytic process of the active center of nitrogenase, the iron-molybdenum cofactor. The experiment used more than 1 million quantum bits for the relevant calculations, and is a key step towards improving the energy-intensive fertilizer industry efficiency by improving the Haber process. This is not only a commercial breakthrough, but in the long run, the improved agricultural fertilizer production process achieved through quantum computing will help meet the food needs of the 7.5 billion people on Earth and address the impacts of climate change.

The application of quantum computing in the chemical industry mainly focuses on the exploration of new materials, including biomaterials, to solve problems in industrial and agricultural production and daily life. In 2022, China's MiQro Era made a significant breakthrough in solving the ground state of large molecules in quantum chemistry using quantum encoding, which is expected to bring about significant changes in the fields of computational chemistry and quantum algorithms. The company's classical+quantum software platform also fills the gap between algorithms and application software in China. HQS Quantum Simulations in Germany is developing quantum algorithms for predicting the properties of high-performance materials, specialty chemicals, and molecular properties of pharmaceutical companies. Good Chemistry in Canada provides QEMIST Cloud, a cloud-native, AI-driven quantum computing compatible platform that enables high-throughput, high-precision chemical simulations. Qu&Co, a quantum computing algorithm and software developer in the Netherlands, enables its corporate clients to solve valuable problems in chemistry, materials science, fluid dynamics, and computational finance with unprecedented accuracy and speed.

Pharmaceutical R&D

In the field of pharmaceuticals, the characterization testing of products requires repeated experimentation in order to obtain the necessary data, which can slow down the drug development process. Quantum computing has the potential to simulate molecular properties, allowing researchers to obtain large-scale molecular characteristics through digital computation, shortening the time required for theoretical validation. As a result, the development of new treatments for diseases such as COVID-19 and cancer may be accelerated. The maturation of quantum computing may also lead to reduced costs for sample preparation in the development process, with increased expenses being directed towards quantum computing development to enhance its digitization. Furthermore, due to the rich product pipeline of new drugs, the market size is expected to experience exponential growth.

There are many companies utilizing quantum computing in the development of new drugs. One notable example is Polaris Quantum Biotech in the United States, which combines quantum computing with artificial intelligence and precision medicine to revolutionize drug design. The company's platform is capable of producing up to 100 drug blueprints per year, and has reduced the delivery time of pre-clinical drug candidates from 5 years to 4 months, achieving real-time adaptability to the precision medicine market. Another example is ProteinQure in Canada, a biotechnology company that uses computational research tools to perform drug design in a computer, primarily utilizing quantum computing, molecular simulation, and reinforcement learning to design new therapeutic methods.

In addition, Qubit Pharmaceuticals in France has developed a software simulation platform called ATLAS, which aims to change the way drugs are developed from approximation to prediction. The platform allows for the highest accuracy calculation of the absolute free energy of a molecule. Another company, Menten AI in Canada, uses the next generation of technology utilizing machine learning and quantum computing to develop protein design software platforms. The team has made significant progress towards achieving its goals by developing the first fully scalable peptide and protein design algorithm on a quantum computer and creating the world's first peptide on a quantum computer.

Finance

The growth in computing power brought about by quantum computing has created limitless possibilities for the development of new financial services and products. The applications of quantum computing in the field of finance mainly consist of three subfields: portfolio optimization, high-frequency trading, quantitative trading, trading, and fraud detection.

There are highly complex or exceptionally fast model use cases. Stock and forex trading offer immense possibilities as market risk and scenario calculations become increasingly precise, and the utility of raw computing power in intelligent routing and trade matching becomes increasingly important. For example, in terms of valuation, the ability to quickly determine the optimal risk-adjusted investment portfolio may create significant competitive advantages. For loan and bond investment portfolios, more accurate estimation of credit exposure should lead to better optimization decisions.

More broadly, by gaining insight into the scale and importance of risks, it is possible to improve the capital allocation of a range of corporate financing activities while also protecting payments and transfers through better encryption.

It is foreseeable that the future application areas of quantum simulation will be very extensive, especially in applications with high randomness and complexity. Corresponding quantum simulation software for the massive downstream sub-sectors will also usher in a new round of explosive growth in the near future due to the huge demand.

Active collaboration with various verticals

Currently, leading companies in multiple fields have partnered with quantum computing-related companies to jointly explore their potential application scenarios. With the continuous development and expansion of application software by various companies, in addition to the main application directions such as medicine, chemical industry, and finance, there will also be more opportunities for deep collaboration with an increasing number of fields in the future.

Quantum Algorithms

As the application prospects of quantum computing become increasingly broad, algorithms such as HHL, QAOA, QSVM, VQE, etc. are emerging like mushrooms and constantly being optimized. The number of quantum bits on the hardware side is also increasing year by year, and there is a continuous stream of companies involved in algorithm research and development.

With the increase of quantum technology researchers, the development speed of quantum algorithms has been greatly improved. Currently, quantum algorithms have been applied in multiple practical industries such as medicine, chemistry, finance, and transportation. Since the realization of universal quantum computing still has a long way to go, specialized quantum computers that solve specific problems are expected to be launched one after another in the next 5-10 years. These specialized quantum computers will be more closely associated with specific industries to solve specific problems, and quantum algorithms will serve as the bridge between quantum computers and a particular research field.

Quantum Algorithm Advances

Optimization Algorithms for Practical Problems Still Need to Be Strengthened.

Quantum algorithms are often faster than classical algorithms for many problems. However, due to the high cost of quantum computers and the difficulty in meeting the requirements for the number of qubits (or only being available in specific fields, such as Gaussian boson sampling), the theoretical analysis and experimental costs of quantum algorithms are currently high.

Continuous-variable quantum optimization algorithms have been a development focus in recent years and will continue to be a hot field for a long time. However, this does not mean that combinatorial optimization is not important, but rather finding an effective quantum algorithm for many NP problems is a challenging problem.

The core ideas of the basic quantum technologies used in quantum optimization were mostly proposed between 1995 and 2008. The HHL algorithm and the Jordan quantum gradient estimation method are extensions of the phase estimation algorithm framework proposed in 1995. The amplitude amplification technique is an extension of the Grover algorithm proposed in 1996. The Hamiltonian simulation algorithm and the quantum random access memory technology have a history of 10 to 20 years.

In terms of overall optimization problems, there have been some good technological advances in 2022. For example, in April, the University of Innsbruck in Austria used Rydberg atoms to implement a new approach to quantum approximate optimization algorithms (QAOA), simulating how to precisely calibrate interactions between nearby atoms in an electrically neutral atomic system captured by an optical tweezer (fixed in place by laser beams) and Rydberg atoms (which have more energy and are larger than other atoms).

In October, institutions such as NIST and JPMorgan Chase used quantum computers to solve industry-related constraint optimization problems, which is expected to be a powerful way to achieve quantum advantage. They refined and summarized constraint optimization problems in their exploratory path, and demonstrated the largest quantum optimization algorithm execution at the time, which basically preserved constraints on quantum hardware.

However, overall, there are still very few existing optimization problems, and there are many issues that need to be researched in the field of optimization, such as the challenging non-convex optimization problem. But in the next 5-10 years, quantum computers will have tremendous advantages in various optimization calculations. According to IBM's three-stage roadmap for quantum computing applications proposed in 2019, in the second stage, the downstream application exploration of the NISQ era, with the widespread popularity of quantum optimization, related software companies will usher in a new round of explosive growth.

Urgent Need to Explore New Algorithms

Quantum computing has been demonstrated to possess powerful parallel computing capabilities through algorithms such as Shor's algorithm, Grover's algorithm (or its optimized form), and quantum simulation algorithms. The requirement for unitary evolution in traditional algorithms has limited the development of new algorithms. Dual quantum algorithms, as a new computing mode, can achieve non-unitary evolution through linear combinations of unitary operators. Therefore, dual quantum computing can implement non-unitary quantum algorithms.

Recently developed quantum algorithms, such as the HHL dual quantum algorithm, dual quantum simulation algorithms for sparse Hamiltonian systems, high-precision dual quantum simulation algorithms, and open system dual quantum simulation algorithms, all use linear combinations of algorithms for computation, showing their advantages over traditional quantum algorithms. For example, the Boolean satisfiability problem (SAT) is a well-known hard (NP-complete) computational problem, and the process of finding solutions to these problems can be performed using a quantum computer, such as solving SAT problems on the Classiq platform on Amazon Braket.

In 2022, new quantum algorithms were also developed, such as in August, where Tsinghua University and Information Engineering University proposed a quantum amplitude amplification algorithm with fixed-point forgetting through damping, based on A. Mizel's method. Additionally, they constructed a quantum circuit in the framework of dual quantum computing to implement the algorithm. In September, Brookhaven National Laboratory (BNL) of the US Department of Energy (DOE) and Stony Brook University designed a new quantum algorithm for calculating the lowest energy of a specific configuration of molecules in chemical reaction processes. Compared with similar existing algorithms, the new algorithm significantly improves the ability to compute potential energy surfaces in reaction molecules. In October, Multivers Computing demonstrated how a new algorithm running on a quantum annealing system (a technology for finding the best solution) automatically optimizes investment portfolios and achieves returns matching traditional investment portfolios.

However, since Shor proposed the large number prime factorization algorithm, compared to various classical computer algorithms, there are few good quantum algorithms. There are several reasons for this. Firstly, it is not easy to find a good classical algorithm, such as the classical large number prime factorization algorithm. Secondly, quantum algorithms must be superior to classical algorithms to be practically meaningful; otherwise, the cost of developing quantum computers outweighs the benefits. Finally, human intuition tends to favor the classical real world, and quantum language does not have the "quantum thinking" of a cat being both dead and alive, making it challenging to think from a superposition perspective.

Examples of Quantum Algorithm Applications

Quantum Machine Learning

Quantum Machine Learning (QML) is an interdisciplinary field that has emerged from the high parallelism of machine learning based on quantum computing, aiming to optimize traditional machine learning using quantum mechanics. QML has gone through three different stages: quantum linear algebra, quantum machine learning, and quantum deep learning.

The significance and value of QML research lie in utilizing the high parallelism of quantum computing to enhance the processing, analysis, and mining capabilities of machine learning for big data, promoting the development of new machine learning algorithms based on quantum mechanics, and proposing new research methods in the field of quantum mechanics, such as new quantum fault analysis methods.

For example, in July 2022, researchers from Zapata Computing and IonQ demonstrated the first practical and experimental implementation of a quantum-classical generative algorithm that can use state-of-the-art gate-based quantum computers to generate high-resolution images of handwritten digits. This result is an important step towards building quantum devices that can surpass the capabilities of classical machine learning.

In August, 1QBit, the University of Waterloo, and the Perimeter Institute for Theoretical Physics jointly developed a new strategy called neural error mitigation, which is a machine learning algorithm that can improve the estimation of ground states obtained through quantum simulation.

Examples of Quantum Algorithm Applications

Simulation

Random processes are often used to model phenomena in physical science, biology, epidemiology, and finance. In finance, stochastic modeling is often used to help make investment decisions, with the goal of maximizing returns and minimizing risks. Quantities describing market conditions, such as stock prices, interest rates, and their volatilities, are often modeled using stochastic processes and represented as random variables. Most financial models involve more complex forms of SDE and require the use of Monte Carlo integration algorithms to solve stochastic differential equations.

The Monte Carlo algorithm is a technique used to randomly estimate the properties of a system through statistical sampling. This algorithm was developed to solve problems in mathematics, physics, engineering, and other areas. The basic idea is to establish a probability model or stochastic process whose parameters are equal to the solution of the problem. Then, the statistical features of the calculated parameter are determined through observation or sampling experiments of the model or process, and the approximate value of the solution is given.

In February 2022, the University of Hong Kong developed a new and more efficient quantum algorithm for Monte Carlo techniques, which was used to measure the Rényi entanglement entropy of objects. Using this new tool, they measured the entropy at the quantum critical point (DQCP) and found how it changes with system size, forming a sharp contrast to the description of classical LGW-type phase transitions.

The Monte Carlo algorithm stands out in its ability to handle super-large or complex systems that cannot be processed through analysis or other methods. In finance, stochastic methods are typically used to simulate the uncertainty that affects stocks, investment portfolios, or options, making Monte Carlo methods suitable for portfolio evaluation, personal financial planning, risk assessment, and derivative pricing.

Optimization

In December 2022, Quantum-South found a solution to optimize aircraft cargo by using a hybrid approach with quantum annealing machines, improving the loading plan. They used a combination of technologies, including quantum annealing machines from D-Wave to Amazon Braket. IAG Cargo, the cargo processing department of International Airlines Group (IAG), tried Quantum-South's new service to explore the use of quantum algorithms to optimize air cargo.

Since May, Quantum-South has been exploring the possibility of using quantum computing to optimize ULD flight loading, especially in the flight transfer stage. In a test case with IAG Cargo, Quantum-South's algorithm revealed business rules for planning ULD loading, actual flight, shipping, and specific ULD data samples to simplify the loading plan. Quantum-South's solution combines quantum annealing technology from D-Wave with traditional systems from cloud providers such as AWS and Amazon Braket to provide support. The available transport packaging is divided into several ULDs, which are then organized to fit each ULD.

The initial test results showed that the further application of this solution can improve flight payload planning, bringing benefits in prioritizing combinations, weight, and volume loading on busy flights. It is also expected to improve process efficiency, reducing the time required for manual analysis and optimization for each flight. The solution can also bring significant workload efficiency, as the current optimization process focuses on a subset of all flights and may allow optimization of the entire cargo carrier network.

Prospects of Quantum Algorithm Applications

Currently, quantum algorithms have been applied in many fields, including finance, chemistry, biology, medicine, artificial intelligence, and aviation. For example, in finance, quantum algorithms are used for portfolio optimization, pricing simulation, and machine learning. In chemistry, they aid in the design of chemical industries and catalysts, biopharmaceuticals, and material research. In the field of artificial intelligence, quantum algorithms are utilized to speed up robot learning time and to use the latest machine learning techniques. In aviation, they assist in the development of more flight routes for city air traffic and the rescheduling of railway traffic routes. Quantum algorithms provide an acceleration advantage over classical algorithms in many problems. However, due to the current expensive cost of medium-sized quantum computers and the rarity of large-scale general-purpose quantum computers, the design of quantum algorithms faces difficulties in theoretical analysis and high experimental costs. Further breakthroughs in the basic theory and software and hardware technology of quantum computing are crucial for the development of quantum algorithms.

Quantum algorithms significantly expand the application range of quantum computers, demonstrating considerable potential in many areas, such as rapid data search and sorting, quantum chemistry simulation, artificial intelligence, and machine learning. Seeking algorithms that can run on NISQ-era quantum processors and solve practical problems is a core research issue in the current field of quantum computing.

Quantum computing cloud platform

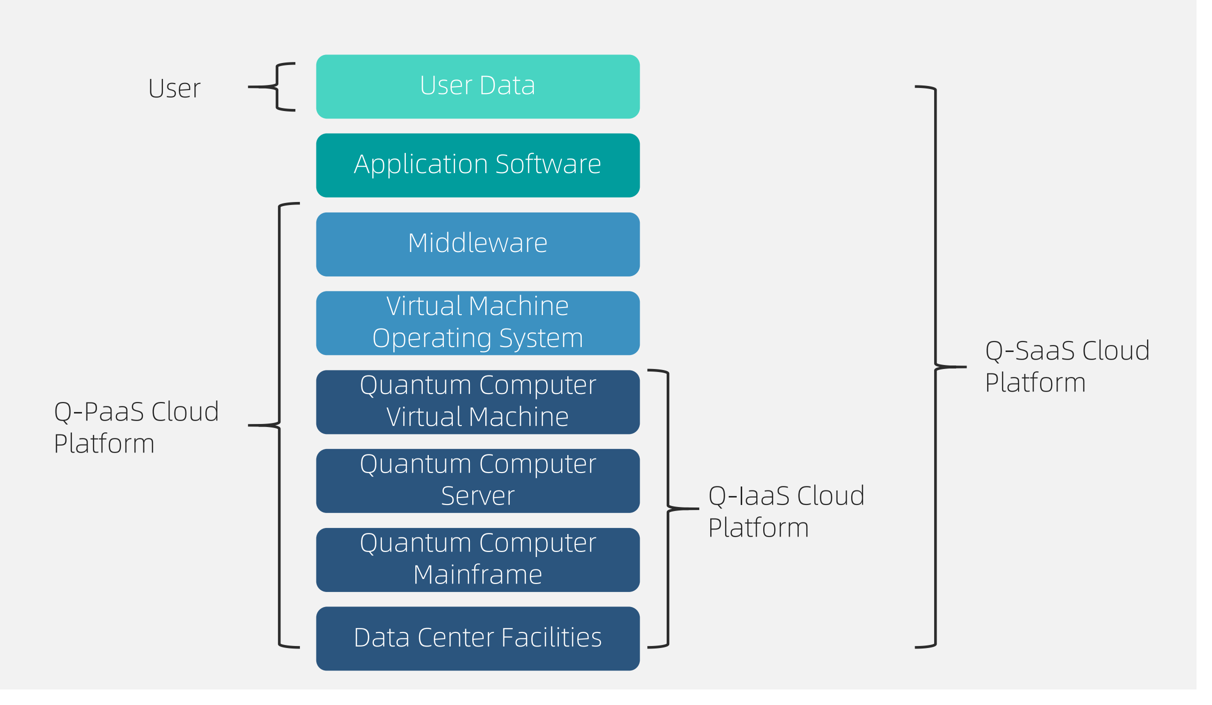
Cloud computing is a pay-as-you-go model that provides on-demand, convenient, and configurable access to a shared pool of computing resources, including networks, servers, storage, applications, and services. These resources can be rapidly provisioned with minimal management work or interaction with service providers.

A quantum cloud platform acts as a bridge between quantum computers and users - users access the quantum cloud using classical computers, and the quantum cloud transmits processed instructions to the backend, where quantum computing is performed, before sending the results back to the user through the quantum cloud. With a quantum cloud platform, users can perform quantum computing tasks even without access to a physical quantum computer.

Quantum Computing Cloud Platform Service Types

The logical architecture of current quantum cloud platforms is basically the same and similar to the classification of cloud computing. Depending on the type of service provided, the services offered by quantum cloud platforms are divided into three categories: Quantum Infrastructure as a Service (Q-IaaS), Quantum Platform as a Service (Q-PaaS), and Quantum Software as a Service (Q-SaaS). Some quantum cloud platforms offer two or three types of quantum computing services, such as D-Wave, which offers Q-IaaS and Q-SaaS, and IBM, which includes all three.

Exhibit 4-5: Types of Quantum Computing Cloud Platform Services



- Q-IaaS refers to providing the hardware and supporting facilities of a quantum computer as a service on a quantum cloud platform to users. For quantum cloud platforms that provide Q-IaaS services, users can call all the hardware of a quantum computer through the cloud platform without the need for maintenance. The main users of this type of quantum cloud platform are quantum computer developers and researchers.

- Q-PaaS refers to providing the infrastructure and middleware of a quantum computer as a development platform as a service on a quantum cloud platform. With this type of quantum cloud platform, all users can easily develop their specific software on the cloud platform, but this also limits users from migrating to different cloud platforms. Currently, there are few quantum cloud platforms that provide Q-PaaS type services because it cannot completely avoid the complexity of quantum knowledge to develop software that meets its own needs and cannot meet the needs of research institutions and universities that focus on specific quantum characteristics.。

- Q-SaaS refers to the entire quantum cloud platform providing a type of software service. Currently, Q-SaaS type quantum cloud platforms are mainly aimed at large enterprises in other fields. These enterprises hope to rely on the powerful computing power of quantum technology to solve practical problems that are difficult to solve in the current era and continue to maintain their leading position in their industry. Although the computing power provided by current quantum cloud platforms is not enough to meet the practical application needs of most enterprises, they have been developing and improving software suitable for their own needs through cooperation with quantum cloud platforms, waiting for the next breakthrough in the field of quantum hardware

Currently, most quantum cloud platforms focus on providing Q-SaaS services, mainly due to the shortage of talent with both quantum knowledge and programming skills in the field of quantum computing. Q-SaaS services can bypass these human resources and technical barriers.

In the future, as the number of quantum developers increases, it is expected that some large enterprises will gradually shift from choosing Q-SaaS services to choosing Q-PaaS and Q-IaaS services to ensure their data security, reduce operational risks, and differentiate their own products.

Quantum Computing Simulator

Currently, the number and computing power of quantum computers that can be accessed by quantum cloud platforms cannot meet the set value of quantum bits, which will affect the verification process and results of many practical applications. To address this issue, quantum computing simulators have emerged.

A quantum computing simulator refers to a computer program that simulates quantum properties using low-level programming, allowing for the construction of a simulated "quantum computer" to perform corresponding calculations. Quantum computing simulators can simulate quantum error correction, quantum noise, and support quantum instructions, meeting the needs of quantum software and algorithm development. Compared to current real quantum computers, quantum computing simulators have the advantages of lower cost, stronger computing power, support for higher quantum bit numbers, and less susceptibility to external environmental interference. Therefore, they are widely used in the development of quantum algorithms and software.

Currently, various quantum cloud platforms provide real quantum computing ranging from a few to a dozen quantum bits. However, quantum computing simulations using supercomputers on the same platform can provide from dozens to thousands of quantum bits. For example, IBM provides various quantum computing simulators, including the 5,000-qubit simulator_stabilizer for noise simulation and the 100-qubit simulator_mps for simulating quantum weak entanglement. Origin Quantum provides four types of simulator backends, including the 35-qubit full amplitude quantum computing simulator, the 68-qubit partially excited quantum computing simulator, the 200-qubit single amplitude quantum computing simulator, and the 32-qubit noisy quantum computing simulator.

Google's high-performance open-source quantum circuit simulator Qsim has been proven to simulate a 32-qubit quantum circuit with 14 gate depth in 111 seconds on a Google Cloud node. Amazon Braket provides a fully managed high-performance tensor network simulator (TN1), which is a tensor network-based circuit simulator that can support up to 50 qubits of quantum computing simulation. Atos is the first company to successfully simulate quantum noise, and its quantum simulator Atos Quantum Learning Machine (Atos QLM) is known as the world's best commercial quantum simulator. The simulator combines high-power, ultra-compact machines with a general-purpose programming language, allowing researchers and engineers to develop and test quantum software.

Exhibit 4-8 Types of Quantum Computing Cloud Platform Services

	Type	Name	Quantum Bit	Noise Modeling
Statevector	Schrödinger wavefunction	simulator_statevector	32	Yes
Stabilizer	Clifford	simulator_stabilizer	5,000	Yes (Only Clifford)
Extended stabilizer	Extended Clifford (e.g., Clifford+T)	simulator_extended_stabilizer	63	No
MPS	Matrix Product State	simulator_mps	100	No
QASM	General, context-aware	ibmq_qasm_simulator	32	Yes

Source: Comparison of quantum computing simulators released by IBM

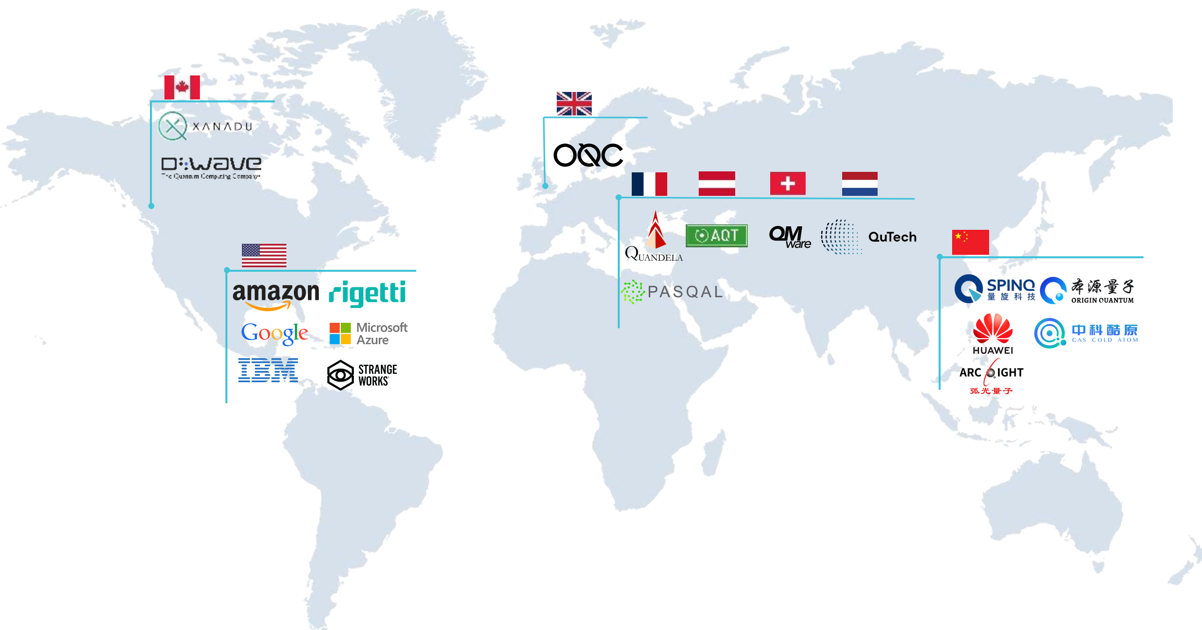
Although the development of quantum computing simulators has greatly facilitated the development of software and algorithms for quantum computers, the number of simulated quantum bits of quantum computing simulators is limited by the computing power and related algorithms of classical computers, and the high energy consumption also limits the unlimited increase in the computing power of quantum computing simulators on various platforms. Today, as quantum hardware technology still needs further breakthroughs, the use of quantum computing simulators not only meets the research needs of the vast majority of quantum software and algorithms but also reduces the development cost to the minimum, making it an important supporting force for the current development of quantum computing.

Current Development Status of Quantum Computing Cloud Platforms

The quantum computing cloud platform combines the advantages of quantum computing and cloud computing to meet the needs of quantum computing research and development. Currently, there are more than 20 providers of quantum computing cloud platforms around the world, which enable users to access quantum computing via the internet without the need for physical quantum computers. The emergence of cloud platforms makes it easier for more people to experience quantum computing. Major quantum computing cloud platform providers include Amazon AWS's Braket, D-Wave's Leap, IBM's IBM Quantum Experience, Google's Cirq, Rigetti's Quantum Cloud Service, Microsoft's Azure Quantum, Xanadu's Strawberry Fields, Origin Quantum Cloud Platform, Huawei's HiQ, and more.

In 2022, the achievements of quantum computing cloud platform development are summarized as follows: D-Wave launched the first Advantage™ quantum computer, which can be accessed through its Leap™ quantum cloud service in the United States, providing 5000 quantum bits; Amazon Braket announced support for IBM's Qiskit quantum software development toolkit, and programs written on Qiskit can run on any gate machine on Braket; CooLinkQuantum launched China's first atomic quantum computing cloud platform, "CooLink Quantum Cloud", which currently provides neutral atomic quantum computing simulators and qiskit quantum computing simulators; IonQ announced the launch of IonQ Aria on the Azure Quantum platform, which is the second IonQ system to join the Azure Quantum platform after IonQ Harmony in late 2019; Rigetti Computing launched the public preview version of Rigetti QCS™ on Microsoft's Azure Quantum platform, allowing Azure Quantum users to access Rigetti's Aspen-M-2 80-qubit and Aspen-11 40-qubit superconducting quantum processors on demand to develop and run quantum applications; Arqit deployed its Quantum Cloud platform on Amazon Web Services (AWS) products.

Exhibit 4-7 Global Distribution of Quantum Computing Cloud Platforms



Note: The figure does not include research institutions that have developed quantum computing cloud platforms (such as the Institute of Quantum Information and Quantum Technology Innovation of the Chinese Academy of Sciences, the College of Computer Science and Technology of Zhejiang University, the Institute of Physics of the Chinese Academy of Sciences, and Sandia National Laboratories in the United States).

The Development Trend of Quantum Computing Cloud Platform

The combination of cloud computing and quantum computing, i.e., quantum computing cloud platform, to some extent, has solved the problem of resource scarcity in current quantum computers, expanded the coverage of quantum computing, and will also promote the development of quantum algorithms and software. In the next few years, with the growth of quantum computing business, some important factors may bring new development opportunities to the quantum cloud:

Service Type Conversion

With the breakthrough of quantum foundational technologies, in the future, the expansion of application coverage and the deepening of application degree will inevitably promote a part of Q-SaaS cloud platform users to gradually transform into Q-PaaS and Q-IaaS cloud platform users as they deepen their understanding of quantum computing technology and quantum programming. This development trend can also be seen in the changes in the scale of the current cloud computing market.

Quantum Computing Cloud Platform

The backend (quantum computing hardware) has a set sequence of operations and performs computational tasks in order. After users submit tasks to the cloud, the machines may not be able to run immediately, and delays caused by non-computational factors can affect the experimental process. Some vendors have implemented reservation features to solve the problem of long wait times. In terms of user experience, vendors still need to further improve their service capabilities.

Quantum Computing Simulator

In the NISQ era, quantum computing simulators are a cost-effective choice for current applications, such as quantum algorithm and software development. However, in the error-corrected quantum computing era, the utility of quantum computing simulators may decrease or new developments may be sought

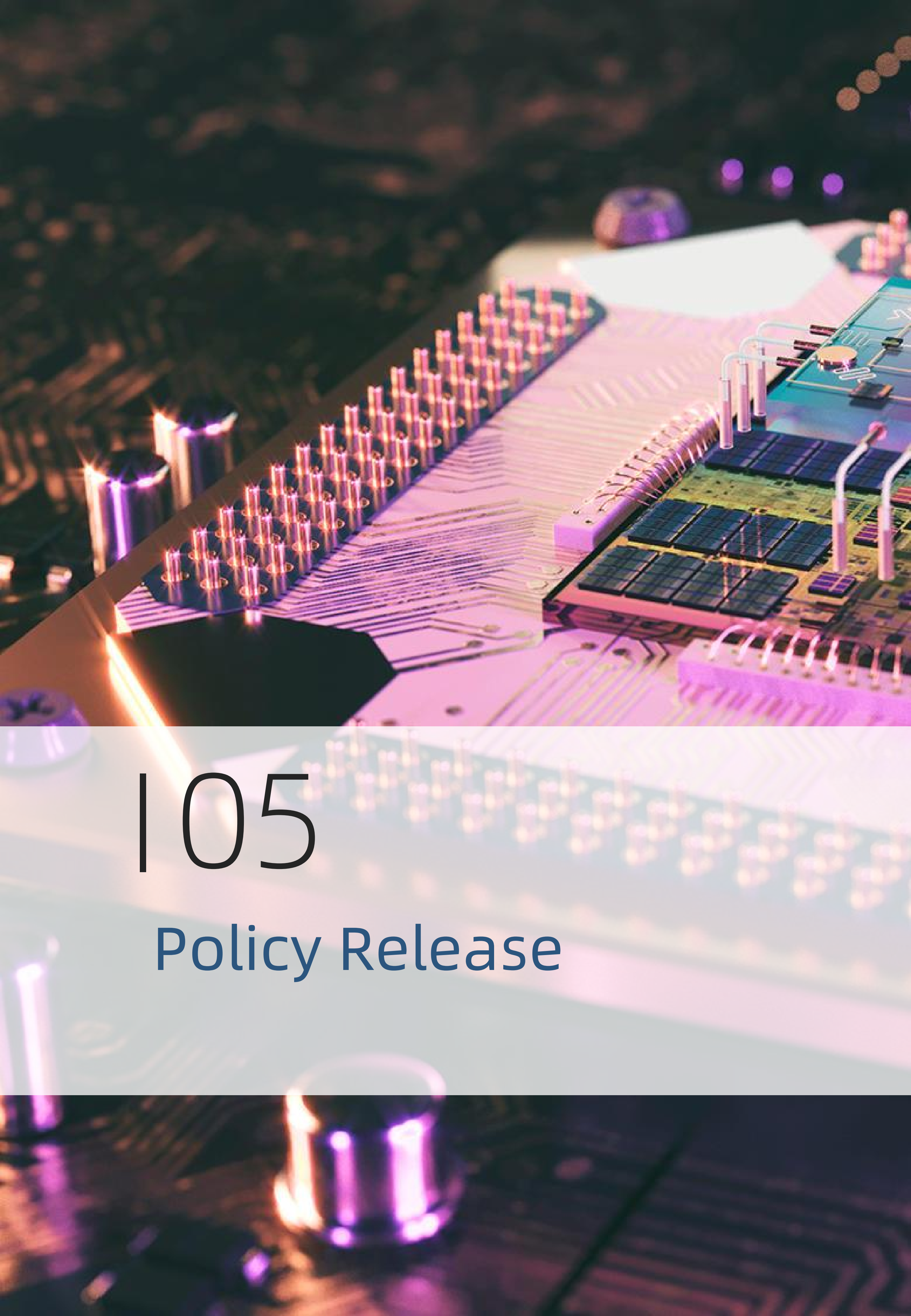
Security Issues

Due to the online nature of quantum cloud platforms, there are inevitable challenges to data security. As quantum computing technology is still in its early stages, research on how to prevent hacking attacks and ensure data security on quantum cloud platforms is still ongoing. The vulnerabilities of cloud encryption are increasing, and in addition to the continuous improvement of technology, policy and legislative support are also needed to be advanced in parallel

Transition to the Quantum Internet

Currently, quantum cloud is accessed through classical cloud, but with the further development of quantum technology, the quantum internet is expected to expand its coverage. The next step is to consider how to integrate classical cloud access into the quantum internet for transmitting quantum bits.

Overall, the quantum cloud platform will be an essential part of the quantum computing field for a long time to come and will contribute vitality to the commercialization of the quantum computing industry. The primary task at present is to continue optimizing the quantum cloud platform products and services, to expand market share by providing services such as quantum infrastructure or differentiated software development, and to prepare for the upcoming era of quantum computing.



05

Policy Release

After evaluating the main quantum participating countries globally in six dimensions, including capital investment, research output, number of researchers, patent quantity, paper publication quantity, and quantum company quantity, it can be observed that currently, the United States and China are the most advanced. Following them are various European countries such as Germany and France. Additionally, Canada and Australia also rank high in terms of the number of patent applications.

Exhibit 5-1 Evaluation System for Major Global Quantum Participants

Country	Capital	Research results	Number of researchers	Number of patents	Number of papers	Number of quantum companies	Comprehensive strength
USA	●	●	●	●	◕	●	↑
China	●	◕	◕	◕	●	◑	↑
EU	◕	◕	◕	◕	◑	◕	↑
Fance	◑	◑	◑	◑	◑	◑	→
Germany	◕	◑	◑	◕	◑	◑	→
Netherlands	◑	◑	◑	◕	◔	◔	→
Spain	◑	◑	◔	◑	◔	◔	→
Finland	◔	◑	◔	◔	◔	○	↓
Italy	◑	◔	◑	◑	◔	○	↓
Switzerland	◔	◑	◔	◔	◔	○	↓
UK	◕	◑	◑	◕	◑	◑	→
Japan	◔	◑	◕	◔	◑	◔	→
Canada	◑	◑	◕	◕	◑	◑	→
Australia	◔	◑	◕	◔	◑	◑	→
South Korea	◔	○	○	○	○	○	↓
Singapore	◔	○	○	○	○	○	↓

Note : The rating is based on 5-point scale. with 1 being the worst and 5 being the best, with ○ representing 1 and ● representing 5

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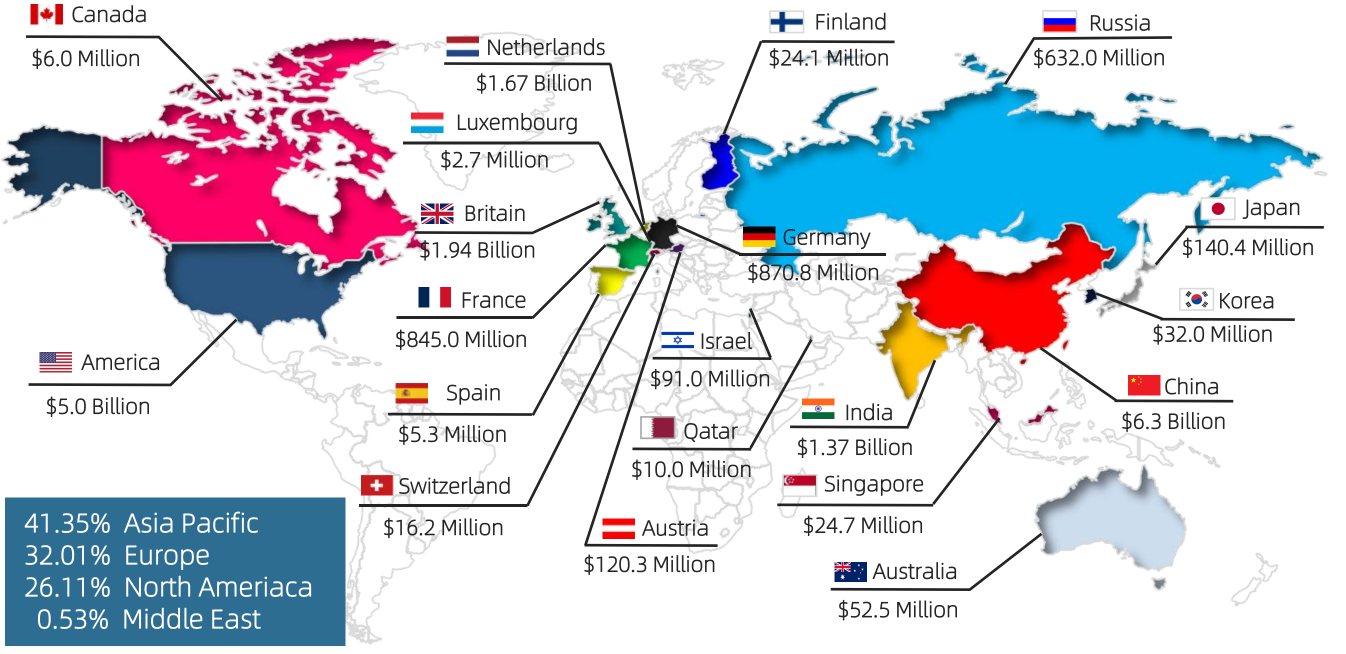
The report outlines the relevant policies released by major quantum computing participant countries globally in 2022, and analyzes them from three aspects: policies related to funding support, international cooperation, and strategic development.

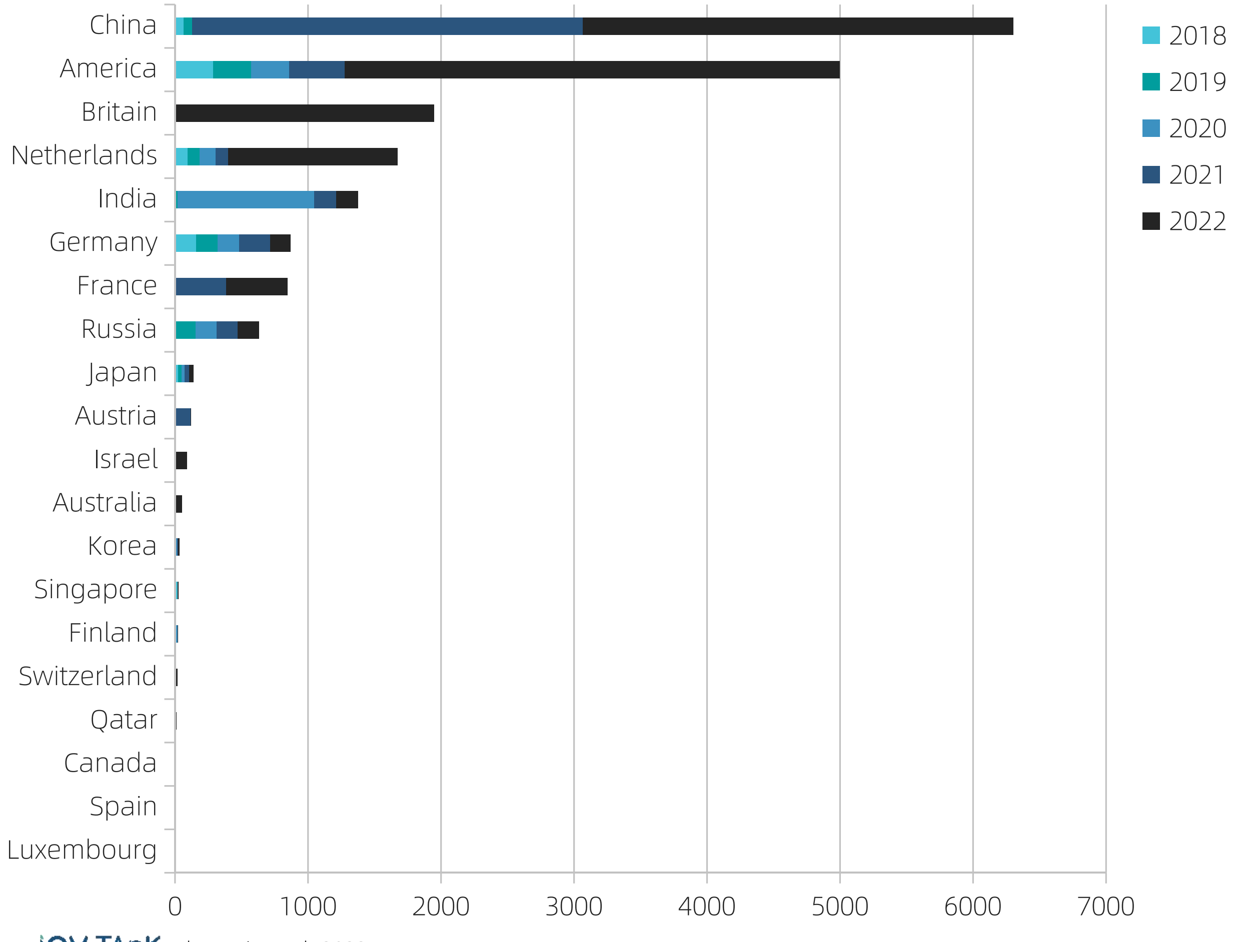
Increasing Government Funding Support

Quantum technology belongs to the forefront of scientific and technological fields and is currently in its early stages of development. However, all major technological powers have clearly recognized that quantum information technology is the shining jewel of future technological competition, and requires a significant amount of funding to support its development both now and in the future. Therefore, governments around the world must be the main investors in the development of quantum technology.

Exhibit 5-2 2018-2022 Global QIS Investment



Global Total QIS Investment by Major Countries 2018-2022 (Unit: Million USD)



In 2022, major technological countries around the world have proposed policy funding support in the field of quantum technology. However, there are significant differences among countries in terms of funding support, with the majority of funding being concentrated in developed countries or other countries that have begun to lay out quantum technology, such as the United States, China, the European Union and its member countries, the United Kingdom, Israel, Canada, Australia, and Japan.

Overall, the main areas of investment in terms of funding include quantum computing, quantum talent, and the establishment of quantum research institutions.

In terms of quantum computing, in February 2022, Israel allocated 62 million US dollars to build the country's first quantum computer, and in October, Germany invested 200 million euros to develop a quantum computer based on ion traps.

In terms of quantum talent, in May 2022, the Australian Labor Party pledged to provide 4 million US dollars to support the development of quantum research talent. In June, the K12 Quantum Talent Development Program, operated by George Mason University's Quantum Science and Engineering Center in the United States, received 650,000 US dollars from the House Appropriations Bill of 3.5 trillion US dollars. In July, the US government invested 3 million US dollars for a graduate training program in quantum science research.

In terms of the establishment of quantum research institutions, in April 2022, Qatar allocated $10 million to launch a national quantum computing program to support the establishment of the Qatar Computing Research Center (QC2) and conduct innovative research in related areas of quantum computing, quantum cryptography, and quantum artificial intelligence (AI). In July 2022, Israel announced the establishment of a quantum computing research and development center with an investment of $29 million.

Countries are Formulating Quantum Strategies

In 2022, countries and regions such as the United States, China, the United Kingdom, Australia, Germany, and the European Union have all released quantum technology plans or bills to support the development of quantum technology.

UK	Feb.	In 2022, the UK issued the "Spring Statement", which supports the development of artificial intelligence, quantum computing, and robotics technologies.
EU	Feb.	In 2022, the European Union released the "European Chips Act" and announced a 43 billion euro chip act to support the development of quantum chips. The act stated that by 2030, the European Union plans to invest over 43 billion euros (approximately 49 billion US dollars).
AU	Apr.	In 2021, the National Research Infrastructure Roadmap was issued, which prioritizes quantum as a key research area in the new roadmap.
GER	Jun.	Germany released the "Quantum Systems Research Program" with the aim of bringing Germany to a leading position in the European quantum computing and quantum sensing fields over the next decade, and improving its competitiveness in the field of quantum systems.
US	FY.	Several documents have been issued to support the development of quantum technology, including the "Quantum Computing Network Security Prevention Act", the "Executive Order on Strengthening the National Quantum Plan Advisory Committee", the "National Security Memorandum to Promote US Leadership in Quantum Computing while Reducing Risks to Fragile Cryptosystems", the "Chip Act", and the "National Security Memorandum to Promote US Leadership in the Quantum Computing Field while Reducing Risks to Vulnerable Cryptosystems".

Coexistence of International Cooperation and Confrontation

The G7 countries, including the United States, Canada, Australia, France, Germany, Switzerland, Finland, and Japan, have significantly strengthened their alliance in the field of technology in 2022. They have been engaging in strategic collaboration at the government level, jointly formulating development plans or investing in quantum projects, cooperating in nurturing the next generation of quantum talents, jointly investing in research and development infrastructure, and promoting quantum technology research and the development of quantum industries.

Coexistence of International Cooperation and Confrontation

For example, in 2022, the United States signed the Joint Statement on Quantum Information Science and Technology (QIST) cooperation with the United Kingdom, Australia, Finland, Sweden, and France. The Joint Statement enables the respective parties to leverage their strengths in QIST, establish global markets and supply chains, create mutually respectful and inclusive scientific research communities, and cultivate the skills and potential of future generations.

Compared to the close cooperation between the United States and developed Western countries, the United States has led its allies in imposing technological restrictions on China. Whether it is the US Executive Order "Strengthening the National Quantum Initiative Advisory Committee" and "National Security Memorandum on Promoting US Leadership in Quantum Computing while Reducing Risks to Fragile Cryptographic Systems," or the "2022 Chip and Science Act" targeting the semiconductor industry, they all continue to restrict China's quantum science and technology research and industrial development. Unlike the extensive and in-depth quantum technology exchanges and cooperation among the United States and its allies, China can only rely on its own internal talent, technology, upstream equipment and device supply to achieve progress in quantum technology.

If we examine the remarkable national science and technology projects that China accomplished under extreme international isolation in the 20th century, and now with quantum computing as a major national science and technology goal, leveraging the advantages of its national system, it is unlikely that the United States would be willing to see the final competition results.

06

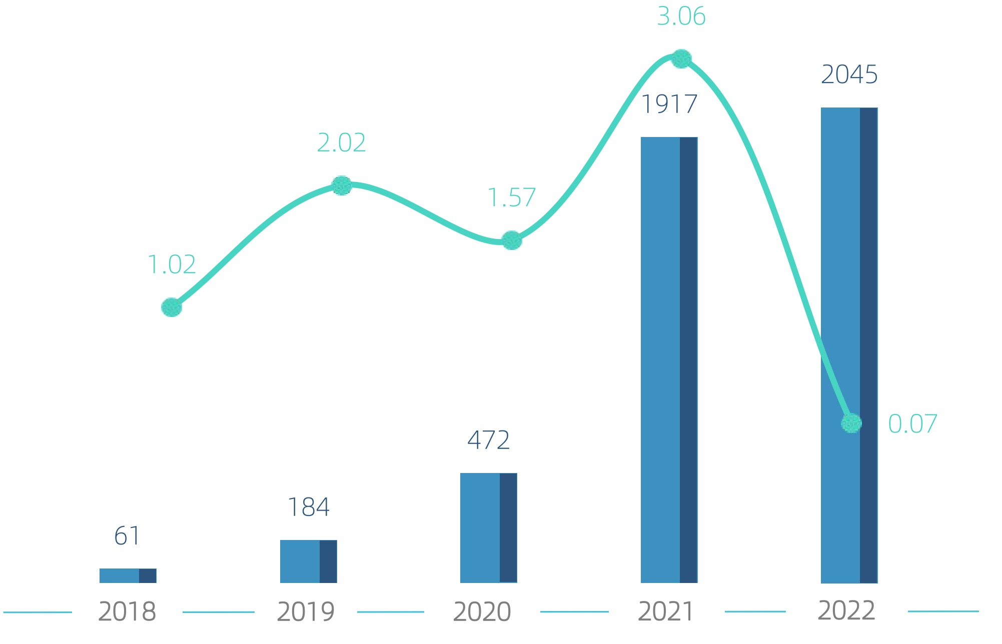
Investment & Financing

The Growth Rate of Financing Scale Has Slowed Down

As a cutting-edge technology and a key industry of the future, quantum computing is a disruptive technology, and investment enthusiasm from investment institutions comes from two factors: national support and international competition, as well as expectations brought by technological breakthroughs.

ICV has compiled the financing situation of major quantum computing enterprises worldwide from 2018 to 2022, involving 14 countries, 67 quantum computing companies, and 136 financing rounds. Specifically:

Exhibit 6-1 : Financing Amount and Growth Rate (2018-2022)(Unit: Million USD)



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From 2018 to 2022, the global quantum computing financing amount increased rapidly from $0.61 billion to $2.045 billion, a 33.5-fold increase in five years, with a five-year CAGR of 140.6%. In particular, in 2021, the global quantum computing financing amount exploded, about 4.5 times that of 2020.

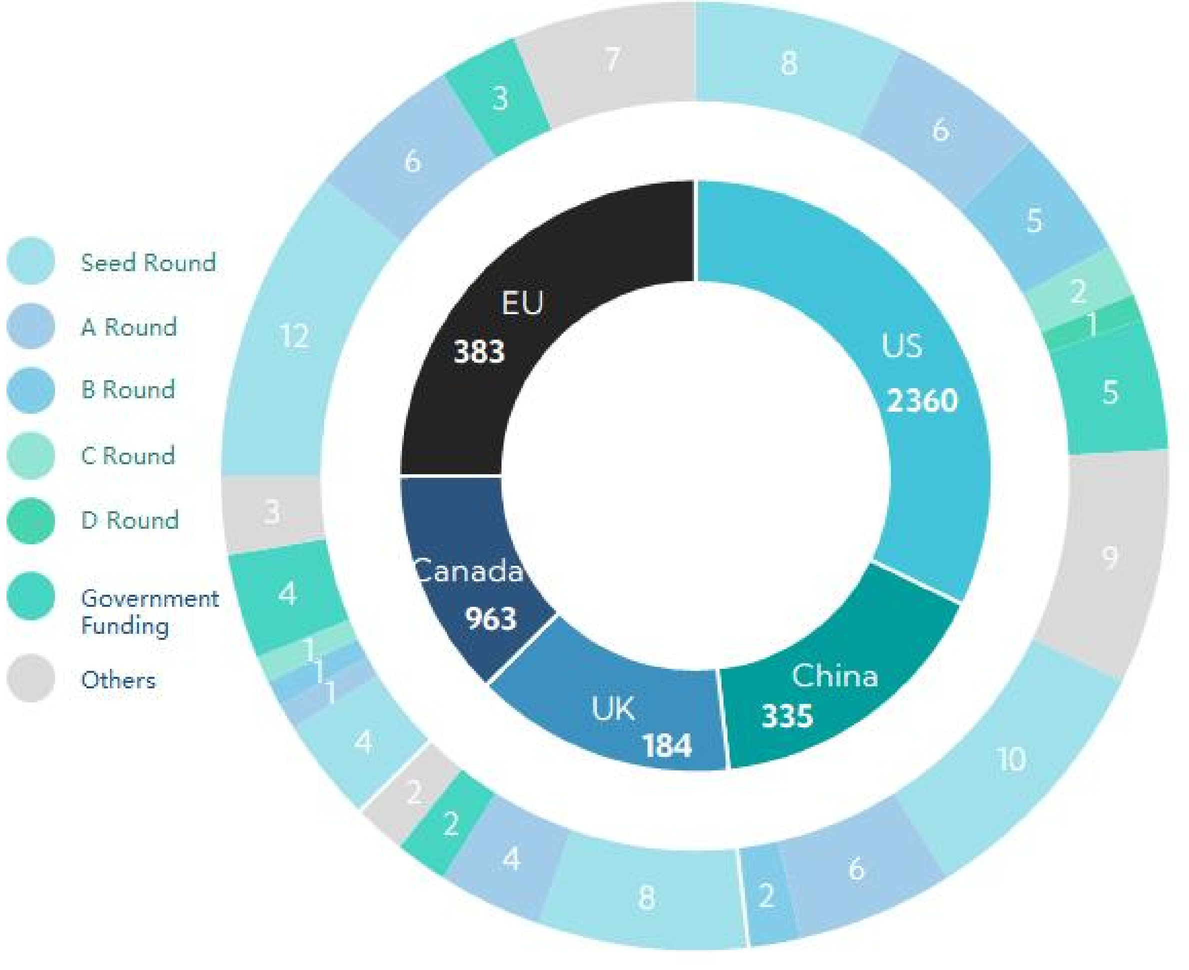
Although the 2022 financing amount has increased compared to 2021, the growth rate is only 7%, and it seems that the global investment enthusiasm for quantum computing has experienced a brief decline, failing to continue the momentum of the previous few years.

There are several possible reasons behind the investment performance in 2022: First, the global demand for safe-haven funds has increased due to the impact of inflation, the Fed's interest rate hikes, and economic recession, and the VC market has entered an adjustment period; Second, several listed quantum computing companies performed very poorly in 2022, and the investment return in the secondary market greatly hit the confidence of institutional investors in the primary market; Third, practical quantum computers still need several years of waiting, and the long-term investment model has compressed the scope of institutions; Finally, in 2022, there was a decline in the number of new quantum computing companies worldwide, and there were no more financing entities appearing in the market. Overall, investment enthusiasm and confidence of institutional investors have encountered problems.

Analysis of Global Financing Characteristics in 2022.

In 2022, the quantum computing industry raised a total of 2.045 billion U.S. dollars in financing, which represents a slight slowdown in growth compared to the total financing in 2021. However, overall, the quantum computing industry's investment and financing trend remains on a long-term growth trajectory. The more detailed expressions of the slowdown in the growth rate of the investment and financing market are as follows.

Exhibit 6-2 : Financing Rounds, Number, and Amount by Country (2018-2022)(Unit: Rounds, Count, Million USD)



Note: Others include IPO (1), undisclosed (4), grants (3), third-party allotment (1), venture capital (1), equity + grants (2), equity investment (1), merger capital injection (1), contract signing (1), convertible notes (1), convertible bonds (1), debt financing (2), PIPE (2).

EU: Netherlands, Finland, Germany, France.

In 2022, the quantum computing industry raised a total of $2.045 billion in financing, showing a slight slowdown in growth compared to the total financing amount in 2021. However, overall, the quantum computing industry's investment and financing have maintained a long-term growth trend. More detailed expressions of the slowing growth in the investment and financing market are as follows.

The financing events show a linear growth trend.

From 2018 to 2022, global quantum computing companies have seen a linear growth trend in the number of financing events, with growth becoming more significant after Google announced achieving quantum supremacy in 2019.

Analyzing financing events, there hasn't been a clear trend of slowdown in financing scale. While there were only 8 more financing events in 2022 than 2021, there were 17 more in 2021 compared to 2020. However, looking at the financing stages, there was a significant decrease in angel round financing in 2022.

The lack of talent may be one of the important reasons, as the overall cultivation cycle of quantum talent is longer compared to other industries. It takes about 7-8 years to cultivate quantum-related talent, and after completion, only 70%-80% have the opportunity to join research teams. Moreover, it takes about a year to fully adapt to their positions after entering the research team. In addition, some members may switch careers due to the inability to adapt or failure to meet their psychological expectations, resulting in a waste of related educational resources.

The shortage of talent can also lead to a decrease in the number of startups and slow progress in research and development, indirectly causing a decline in total financing demand.

US companies secured the most financing globally.

From 2018 to 2022, the total funding raised by quantum computing companies in the United States reached $2.36 billion, making it not only the country with the largest single financing amount, but also surpassing the combined financing of nine other countries including Canada, China, Finland, the United Kingdom, Australia, Israel, France, the Netherlands, and Germany, demonstrating the competitiveness of the United States' quantum computing startups and its mature capital market system.Canada ranks second, with two quantum computing stars, Xanadu and D-Wave, and strong competitiveness in technology and talent.

Since 2018, several quantum computing startups have emerged in China, although their true technical capabilities are generally reflected in research institutions, it has not hindered these companies from receiving capital investments. For example, Origin Quantum has raised close to $1.3 billion in four to five rounds of financing.

In 2022, SPAC became the main method for quantum companies to go public.

In February 2022, D-Wave signed a final agreement with the publicly traded special purpose acquisition company (SPAC) DPCM Capital, Inc. (NYSE: XPOA) and completed the transaction on the New York Stock Exchange (NYSE). The SPAC raised $340 million in its initial public offering, with a valuation of approximately $1.6 billion, but ultimately fell short of its target. In March, Rigetti Computing (NASDAQ: RGTI) completed a business merger with Supernova Partners Acquisition Company II, Ltd. (NYSE: SNII), with Rigetti's common stock and warrants trading on the Nasdaq Capital Market. The SPAC raised approximately $260 million for Rigetti in total.

It can be seen that quantum computing companies in the secondary market mainly went public and raised funds through SPACs in 2022. SPAC financing not only saves time and costs, but also fully complies with the US Securities and Exchange Commission's minimum public listing standards. Compared with traditional shell mergers, SPAC shells have clean resources without historical debts and related legal issues.

The sharp decline in stock prices highlights the overall downturn trend of the quantum industry.

Currently, the overall trend of quantum computing-related startups in the US stock market is very sluggish and involves some negative news, such as poor cash flow, and some even face delisting risk. Converting disruptive technology into business success is extremely difficult and rare. It not only requires the transformation of scientific progress into practical products and the creation of demand from paying customers, but also requires raising sufficient funds from patient investors.

Currently, quantum computing is in the early stage of the NISQ era, which is the era of noisy quantum computing. The long wait for technological breakthroughs and the scarcity and stinginess of paying users are ongoing threats to the entire quantum computing industry. 2022 has obviously brought a real threat, although it is mixed with multiple factors such as the COVID-19 pandemic, global economic slowdown, and technological competition, but this threat has just begun.

How to transform advanced technology into effective demand and obtain sustained patient funding is the primary issue that all quantum information practitioners must focus on.

07

CTF Model Analysis

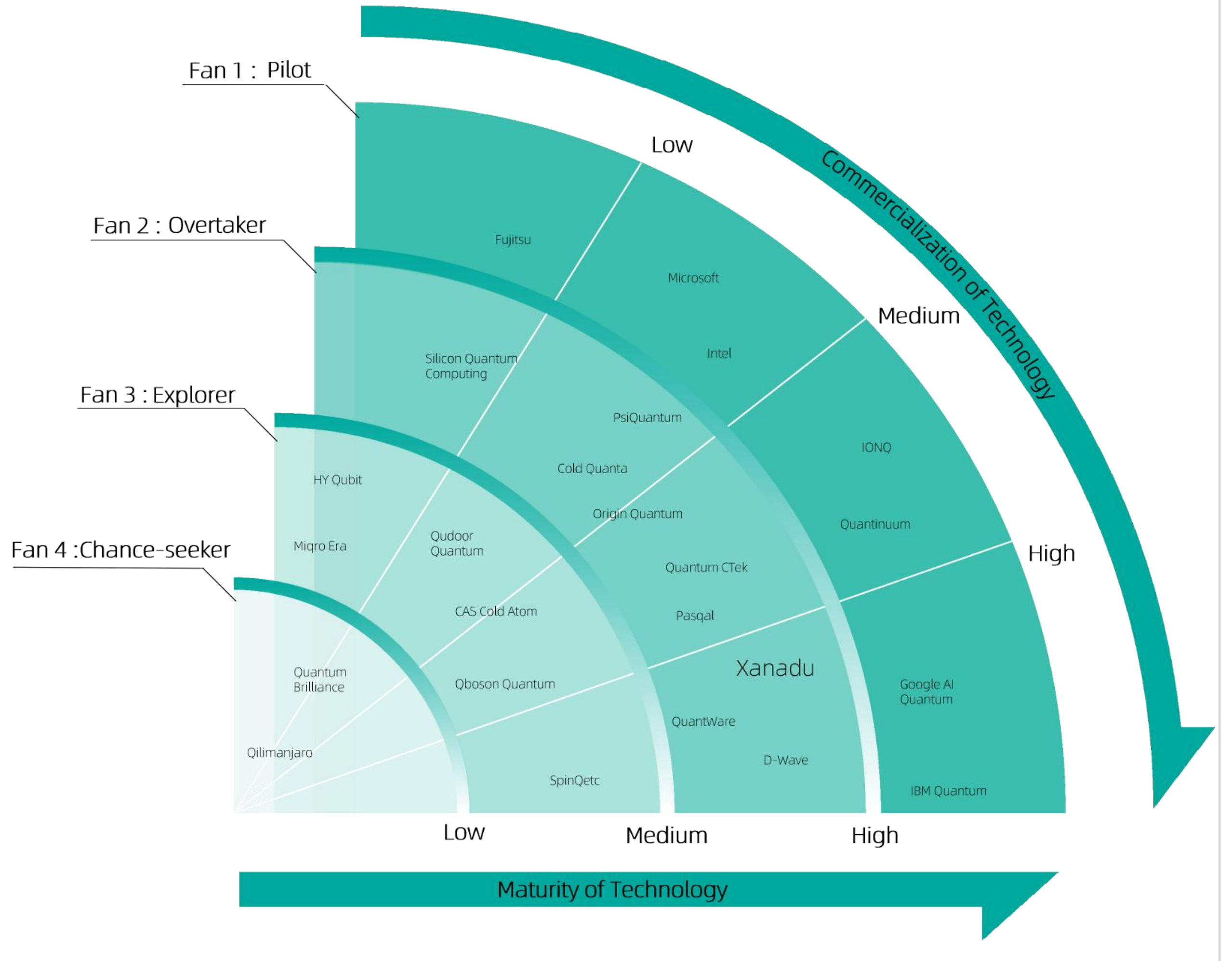
The CTF model is to help the public understand the cutting-edge technology field and the development situation of the corresponding company. The cutting-edge technology has many characteristics such as unconverged technical route, high uncertainty in technology development, and early commercialization. With the continuous development of technology, the company The evaluation needs a set of reasonable models to form a "consensus" for the comprehensive evaluation of frontier technology suppliers in a specific period.

The CTF model is composed of 4 layers of fan-shaped areas of different sizes in depth, and 3-dimensional coordinates. The horizontal coordinate Maturity of Technology (technical level, that is, the supplier's technology, R&D, team, etc.), the lateral coordinate Commercialization of Technology (commercial level, that is, the supplier's revenue, customers, use cases, etc.) and the implicit variable Implicit Variable (At the level of foundation, that is, the elements accumulated by the supplier's long-term operation that can boost the development of the enterprise). According to the comprehensive performance of suppliers in different dimensions, the CTF model divides them into the following four sectors: Pilot, Overtaker, Explorer and Chance-seeker.

As emerging technologies are in a period of rapid growth and there is also a high degree of uncertainty, therefore, the CTF charts of each segment need to be updated from time to time.

2022 Global QC CTF Analysis

Exhibit 7-1 Evaluation System for Global Quantum Machine Supplier



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Analysis of Global Quantum Computing Competitive Landscape

Fan1—Pilot

Suppliers in this region are leaders in the quantum computing industry, which can be roughly divided into three categories:

The first category, such as IBM, is an absolute leader in the industry, leading the entire quantum computing track with its huge company The second category is companies such as Intel or Rigetti, whose technology readiness is in a leading position in their respective routes, and they are also listed companies with large scale but lack of certain commercialization means, resulting in overall progress compared with IBM, Google and other top companies. Echelon has slowed down.

The third category, such as Microsoft, is a large-scale and mature technology company. However, due to the choice of a more difficult topological quantum computing track, it has been delayed in making breakthroughs in technology, which has also dragged down the company's commercialization process.

Fan2—Overtaker

This regional supplier is the mainstay of the quantum computing industry, and after a certain amount of precipitation, it is likely to rank among the forefront of the track in the future. This area can be roughly divided into two categories:

The first type of company, such as D-Wave, has strong commercialization capabilities and has sold the world's first commercial quantum computer. However, because it does not choose logic gate-based quantum computing but uses quantum annealing, it brings technical limitations and cannot be used as a general-purpose quantum computer.

The second type of companies, such as IONQ, Pasqal, and Origin Quantum, Quantum CTek, account for the vast majority of the entire quantum computing supplier. Their characteristic is that there is still a certain gap in their technical level compared with the first echelon, but they are all developing steadily on their respective routes, and after several years of operation, the company has begun to take shape, gradually has its own personalized products, and has gradually gained downstream Recognized by the cooperative company, actively explore the possible application of the company's products, and become the backbone of the entire quantum computing track.

Fan3—Explorer

Most of the companies in this area are emerging forces in the quantum computing track. They have young technical teams and creative thinking, as well as some flexible commercialization ideas. The region can also be generally divided into two categories:

The first category of companies, such as Spin, has been commercialized earlier and has its own mature products. For example, Quantum Technology, the company released the world's first portable nuclear magnetic resonance quantum computer, and constantly updated its cloud platform to seek cooperation with downstream application companies. At the same time, the company's research on superconducting routes is also in full swing. Although there is a big gap in overall technology compared with IBM, the leading company, it also has a certain degree of latecomer advantage.

The second category is CAS Cold Atom, MiQro Era, etc. Although these companies are still lacking in commercialization, they also produce prototypes or teaching machines, which have brought considerable benefits to the company. . In terms of technology, each company has made some achievements in its technical route, but overall there is still a certain gap between the first and second echelons.

Fan4—

Chance-seeker

Most of the companies in this area are newly entered the industry for 1 to 2 years. The overall scale is small, and they are developing at a high speed, and they are eager to seek talents.

Typical companies such as Bleximo, Qilimanjaro Quantum Tech, Nord Quantique, etc. The founding teams of these companies all have their own fields and technologies that they are good at. The single point is how to smoothly pass the initial stage and have products as soon as possible Or prototype output, find a suitable market position, actively participate in various quantum industry summits and cooperate with third-party consulting companies to promote and display, so as to gradually increase the exposure of the company.

Analysis of Typical Enterprises

IBM Q Superconducting Full Stack	Started the earliest, has more than 20 years of research experience; has advantages in the number of quantum computers and qubits; has built a world-leading quantum ecosystem, and the Quantum Alliance has more than 140 members; hardware, software, algorithms, and cloud platforms are full-stack Layout; IBM is a leading company in quantum education. The Osprey chip with 433 qubits will be launched in late 2022, tripling the previous record for the highest number of qubits on a chip.
QUANTINUUM Ion Trap	Started late but developed rapidly. In mid-2022, the performance of Quantinuum's System Model H1-2 quantum computing system has doubled, and after a commercial quantum computer with 4096 quantum volume (QV), it has been expanded to 20 fully connected qubits; At present, the talent reserve is sufficient, with more than 100 team members. Reached strategic cooperation with Fortune 500 companies such as Samsung, BMW, and JPMorgan Chase.
Microsoft Topology Quantum Cloud Platform	Started early, in 2005 began to focus on topological quantum computing; laid out a number of technical routes, jointly built a quantum laboratory with Delft University of Technology, invested heavily in the optical quantum computing company PsiQ, and connected ion traps and superconductors to the cloud platform Quantum computer; software has an unparalleled position, launching quantum development tools, including Q# quantum programming language. In 2022, the "Topological Gap Protocol" (TGP) proposed by Microsoft removes the biggest obstacle to the generation of topological qubits.
intel Superconducting Semiconductor	The world's leading semiconductor company, which has an advantage in integration technology, has increased the operating temperature of silicon qubits to 1K. The enterprise selected for the route of topological quantum computing with hardware error correction. At the end of 22, the yield rate of its silicon spin (semiconductor) qubit chip was as high as 95%, and set a new record for the number of silicon spin qubits - 12

aws Superconducting Cloud Platform	The world's largest cloud computing service provider, four types of hardware (annealing, superconducting, ion trap, photon) can be accessed on its cloud platform. Some achievements have been made in the research of fault-tolerant quantum computing. In 2022, Amazon used AWS Parallel Cluster (parallel cluster) and QuEST (Quantum Accurate Simulation Toolkit) to perform large-scale quantum circuit simulations, demonstrating a computing resource deployment of up to 4096 computing instances.
Google AI Quantum Superconducting Full Stack	The first demonstration of quantum superiority in human history; completed quantum chemical simulation; has strong artificial intelligence capabilities, is a leader in quantum computing + AI research; strong financial strength. In 2022, for the first time, Google achieved "the more corrections, the more correct" it broke through the break-even point of quantum error correction.
IONQ Ion Trap	The founder is a pioneer in the field of ion trap quantum computing, with rich research experience; the first listed quantum computing start-up company, financing hundreds of millions of dollars. Efforts are underway to develop distributed quantum computing. In 2022, the readout fidelity of IONQ's new barium-based quantum computer, the state preparation and measurement (SPAM) fidelity, has increased from 99.5% to 99.96%, and its latest generation containing 32 Qubit quantum system IonQ Forte.
rigetti Superconducting Full Stack	A full-stack quantum computing listed company, covering the entire process from quantum processors to control systems, cloud platforms, quantum programming, and applications. Realized scalable quantum chip technology. In 2022, the company launches Rigetti QCS™ in public preview on Microsoft's Azure Quantum platform, with Azure Quantum users gaining on-demand access to Rigetti's Aspen-M-2 80-qubit and Aspen-11 40-qubit superconducting quantum processors , to develop and run quantum applications.

ColdQuanta Neutral Atom	The world's largest quantum computing company with a neutral atom route, has a financing of 179 million US dollars. The company has been working to accelerate the commercialization of quantum computing technology based on neutral atoms, and is developing quantum computers based on laser-cooled neutral cesium atoms. Thanks to the explosion of neutral atom technology this year, in mid-2022, the company acquired Super.tech, a Chicago-based quantum computing software company, and launched the world's first gate-based commercial cold-atom quantum computer, Hilbert Beta.

国盾量子 QuantumCTek Superconducting Cloud Platform	The only listed quantum company in China has launched an optimized version of the room-temperature superconducting quantum computing control system "ez-Q Engine" 2021 version. The company began to provide low-temperature signal transmission systems (such as low-temperature electronic devices, low-temperature cables) and other related component products this year. extend. The joint research team of the University of Science and Technology of China and the Shanghai Institute of Technical Physics of the Chinese Academy of Sciences completed the research and development of the superconducting quantum computing prototypes "Zuchongzhi No. 1" and "Zuchongzhi No. 2" and realized the "superiority of quantum computing". In 2022, the company and the Institute of Quantum Information and Quantum Science and Technology Innovation of the Chinese Academy of Sciences upgraded its "quantum computing cloud platform" cooperation, and deployed "QCIS", "isQ-Core", "Quingo" and other compiled languages to realize online operation of quantum algorithms .
HUAWEI Superconducting Quantum Simulation Cloud Platform	Launched China's quantum chemistry simulation platform; it is in a leading position in algorithm; it pays attention to the mining of quantum talents, and has held many national quantum computing competitions. At the end of 2022, the patent for the "superconducting quantum chip" designed by the company was approved by the State Intellectual Property Office (CN115271077A), which reduces the crosstalk between qubits.

Superconducting Semiconductor Cloud Platform	It has laid out multiple technical routes, and has launched superconducting and semiconductor quantum chips respectively. It is also a full-stack company and has China's leading quantum computing cloud platform and algorithm team. Its algorithms are applied in finance, chemistry, aviation, etc. At the beginning of 2022, the Quantum Computing Global Developer Platform jointly created by Origin Quantum and Hefei Big Data Company will be officially launched. The platform was formerly China's innovation and entrepreneurship platform featuring "quantum computing". In addition, the company also released China's quantum computer and supercomputer collaborative computing system solution and realized the ultrafast control of silicon-based semiconductor spin qubits. (Spin bit manipulation rate up to 542MHz)
Optical Quantum, Coherent Ising Machine	In 2022, QBoson became one of the first companies to achieve commercialization of optical quantum computing scenarios with the "quantum AI molecular docking simulation platform" and the "Tiangongjingshi quantum financial strategy platform." QBoson has built a matrix of dozens of core proprietary technology patents in the field of optical quantum computing, covering quantum neuron chip solutions for various types of optical quantum computers, as well as a "3+1" universal optical quantum system architecture topology.In the same year, QBoson's first-generation Tiangong optical quantum computing validation platform achieved coherent quantum computing optimization and verification for MAX-CUT problems with 25 arbitrarily connected nodes in China, and was able to select one of the four optimal solutions from over 30 million possibilities in 50 microseconds. This initial validation of the "practical superiority" of quantum computing has profound application significance and extensive practical value.
Superconducting Quantum Simulation Cloud Platform	One of the earliest companies in China investing in quantum computing, it has jointly built a laboratory with the Chinese Academy of Sciences, and has jointly launched a cloud platform based on superconducting quantum computers; self-developed quantum computing simulator "Tai Zhang" and "Tai Zhang 2.0"; China's largest, The world's leading cloud computing service provider. At the beginning of 2022, the company designed and manufactured a two-bit fluxonium quantum chip, which achieved a single-bit control accuracy of 99.97%, and a two-bit iSWAP gate control accuracy of up to 99.72%, reaching the best level in the world among such bits.

中科酷原 CAS COLD ATOM

Neutral Atom Cloud Platform

China's industrialized company with both quantum computing research and development and precision measurement capabilities; atomic single-bit gate fidelity, coherence time, and double-bit gate fidelity are high; the first domestic atomic quantum computing cloud platform on the line - " Kuyuan Quantum Cloud" ; in 2022, the company completed the construction of the quantum computing research and manufacturing center; the lasers, optical amplifiers and EOMs in the optical system have realized the company's independent research and development; for the current neutral atom quantum computing route Head enterprises.

SPINQ 量旋科技

Superconducting Nuclear Magnetic Resonance

The world's first programmable desktop nuclear magnetic resonance quantum computer; at present, it has completed a practical superconducting chip quantum computer that integrates superconducting quantum chips, radio frequency measurement and control systems, dilution refrigerators, quantum cloud platforms, quantum operating systems and application software. The company will launch a portable quantum computing teaching machine "Gemini mini" in 2022. The new model is more suitable for quantum computing education and popularization.

QUDOOR 启科量子

Full Stack Distributed Ion Trap

China's ARTIQ architecture quantum computing measurement and control system with independent intellectual property rights - QuSoil. QUDOOR officially released the engineered ion trap cryogenic vacuum system <Aba|Qu|Cryovac> at the end of 2022, and officially released the engineering machine <Aba|Qu>1.0 ("Tiansu No. 1" for short in Chinese) in 2023.

PASQAL

Neutral Atom

At the beginning of 2022, the company will become the first neutral atom-based quantum computer service launched on this platform, providing end users with a series of digital and analog capabilities of quantum computing. In July, a large assembled array of up to 361 atoms was realized in optical tweezers, demonstrating the ability to expand neutral atom qubits, and a quantum processor with 324 atoms (qubits) was launched in September

XANADU Photonic Quantum Full Stack	It has realized the programming of optical quantum computer, launched the optical quantum computing chip and the first optical quantum computing cloud platform, and has a full-stack quantum software platform. In mid-2022, the company will use the newly released 216 optical qubit programmable optical quantum computer Borealis (Northern Lights) to complete the Gaussian Bose sampling experiment, demonstrating the superiority of quantum computing.
D:Wave The Quantum Computing Company Superconducting, Annealing	The world's first quantum computing company with rich research experience and the highest financing amount; the earliest application of quantum computing technology, with many customers in the fields of finance, automobiles, materials, and aviation. Several quantum annealers have been sold. The company will launch the first Advantage™ quantum computer accessible through the US-based Leap™ quantum cloud service in 2022, currently offering 5,000 qubits.

Silicon Quantum Computing Semiconductor	A pioneer in silicon quantum computers, utilizing silicon-based qubit technology that CQC2T has been researching. The company has more financing in this route, benefiting from the commonality with superconducting quantum computer hardware equipment and mature CMOS technology. In mid-2022, the company unveiled the world's first atomic-scale quantum integrated circuit. And at the end of this year, a new room temperature, anti-interference spin qubit readout technology was created
QUANTUM BRILLIANCE Diamond NV Centre	Using synthetic diamonds to produce lunchbox-sized quantum accelerators is leading the way in the development of diamond quantum accelerators that operate at room temperature, enabling simplification and extreme miniaturization of quantum technologies. The properties of this new technology can be used to produce hardware and software that yield the longest coherence times of any room-temperature quantum state. This means that form of quantum computing can be used anywhere a conventional computer can.

08

Industry Analysis & Forecast

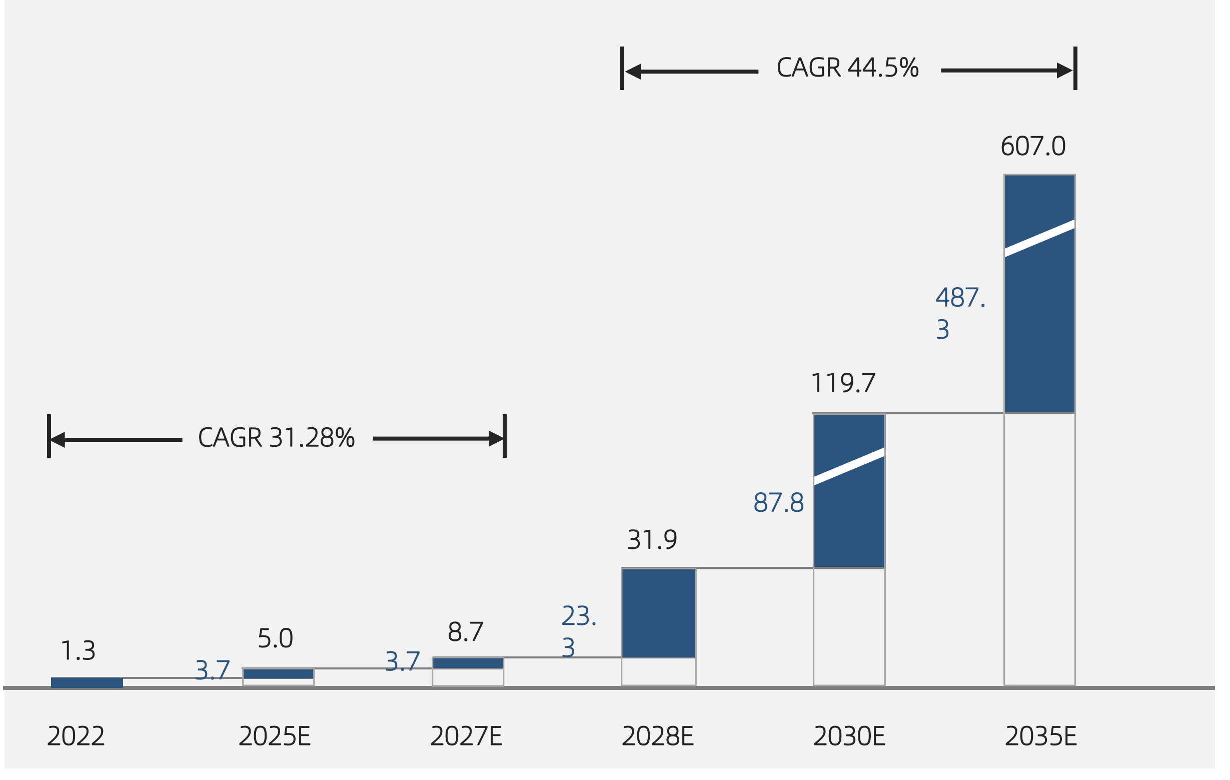
ICV still believes that 2027 will be an important milestone for the entire industry. In the five years leading up to that, we are still in a critical stage of the NISQ era. On the one hand, major companies are likely to achieve their respective technology roadmap goals, and general-purpose quantum computers will achieve technological breakthroughs in areas such as qubit number and fidelity. However, general-purpose quantum computers will still only be used to meet the needs of scientific research laboratories and a small number of cloud platform businesses, growing slowly and steadily. On the other hand, special-purpose quantum computers may be used for specific problems, such as coherent manipulation of hundreds of qubits for applications in combinatorial optimization, quantum chemistry, and machine learning, to guide material design, drug development, and more.

The industry scale will increase to 31.9 billion USD in five years.

In 2022, the global quantum industry reached a scale of 1.29 billion USD, a 61.25% increase from 2021, which is in line with industry development patterns. The growth in industry scale is driven by both an increase in industry participants across various segments, including whole machine companies, multi-technology companies, software companies, and industry users, as well as investment, which has brought in more funding for talent and equipment, from both primary markets and U.S. SPAC listings.

However, in 2022, the revenue of major global quantum computing companies remained bleak, and the industry is expected to rely on government and military procurement for several more years. In the context of industry investment unable to achieve expected returns, companies may reduce investment in technology and talent, with more industry development coming from government and research institutions. Whether 2022 marks the beginning of a new cycle of strong momentum or a low point for the global quantum industry remains to be seen.

Exhibit 8-1 Global Quantum Computing Industry Size (2022~2035E)
Unit: Billion USD

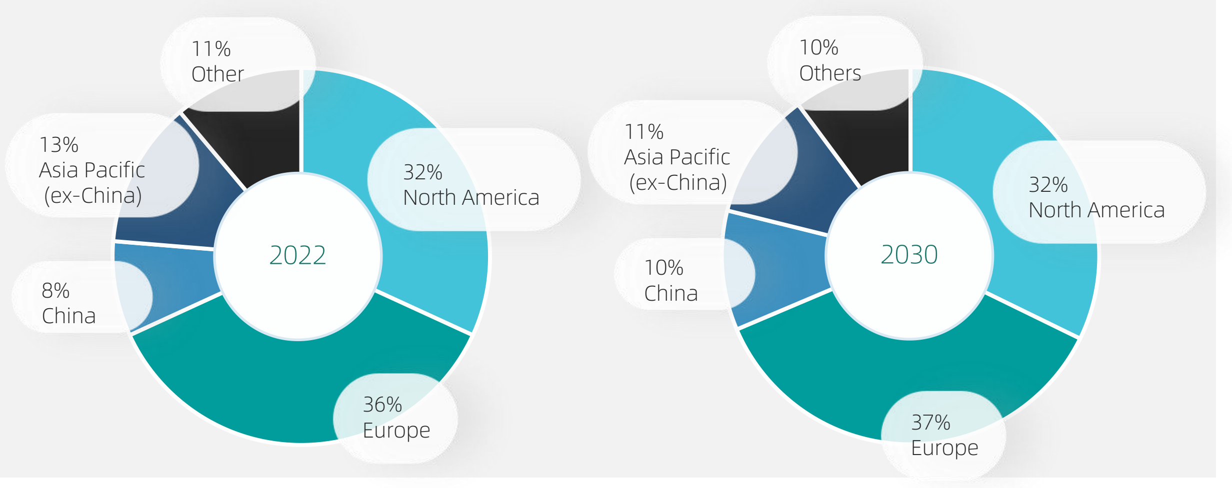


ICV TAnK | Version Feb 2023

We have revised our projections for the year 2021 and estimate that by 2027, the global quantum computing industry will have a market size of 8.7 billion USD, which will rapidly increase to 31.9 billion USD by 2028. The industry is expected to enter a period of explosive growth, and by 2030, the overall market size is expected to reach 119.7 billion USD. At this stage, there will be a significant promotion of the industry's applications, and the procurement of complete machines, cloud services, and application solutions will see substantial growth. In the subsequent 5 to 10 years, the industry is expected to grow to a market size of 607 billion USD by 2035. The compound annual growth rate (CAGR) of the global quantum computing industry is projected to be 31.28% from 2022 to 2027, and 44.5% from 2027 to 2035, moving towards a trillion-dollar industry.

Forecast of Industry Scale by Region

Exhibit 8-2 Global industry scale of quantum computing by region (2022 & 2030)
Unit: %



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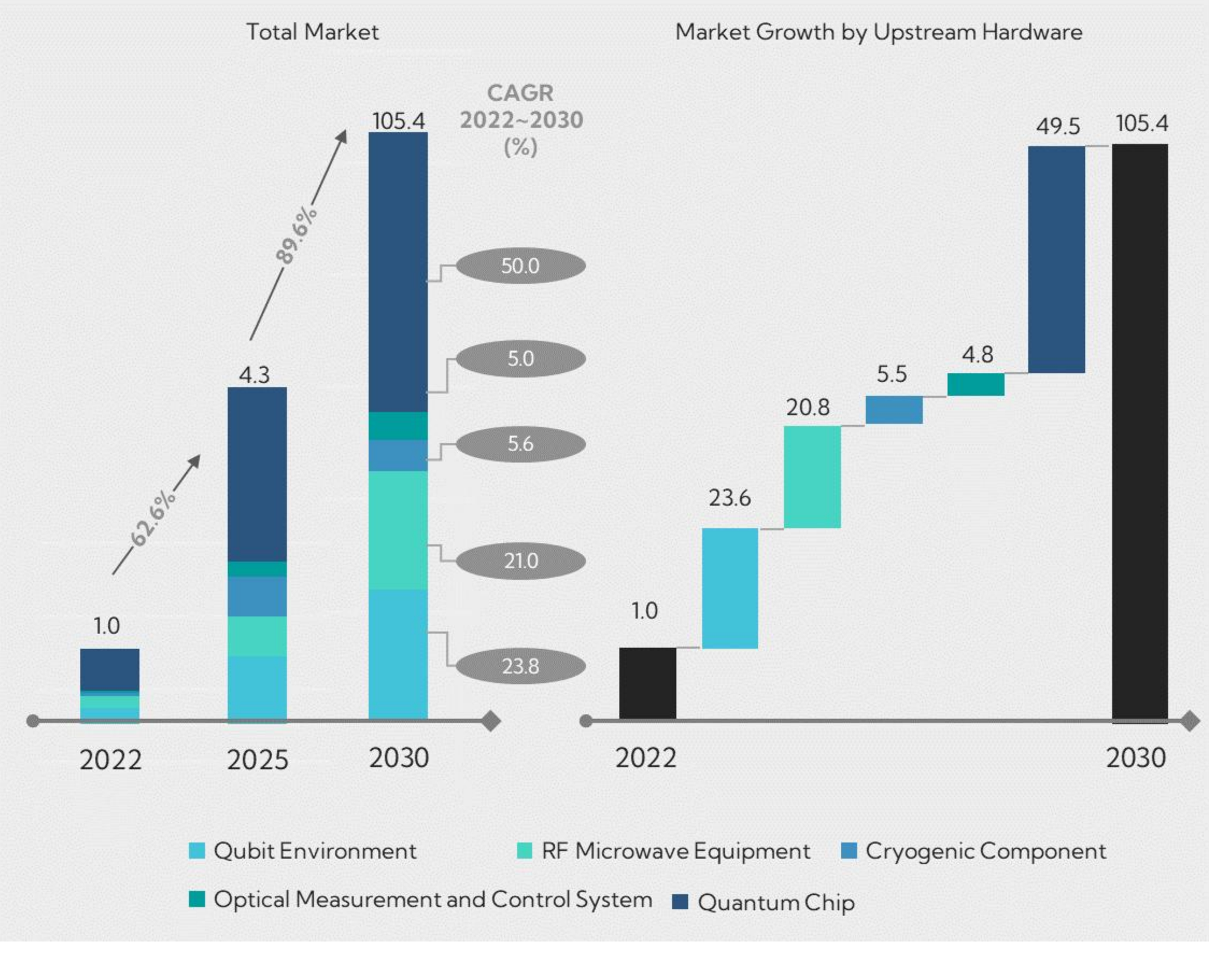
In 2022, the market size of the quantum computing industry is projected to be 430 million USD in North America, 490 million USD in Europe, 110 million USD in China, 170 million USD in the Asia-Pacific region (excluding China), and a total of 150 million USD in other regions, accounting for 32%, 36%, 8%, 13%, and 11% of the market share, respectively.

By 2030, the market size of the industry in each region is expected to increase to 385.9 billion USD in North America, 435.6 billion USD in Europe, 122.7 billion USD in China, 131.5 billion USD in the Asia-Pacific region (excluding China), and a total of 121.6 billion USD in other regions, accounting for 32%, 36%, 10%, 11%, and 11% of the market share, respectively.

In terms of growth rate, each region is developing synchronously. It is worth noting that although the market size in other regions is increasing along with the nodes of various technological breakthroughs due to the expansion of the overall market size, the growth rates of other regions have been decreasing year by year since 2028. This is because major technological powers have a certain degree of advantage in terms of innovation, and quickly occupy the market with both hardware and software after technological breakthroughs. With the support of massive capital, they constantly expand, thus squeezing out the development of quantum computing in other regions such as Africa.

Forecast of Upstream Hardware Segment Market Size

Exhibit 8-3 Global scale of quantum computing upstream industry (2022&2030E)
Unit: Billion USD



ICV TAnK | Version Feb 2023

In terms of the market size of upstream hardware in 2022, the highest market share is occupied by quantum chips, which accounts for $545 million. The second highest market share is held by dilution refrigerators (which together with ultra-high vacuum systems constitute the quantum bit environment), which accounts for $193 million. The third highest market share is occupied by radio frequency (RF) microwave equipment (quantum computing measurement and control systems) with $160 million market share. In addition, ultra-high vacuum systems account for $33 million and low-temperature electronic devices account for $34 million, representing a small portion of the market share. The reason for the high market share of quantum chips is that, on the one hand, the high R&D investment in the early stage has led to high production costs for chip development and production, coupled with low chip shipment volume, resulting in a high unit price. On the other hand, the high premium brought about by the scarce market supply.

By 2030, the market size of quantum chips is expected to reach $50 billion, followed by quantum computing measurement and control systems with a market size of $21 billion, and dilution refrigerators with a market size of $20.6 billion. In addition, the market size of ultra-high vacuum systems is expected to increase to $3.2 billion, and the market size of optical systems is expected to grow from $0.3 billion (in 2022) to $5 billion.

And from 2030 onwards, the market share of quantum chips will decline compared to 2022 due to the commercialization of quantum computers on a large scale after 2028, resulting in a decrease in production costs. The market size of ultra-high vacuum cavities will increase due to the crucial role that ion traps, especially neutral atom routes, play in the development of specialized quantum simulation computers. In addition, breakthroughs in technology over the past two years have led to an increase in demand for vacuum cavities.

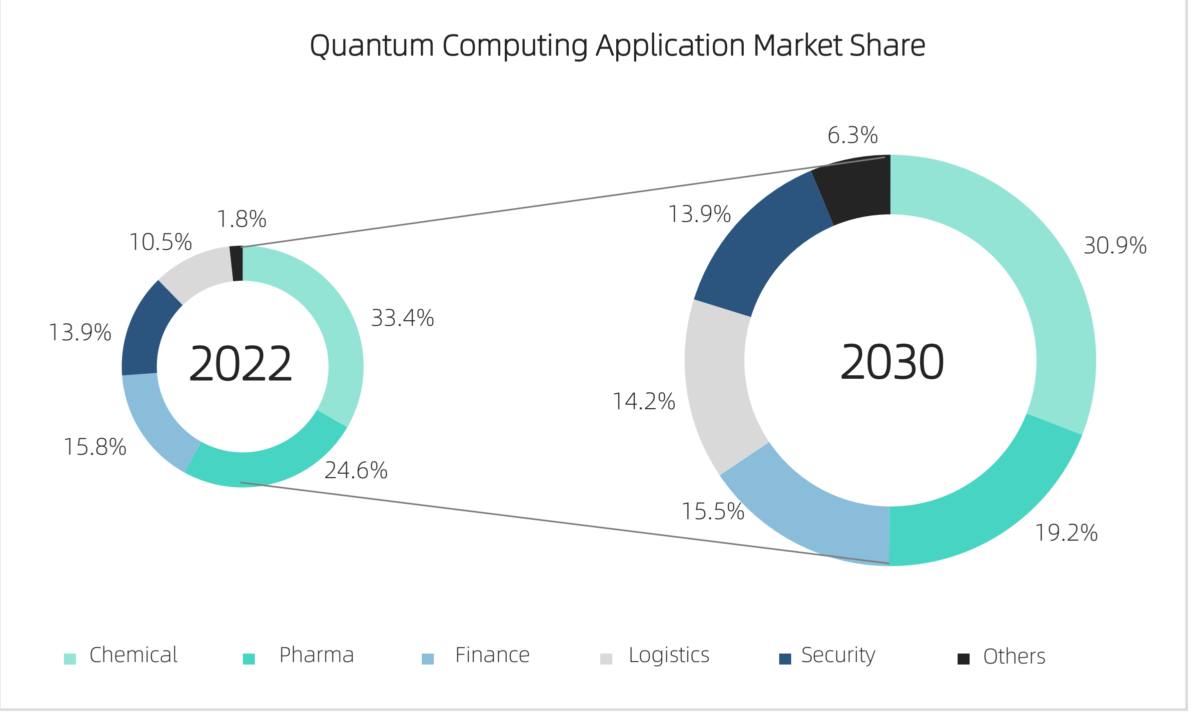
For the development of superconducting and semiconductor routes, there are both promoting and inhibiting factors. The continuous expansion of refrigeration power and adaptation optimization for quantum computers has promoted the development of dilution refrigerators, but the lack of specialized dilution refrigerators for quantum computing has limited their potential. As the number of quantum bits increases geometrically, and with the doubling of measurement and control lines, this trend will become more apparent.

Furthermore, the market share of RF microwave cables and low-temperature electronic devices, especially RF microwave equipment, in superconducting and semiconductor measurement and control systems, will continue to increase. This is due to the increasing demands of measurement and control systems as the complexity of the overall system increases, and the need for chip-based or distributed solutions to affect the final performance of quantum computers. Additionally, the trend towards quantum error correction and the need for fault-tolerant quantum computers will increase the requirements for measurement and control systems. This will lead to increased development and usage costs. The market share of laser, single-photon detectors, and other optical components will also increase significantly compared to 2022. This is due to the higher level of technical readiness for quantum computing in optical quantum, ion trap, and neutral atom routes compared to the superconducting route. Furthermore, as quantum computing develops towards specialized quantum simulation computing in the next 5-10 years, the market size of optical measurement and control systems is expected to increase significantly, leading to a gradual increase in market share for laser, single-photon detectors, and other optical components after 2030.

Market Size Forecast for Downstream Applications

At present, the downstream applications of quantum computing are mainly focused on the chemical industry, financial sector, pharmaceutical R&D, logistics industry, and security industry.

Exhibit 8-4 Global downstream application market size of quantum computing(2022~2030E)



ICV TAnK | Version Feb 2023

In 2022, the market share of the chemical industry was 33.4%, pharmaceutical research and development (R&D) sector was 24.6%, the financial sector accounted for 15.8%, the security industry accounted for 13.9%, the logistics industry accounted for 10.5%, and other sectors accounted for 1.8%.

Since 2027, the entire quantum computing sector has experienced rapid growth, and by 2030, the market share of the chemical industry is projected to decrease to 30.9%, while that of the pharmaceutical R&D sector is expected to decline to 19.2%. The financial sector's share is predicted to remain constant at 15.5%, while the logistics sector is anticipated to increase to 14.2%. The security industry's market share is projected to remain stable at 13.9%, and other sectors are expected to account for 6.3% of the market share.

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Industry Outlook

The future development of quantum computing will focus on three main areas:

Firstly, the ongoing improvement of quantum computing performance. To achieve fault-tolerant quantum computing, the primary consideration is how to accurately expand the quantum computing system scale. When expanding the number of quantum bits, both the quantity and quality of the bits are extremely important. Each step of quantum state preparation, manipulation, and measurement must maintain high precision and low noise. As the number of quantum bits increases, errors caused by noise and crosstalk also increase, which brings huge challenges to the design, fabrication, and control of quantum systems. It still requires a great deal of scientific and engineering collaboration.

Secondly, the realization of dedicated quantum simulators and the continuous exploration of quantum computing applications. This involves the coherent manipulation of hundreds of quantum bits, applied to specific problems such as combinatorial optimization, quantum chemistry, and machine learning, to guide material design, drug development, and other areas. From now until 2030, the main research task worldwide should focus on this.

Thirdly, the realization of a programmable universal quantum computer, which involves the coherent manipulation of at least millions of quantum bits and can have a huge impact on classical cryptography, large-scale data search, artificial intelligence, and other areas. Since quantum bits are easily affected by environmental noise and prone to errors, for large-scale quantum bit systems, it is necessary to ensure the correct operation of the entire system through quantum error correction, which is a major challenge for a period of time. Due to the technical difficulties, it is still unclear when a universal quantum computer can be realized, and the international academic community generally believes that it will require 15 years or even longer.

Technology Trend

Quantum error correction will be the main focus of development in the future for a long time.

After various countries raced to achieve quantum supremacy, quantum computing has officially entered the era of medium-sized, noisy systems. How to understand and overcome noise has become a key research focus for making quantum computing practical. Currently, there are several different methods for dealing with errors in these computations, which can be divided into three core components: error suppression, error mitigation, and error correction.

Firstly, error suppression is the most basic level of error processing. In most cases, it represents processing errors at the level closest to the hardware. These techniques are often performed without the user's knowledge and typically involve changing or adding control signals to ensure that the processor returns the expected results.

Error suppression techniques can be traced back several decades and have been developed in some of the earliest controllable quantum systems, such as nuclear magnetic resonance (NMR) devices, which are the core of magnetic resonance imaging (MRI). Some of these techniques have already been adopted by quantum computers, such as spin-echo - a pulse sequence that helps refocus a qubit to maintain its quantum state for a longer time. In addition, the use of the derivative of the DRAG (Derivative Removal by Adiabatic Gate) technique can remove a component added in the standard pulse shape to reduce the number of qubits entering states higher than the computational 0 and 1 states. For example, IBM's Qiskit Pulse allows users to generate custom pulses to explore error suppression.

Error mitigation is the use of circuit-integrated output to reduce or eliminate the impact of noise when estimating expected values. Probabilistic error cancellation involves simulating a noise-inverting channel to cancel out noise, enabling us to calculate noise-free (unbiased) expected values. Currently, IBM's team is exploring and developing a different combination of error mitigation techniques. For example, probabilistic error cancellation involves sampling from a circuit set and, on average, mimicking a noise-inverting channel to cancel out noise. This process is a bit like how noise-canceling headphones work, but it works by averaging instead of canceling noise sequentially.

Quantum error correction is the ultimate goal to be achieved. Fault-tolerant quantum computing involves establishing system redundancy so that even if several quantum bits are in error, the system will still return an accurate answer. Error correction is a standard technique in classical computing, where information is encoded with redundancy to check for errors.

Quantum error correction is also based on the same idea, but it must take into account new types of errors that occur in quantum computing. In quantum error correction, the value of a single quantum bit (called a logical qubit) is encoded among multiple physical qubits to perform gate operations, and the structure of the physical qubits is treated as a logical qubit with minimal errors. Errors are detected and corrected by performing a set of specific operations and measurements (called error-correction codes). According to the threshold theorem, the hardware used must achieve the minimum error rate before error correction can be applied.

Looking back over the past few years, the importance of quantum error correction has been increasing year by year. In September 2020, Google planned to use surface codes for error correction; in October 2021, the University of Maryland and IonQ made a significant breakthrough in quantum error correction by creating a high-fidelity logical qubit from multiple low-fidelity physical qubits. In December of the same year, Quantinuum achieved real-time error detection and correction for a quantum computer for the first time in the industry.

By 2022, quantum research teams around the world had made new progress and breakthroughs in error correction, making error correction the main development direction for future quantum computing. In February 2022, the Swiss Federal Institute of Technology in Zurich (ETH Zurich) improved the quantum error correction scheme based on Gottesman-Kitaev-Preskill (GKP) code, thereby extending the lifespan of quantum states threefold. In July, the University of Science and Technology of China and the Swiss Federal Institute of Technology in Zurich (ETH) worked together to achieve repeated error correction with surface codes for the first time. In August, RIKEN's Center for Emergent Matter Science in Japan paved the way for practical quantum computing by demonstrating error correction in a three-qubit silicon-based quantum computing system. In September, Chalmers University of Technology in Sweden successfully developed a high-fidelity generation technology for controlling photonic quantum states in a three-dimensional cavity.

From the development process of quantum computing's error correction in the past few years, it is expected that error correction will be the main theme of the entire track's development in the next 5-10 years. As the number of quantum bits reaches new heights, people are gradually seeing the infinite possibilities of quantum computing in various fields in the future.

the number of quantum bits has not yet reached the level of thousands or tens of thousands, that is, the actual application areas are still limited, and the requirements for error correction are not very high. (That is, the current requirements and importance of quantum bit quantity are still higher than those of quantum error correction). However, it is clear that many companies and research institutions are taking precautions and actively participating in the pre-planning of quantum error correction in advance.

Combinatorial, Optimization and Quantum Materials Toolbox

Along with the main trend of error correction, the modularization and chip integration of measurement and control systems are also developing in synchronization.

Looking at the development of quantum chips, the trend of integration and modularization is more evident. For example, IBM's superconducting quantum chip, Osprey, uses a multi-level wiring architecture by placing quantum bits, resonators, and control lines on different layers of the chip. This approach provides more space to place bits and supports the large-area expansion of the chip. When the number of quantum bits is particularly small, quantum bits, resonators, and radiofrequency lines can be in the same layer. However, when the number of quantum bits reaches a certain level, this can seriously affect the arrangement of the quantum bits. Quantum bits are themselves very fragile and vulnerable to interference, such as defects in quantum chips, temperature noise in the environment, and radiofrequency crosstalk of radiofrequency and control lines. Therefore, if radiofrequency lines and quantum bits can be layered, and with shielding technology, it can significantly reduce radiofrequency signal crosstalk on quantum bits.

Rigetti, also a superconducting circuit, offers another solution to chip modularization. They believe that the processor of a single chip needs to be redesigned for each generation, and the demand for components also grows exponentially with the number of quantum bits, making such chip expansion slow and expensive. Therefore, they have designed a modular quantum chip, and the large-scale processor consists of the same chips. This modular, mass-producible, and scalable multi-chip processor can greatly reduce costs and increase efficiency. It can also fundamentally solve the problem of crosstalk that occurs when quantum bits are scaled up and placed on a single chip.

The quantum material toolbox is also a recent hot topic. In recent years, scientists have been working to find the noise sources of superconducting quantum computing. In superconducting quantum computing, silicon is often used as a substrate or as the basis of a chip. However, researchers at the Superconducting Quantum Materials and Systems Center (SQMS) at the US Department of Energy's Fermilab have shown that silicon substrates may impair the performance of quantum processors. Superconducting quantum bits have a short decoherence time and are very sensitive to external interference. The quantum bits they produce are easily affected by the external environment and decohere. In September 2022, it was finally confirmed that using sapphire as a substrate can reduce this noise and extend the coherence time of quantum bits. Although at present, no substrate material can avoid noise, just like people are always exploring high-temperature superconducting materials, even if they only increase the critical temperature of superconductivity by a few degrees, it is of great significance to the entire industry.

Of course, other routes have also made progress in modularization, integration, and device optimization. For example, in the photonic quantum route, silicon-based photonic quantum chips are currently working to integrate single-photon detectors into chips to improve efficiency and reduce energy loss. Due to limited space, this will not be elaborated further.

In summary, all forms of modularization, including the design and optimization of chip structures, new ultra-low-noise chip materials, and so on, will serve the future main theme of quantum error correction. Whether it is solving the problem of qubit crosstalk, or solving the noise problem caused by micro-nano processing technology or the material itself, it is essentially to reduce the calculation error rate and pave the way for a large-scale fault-tolerant quantum computer.

About Dedicated Quantum Computers

The semiconductor mode of quantum chip manufacturing. Quantum simulators will be developed earlier than universal quantum computers, so it is essential to plan accordingly. Strategic investments and government oversight and control are crucial for quantum simulation. By 2030, ICV envisions the following global development goals for quantum simulators:

From 2023 to 2027, demonstrate "quantum advantage" in a series of simulated tasks, which is seen as an important milestone, but not actual application. Improve control and scalability and further reduce the entropy of various platforms. Develop quantum-classical hybrid architectures that allow quantum simulators to handle industrial and research innovation-related applications. Expand and strengthen the supply chain and the development of key enabling technologies. Launch certification and benchmark testing of the most promising quantum simulators. Develop software solutions to complement the development of quantum simulators and their specific application focuses.

From 2028 to 2030, establish close connections with end-users and develop more practical applications. Design error correction and mitigation techniques suitable for quantum simulators. Develop quantum simulators that offer higher degrees of control and programmability. Build a bridge between industry and quantum simulation research, translating industrial problems into simulation paradigms. Provide general methods for the certification and benchmark testing of quantum simulators.

Converging with HPC

In the NISQ era, hybrid quantum-classical methods are considered an important approach for solving practical problems. In 2022, the industry further clarified the combination of quantum computing and high-performance computing (HPC).

In this regard, Europe has taken the lead globally, with the 5-qubit QPU developed by the Finnish company IQM already deployed in HPC centers. The Leibniz Supercomputing Center in Germany is evaluating exascale supercomputers that use quantum and AI systems for accelerated computing. This combination of quantum and HPC can make good use of current variational algorithms. Chip giant NVIDIA also launched the quantum optimization device architecture QODA this year, which is hailed as the CUDA architecture of the quantum field and can combine quantum and classical computing.

It is expected that this trend will be further highlighted in 2023, for example, with Chinese supercomputing teams starting to participate in quantum computing research. In particular, the National Supercomputing Center in Wuxi, which won the Gordon Bell Prize in 2021, has realized real-time simulation of large-scale quantum random circuits in the new-generation Sunway supercomputer. Therefore, it is only a matter of time before quantum computers enter national supercomputing centers.

Quantum hardware assistance

Looking at the entire hardware system of quantum computing, it can be predicted that in the near future, as the number of quantum bits increases exponentially, hardware assistance may experience an explosive growth. Currently, although many research institutions and even quantum companies have laid out various auxiliary systems, the development of quantum memory is expected to be the most rapid, according to ICV.

In the von Neumann architecture of classical computers, memory plays an important role, which is used to store intermediate calculation results of the processor. Quantum memory technology is too difficult, and most quantum computing experimental research has not yet introduced quantum memory. However, at the end of 2021, the French National Center for Scientific Research proved that the use of a quantum computer equipped with quantum memory can significantly reduce the demand for physical quantum bits.

Prior to this, research on quantum memory mainly focused on applications in the field of quantum communication, such as using multi-mode quantum storage to establish a quantum relay and build a remote quantum internet, or using ultra-long-lived quantum storage to realize a portable quantum USB drive. The achievement of the French team quantitatively demonstrated the value of quantum memory in quantum computing and successfully expanded the application scope of quantum memory.

From a macro perspective of the industry chain, although quantum memory accounts for a very small part, it is very important. In 2023, IBM plans to launch a superconducting quantum chip with more than 1,000 quantum bits. Above this quantity, distributed quantum computing and large-scale quantum interconnection, quantum memory will be an important component.

Currently, the United States is in a leading position in this field, with representative companies such as Qunnect, followed by Europe represented by France's WeLinQ. At the end of 2022, Qunnect realized the first commercial quantum network in the United States, which also used only small room-temperature memory. In the future, as quantum technology continues to develop, other quantum hardware auxiliary devices such as quantum network equipment, quantum interfaces, high-dimensional quantum computing, and new cooling devices for molecular gases will also benefit from exploration of various technological paths and receive good development, which is another strong growth point in the future upstream hardware market apart from traditional core components.

Policy Trend

As an important field of cutting-edge technology and future industry, quantum information technology needs strong support from governments around the world, including the United States, China, the United Kingdom, Germany, France, Russia, Japan, India, South Korea, the Netherlands, Singapore, Austria, Hungary, Iran, Israel, Taiwan, and Slovakia. Currently and in the future, it is certain that China, the United States, and Europe will make every effort to promote policy support related to quantum information, with China and the United States engaged in a long-term confrontation and their policies being more specific, targeted, and executable.

Currently, the United States has the most and most comprehensive publicly released policies. Various government departments and related organizations frequently issue reports aimed at increasing awareness and attention to quantum technology. These government departments and organizations include the National Security Commission on Artificial Intelligence (NSCAI), Government Accountability Office (GAO), National Counterintelligence and Security Center (NCSC), National Science and Technology Council (NSTC), and others. From various policies, it can be seen that quantum technology has been identified by the United States as one of the key technologies that need to be developed in the context of U.S.-China competition.

In China, quantum policies are mentioned in various policies such as the "Government Work Report", the "14th Five-Year Plan and 2035 Vision Outline for National Economic and Social Development", the "National Standardization Development Plan", the "14th Five-Year Plan for the Development of the Software and Information Technology Service Industry", and the "14th Five-Year National Informatization Plan". More than 20 provinces and cities have included quantum technology in their local "14th Five-Year Plan".

Overall, quantum technology policies will be further implemented from the national level to departments responsible for national defense, industry, science and technology, and other fields, with these lower-level departments issuing more targeted policies. For countries that have not yet released quantum technology policies, or for countries and regions that have not yet elevated quantum technology to the national level, as their technological capabilities and awareness improve, they will also be expected to raise quantum technology to higher levels of attention.

Financing Trend

Due to the speed and scale of global economic recovery, there will be a significant level of uncertainty for the quantum information industry in 2023, particularly for the field of quantum computing. This uncertainty can be mainly attributed to two factors:

Financing may become more difficult in 2023

Firstly, quantum computing is still in its early stages and market-oriented capital institutions are unable to provide long-term support. Several companies that went public through SPAC in 2022 seriously damaged investor confidence. The United States has the world's most sophisticated capital market exit system. If the United States cannot set a good investment benchmark for the world, it will be difficult for investment institutions in other countries to follow suit.

In 2023, quantum computing enterprises from various countries will need to adopt strategies to deal with possible funding shortages. They may find it more difficult to attract market attention and funding compared to 2021.

Staff layoffs, business closures, and resulting mergers and acquisitions may occur.

Currently and in the next three years, the majority of quantum computing companies will not be able to establish a stable and positive operating cash flow. Most companies will require external funding, and those that are favored by governments and investment institutions will have a chance to survive. Some companies may be able to expand further with the support of their parent companies, such as IBM, Google, and HUAWEI, but start-ups will face significant challenges, and downsizing may become a keyword in 2023. Some companies may even go bankrupt or be forced to seek mergers and acquisitions due to a break in cash flow.

Since the merger of Honeywell's quantum computing division and Cambridge Quantum Computing in January 2021, there has been a small wave of mergers in the quantum industry in 2022. Innovative drug development company Odyssey acquired a majority stake in the UK quantum computing start-up Rahko, Pasqal acquired Qu&Co, ColdQuanta acquired Super.tech, and quantum computing software company QCI acquired optical quantum systems company QPhoton. Going back further, SK Telecom acquired quantum communication company IDQ, iXblue acquired quantum gravity measurement company Muquans, and Zeiss acquired Quantum Benchmark, among others. There are also some spin-offs from research institutions, such as SandboxAQ being spun off from Alphabet.

In summary, the entire quantum computing industry needs to prepare for a period of "belt-tightening" in 2023, by improving the efficiency of fund utilization, motivating team activities, and enhancing the ability to monetize investments to cope with potential crises. In the next few years, the quantum computing industry will experience a reshuffle, and companies will need to be agile and adaptable to survive.

Business Trend

An Interesting Quantum Education Market

Currently, there is a shortage of quantum computing talent worldwide, and there is an urgent need to cultivate more talent to accelerate the development of quantum computing. Research institutions, tech giants, and startups are already involved in the quantum education industry. Quantum education products provide a more intuitive way for students and the general public to understand quantum computing. Enriching physics experiments in schools can stimulate students' interest in the field of quantum computing and drive more people to work in this field, thus aiding in talent cultivation.

In the United States, IBM's Qiskit has developed an education module and summer school, encouraging developers to use Qiskit through diverse forms. Microsoft has created Quantum Katas on GitHub, which includes a series of programming exercises using Q# language, to be used with the Microsoft Quantum Development Kit. MIT has established the Quantum Practitioner Curriculum, which includes introductory videos on quantum computing basics and quantum computing application courses. Students who complete all courses will receive a certificate from MIT.

In China, Origin Quantum has launched the online education platform "Origin Suzhi," published the quantum computing and programming textbook "Introduction to Quantum Computing and Programming," and built a science museum. SpinQ has released the desktop 2-qubit nuclear magnetic resonance quantum computer "Gemini" and the portable 2-qubit nuclear magnetic resonance quantum computer "Gemini Mini." QUDOOR has launched ion trap quantum teaching machine products, while CAS Cold Atom has introduced a desktop magneto-optical trap teaching instrument. These devices are already being used in many schools in China, and have even been sold to countries such as Norway and Australia.

In Europe, the Dutch quantum research institution QuTech has established QuTech Academy, which provides introductions to quantum education at the bachelor's, master's, and doctoral levels, relying on educational resources from Delft University of Technology, and collaborates with online course websites to offer four courses to the public. From a regional perspective, the United States, China, and Europe have all launched K-12 quantum computing education. In terms of implementation, the United States has a relatively deep accumulation in the development aspect, and may even form a habit of use among developers in the future. China mainly promotes through education machines, while some European countries open up dedicated courses or talent cultivation programs to increase the number of people receiving quantum education.

In the future, quantum labor will still be in short supply, and the quantum education market will launch more diverse forms of educational products to supplement the quantum workforce.

The Semiconductor Modes of Quantum Chip Fabrication

In the field of quantum chip design and manufacturing, will there be the same IDM and Fabless models as in the mature semiconductor industry? The answer is yes.

Currently, the manufacturing process of quantum chips is mainly completed in laboratories. However, some leading quantum computing teams have already begun manufacturing quantum chips in factories. For example, Google's "Sycamore" quantum chip was manufactured in a factory at the University of California, Santa Barbara (UCSB). Some companies have also begun building their own dedicated chip production lines. For instance, Origin Quantum, a Chinese company, has two self-built labs - a quantum chip manufacturing and packaging lab, and a quantum computing assembly and testing lab - which are now officially in operation.

For companies that have their own full set of quantum chip production line processes, because the downstream market has not yet fully opened up, the production capacity is not running at full load. Therefore, quantum chip foundry services, which provide various quantum chip fabrication services to more quantum startup companies without their own independent chip production lines, are also a future trend for the development of entire companies.

Quantum Chip Manufacturing Semiconductor Mode

In addition, there are also models like that of Dutch quantum start-up QuantWare. They are the world's first company to sell quantum processing units (QPUs) to external parties, equivalent to the role that Intel plays in the traditional computing industry. This will bring about a transformation in the business model of quantum computing.

International Competition Trend

It is exciting to see an increasing number of universities, research institutions, and companies from different countries collaborating closely to research cutting-edge topics in the quantum computing industry over the past year. Scientific collaborations involving two, three, or even more countries are common. However, among the many cooperating countries, there is no sign of collaboration between China and the United States. The biggest competition between China and the US is currently in the technology field, particularly in cutting-edge technologies such as quantum computing. For example, the 2021 report "Challenges and Threats from Strategic Competitors" released by the US National Counterintelligence and Security Center (NCSC) specifically mentioned that "five key areas, including artificial intelligence, quantum information technology, biotechnology, semiconductors, and autonomous systems, will determine whether China overtakes the US to become a superpower." The NCSC also stated in the report that China aims to achieve a leadership position in emerging technology fields by 2030. China has become the US's main strategic competitor because it has sufficient resources and comprehensive strategies to promote technological progress.

In October 2022, a key and emerging technology export control list from the US government showed that in addition to chips, the second round of restrictions will likely include materials, isotopes, and manufacturing technologies for quantum devices, post-quantum cryptography, and technologies related to quantum sensing and networking. If these export controls are approved, it will signal an escalation in the technology war between China and the US and a more aggressive signal in the competition for quantum computing. As early as May, the White House issued a memorandum instructing US federal agencies to ensure that the country maintains a global leadership position in the field of quantum information science. The memorandum outlines the security implications of rival countries gaining advantages in quantum computing, particularly regarding "cryptographic-relevant quantum computers (CRQC)" and how they could crack public key encryption systems in the US.

These new export controls related to quantum technology represent a "real deepening of the rift" between the US and China. Currently, both countries have little trust in each other on a wide range of issues, and the potential power of quantum computing can bring significant hegemonic advantages to the US. However, quantum information technology is fair game for China and the US, and the US does not have much of a first-mover advantage. At least for now, Chinese companies have not been left too far behind. Objectively, China's biggest problem comes from the ecological psychology within the country. China needs to establish a system of mutual trust and full cooperation internally, rather than having so-called full-stack quantum computing companies constantly competing for upstream suppliers' market share, which is a waste of resources and misaligned goals.

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光子盒
QUANTUMCHINA

GUANGZIHE was founded in February 2020, as a quantum industry service platform, GUANGZIHE is dedicated to becoming the most trustworthy service institution in the Chinese quantum technology industry by pushing the frontier of quantum technology news, popularizing quantum knowledge, interpreting quantum technology, publishing annual and special reports, etc.

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Date	Country/ Organization	Institution	Event
2022.05	France	PASQAL	PASQAL has launched its Cloud Services, which provide select clients with access to neutral atom quantum computers via OVHcloud's private cloud platform.
2022.05	Canada	D-Wave	D-Wave has launched the Advantage™ quantum computing machine, which boasts 5000 qubits and is accessible via the US-based Leap™ Quantum Cloud Service.
2022.06	US	Amazon Braket	Amazon Braket has announced its support for Qiskit, a quantum software development toolkit by IBM, and programs written on Qiskit can run on any gate-based quantum device on Braket.
2022.06	Japan	Fixstars Amplify	Fixstars Amplify announced an update to its cloud service to support IBM Quantumt for compute optimization problems
2022.08	US	IonQ	IonQ launched IonQ Aria on the Azure Quantum platform, the second IonQ system to join the Azure Quantum platform after the launch of IonQ Harmony in late 2019
2022.09	US	Rigetti Computing	Rigetti Computing has launched its Rigetti QCS™ on the Azure Quantum platform in a public preview. Azure Quantum users can access Rigetti's Aspen-M-2, an 80-qubit, and Aspen-11, a 40-qubit superconducting quantum processor on-demand, to develop and run quantum applications.
2022.11	Canada	Agnostiq	Agnostiq has released a new version of Covalent, an open-source workflow orchestration platform that supports AWS and accelerates the growth of high-performance computing in the cloud.
2022.12	UK	Arqit	Arqit has deployed its Quantum Cloud platform on Amazon Web Services products.

Date	Country/ Organization	Categories	Event
2022.01	France	classical and quantum hybrid computing platform	Invest EUR 170 million to launch the National Quantum Computing Platform to create a hybrid computing platform that interconnects classic systems and quantum computing
2022.01	Switzerland	quantum technology at room temperature	WSS donated 15 million Swiss francs to fund the CarboQuant project, which researches new quantum technologies operating at room temperature
2022.02	Germany	optical quantum processor	BMBF contributed 16 million euros to the PhotonQ project for the development of optical quantum processors
2022.02	EU	quantum chips	Announced the €43 billion chip bill to support the development of quantum chips
2022.02	US	quantum computing automation	Q-CTRL and Sandia National Laboratory received a DoE $230,000 grant for quantum computing machine automation
2022.02	Israel	quantum computing	$62 million was allocated to build the country's first quantum computing machine
2022.02	UK	quantum computing practical interface	The University of Glasgow has received £3 million from the UK Engineering and Physical Sciences Research Council (EPSRC) to develop a practical interface to enhanced quantum computing
2022.03	US	quantum biology	Arizona State University received a three-year, $1 million grant from the Keck Foundation to explore fundamental quantum effects in biological systems
2022.03	US	Quantum software	DARPA provided Zapata Computing with a multimillion-dollar grant to create software tools to make hardware-specific resource estimates for quantum computing machines
2022.03	US	quantum computing	NYU received a $7.5 million grant from the DoD Multidisciplinary University Research Initiative (MURI) to enhance quantum computing
2022.04	US	photonic quantum computing	The $25 million grant supports chip foundry GlobalFoundries and quantum computing company PsiQuantum to develop next-generation photonic quantum computing machines
2022.04	Qatar	quantum computing	Grant $10 million to launch the National Quantum Computing Program to fund the establishment of the Qatar Quantum Computing Center (QC2) to conduct innovative research in areas related to quantum computing, quantum cryptography, and quantum artificial intelligence (AI).
2022.04	US	quantum computing	UMass Boston and Western New England University received $1 million in state grants to support quantum computing
2022.04	Netherlands	quantum computing	Leiden University has received a €2 million grant from the Netherlands NWA to bring quantum computing machines out of the laboratory
2022.04	Germany	quantum computing	The German government approved the DESY Quantum Research Fund to develop diagnostic tools for verifying quantum components
2022.04	Netherlands	quantum computing	Members of the Delft quantum ecosystem received two R&D grants worth €550,000
2022.04	US	quantum computing	Georgia Tech received a $9.2 million grant to develop hybrid quantum-classical systems
2022.04	Japan	quantum computing	The strategy proposes to build the first domestically produced quantum computing machine by 2022, and the strategy should also propose a goal of 10 million quantum technology users by 2030
2022.05	Netherlands	quantum material	The Netherlands Research Council has provided €21.5 million for quantum materials research
2022.05	US	quantum workforce	The K12 Quantum Talent Development Program, run by George Mason University's Center for Quantum Science and Engineering, received $650,000 of the $3.5 trillion House appropriations bill
2022.05	Australia	quantum workforce	Australia Labor has pledged $4 million to support the development of quantum research talent
2022.05	US	quantum technology	NIST allocated $300,000 to support quantum technology
2022.06	US	quantum cloud platform	NSF provides supplemental funding to support the use of the quantum computing cloud platform
2022.06	Netherlands	superconducting quantum processors	QuantWare received a €7.5 million grant from the European Innovation Council for the rapid expansion of superconducting quantum processors

Date	Country/ Organization	Categories	Event
2022.06	US	quantum computing	The Georgia Tech quantum computing program received a $9.2 million grant from DARPA
2022.06	US	quantum computing	SEEQC received a $400,000 grant from the US Department of Energy to research and develop useful, energy-efficient quantum computing systems that provide cost-effectiveness and commercial scalability for problem-specific applications
2022.07	US	quantum computing	The US Army signed a $699 million high-performance computing procurement contract for operations, maintenance, and management services at the Defense Supercomputing Resource Center
2022.07	Israel	quantum computing	Invested $29 million to establish a Quantum Computing research and development center
2022.07	US	quantum workforce	Invest $3 million in a quantum science graduate training program
2022.07	US	quantum computing	The US Senate passed the $280 billion Chip Act, which in addition to subsidizing the semiconductor industry, a large amount of money will be used for research and development in cutting-edge technology fields such as quantum computing
2022.08	US	quantum education	The University of Wyoming topology quantum computing research received a $5 million grant from NSF
2022.08	US	quantum computing	UCLA received a $1.8 million grant to develop molecular qubits for quantum computing
2022.09	Netherlands	quantum technology	The Netherlands Recovery Plan will invest €270 million in quantum technology
2022.09	US	quantum material	DoE provides $12.6 million in funding for quantum materials research
2022.09	US	quantum computing	New York University at Stony Brook received a $400,000 grant from the US DoE to study the advantages of quantum computing
2022.10	US	dilution refrigerator	MoD grants to upgrade dilution chillers for quantum physics research
2022.10	US	quantum computing	AFRL placed a $22.5 million order to build utility-scale quantum computing
2022.10	Germany	quantum computing	Hamburg government invested 34.1 million euros in quantum computing
2022.10	Germany	quantum computing	Invest EUR 200 million to develop ion trap quantum computing
2022.12	Germany	quantum computing	DLR awarded two companies developing diamond quantum computing machines, SaxonQ and XeedQ, to contracts worth a total of €57 million
2022.12	US	quantum computing	DARPA has signed a $1.6 million contract with the University of Rochester for the Quum-Inspired Classical Computing (QuICC) project. QuICC is planned for five years with a total investment of $58 million
2022.12	Canada	quantum computing	BCKDF invested $800,000 to develop a quantum-accelerated supercomputer

<table>
<tr><th>Quantum Computing Cloud Platform</th><th>Developer</th><th>Initial Release Date</th><th>Hardware Technology</th><th>Qubit</th></tr>
<tr><td>Taiyuan Yihao</td><td>College of Computer Science and Technology, Zhejiang University</td><td>2022.07</td><td>Superconducting</td><td>26</td></tr>
<tr><td>Quantum Computing Cloud Platform</td><td>CAS Center for Excellence in Quantum Information and Quantum Physics, Alibaba Cloud</td><td>2017.10</td><td>Superconducting</td><td>12</td></tr>
<tr><td>Quafu Quantum Computing Cloud Platform</td><td>Beijing Academy of Quantum Information Sciences, CAS Institute of Physics,Tsinghua University</td><td>2022</td><td>Superconducting</td><td>10,18,50</td></tr>
<tr><td>Origin Quantum Cloud</td><td>Origin Quantum</td><td>2017.10</td><td>Superconducting</td><td>6</td></tr>
<tr><td>Huawei HiQ</td><td>Huawei</td><td>2018.10</td><td>Simulator</td><td>-</td></tr>
<tr><td rowspan="2">Baidu Liang Yifu</td><td rowspan="2">Baidu</td><td rowspan="2">2020.09</td><td>Superconducting</td><td>10</td></tr>
<tr><td>Ion Trap</td><td>1</td></tr>
<tr><td rowspan="2">SpinQ Quantum Computing Cloud Platform</td><td rowspan="2">SpinQ</td><td rowspan="2">2020.10</td><td>Nuclear Magnetic Resonance</td><td>2,4,6</td></tr>
<tr><td>Superconducting</td><td>8</td></tr>
<tr><td rowspan="2">Huguang Quantum Cloud Platform</td><td rowspan="2">ARCLIGHT</td><td rowspan="2">2022.9</td><td>Superconducting</td><td>12</td></tr>
<tr><td>Ion Trap</td><td>11</td></tr>
<tr><td>IBM Q Experience</td><td>IBM</td><td>2016.05</td><td>Superconducting</td><td>127,65,27,16,7,5,</td></tr>
<tr><td rowspan="3">Cirq</td><td rowspan="3">Google</td><td rowspan="3">2018.07</td><td>Superconducting</td><td>53,80,40</td></tr>
<tr><td>Ion Trap</td><td>20(AQT),</td></tr>
<tr><td>Neutral Atom</td><td>100+</td></tr>
<tr><td>QCS</td><td>Rigetti</td><td>2018.09</td><td>Superconducting</td><td>40,80</td></tr>
<tr><td rowspan="4">Braket</td><td rowspan="4">Amazon</td><td rowspan="4">2019.12</td><td>Superconducting</td><td>40,80,8</td></tr>
<tr><td>Ion Trap</td><td>11</td></tr>
<tr><td>Photonic Quantum</td><td>216</td></tr>
<tr><td>Quantum Annealing</td><td>2000+,5000+</td></tr>
<tr><td rowspan="3">Azure Quantum</td><td rowspan="3">Microsoft</td><td rowspan="3">2019.11</td><td>Ion Trap</td><td>20,12,11</td></tr>
<tr><td>Superconducting</td><td>40,80,8</td></tr>
<tr><td>Neutral Atom</td><td>100+</td></tr>
<tr><td>D-Wave Leap</td><td>D-Wave</td><td>2018.10</td><td>Quantum Annealing</td><td>5000+,2000+</td></tr>
<tr><td rowspan="4">Strangeworks QC</td><td rowspan="4">Strangeworks</td><td rowspan="4">2021.02</td><td>Superconducting</td><td>-</td></tr>
<tr><td>Ion Trap</td><td>-</td></tr>
<tr><td>Neutral Atom</td><td>-</td></tr>
<tr><td>Quantum Annealing</td><td>-</td></tr>
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Quantum Computing Cloud Platform	Developer	Initial Release Date	Hardware Technology	Qubit
Xanadu Cloud	Xanadu	2020.09	Photonic Quantum	216
			Photonic Quantum	8
Quantum Inspire	Qutech	2018.10	Silicon Spin	2
			Superconducting	5
Alpha	QM Ware	2022.01	-	-
SCCE	AQT	2020.04	Ion Trap	20
QSCOUT	Quantum - Sandia National Laboratories	2021.03	Ion Trap	3
Quantum Computing-as-a-Service	Oxford Quantum Circuits	2021.07	Superconducting	8
InQuanto	Quantinuum	2022.05	Ion Trap	12,20
Quandela Cloud	Quandela	2022.11	Photonic Quantum	5

Date	Party	Document	Main Contents
2022.04	U.S., Finland	Joint Statement of the United States of America and Finland on Cooperation in QIST	The United States and Finland have signed a joint declaration on cooperation in the field of quantum information technology, emphasizing the two countries' willingness to strengthen their collaboration in this area.
2022.04	U.S., Sweden	Joint Statement of the United States of America and Sweden on Cooperation in QIST	To enable both countries to leverage their respective advantages in QIST, establish global markets and supply chains, create scientific research communities, and cultivate the skills and potential talent of future generations.
2022.04	India, Finland	-	Facilitate the utilization of the respective strengths of both countries in QIST, establish a global market and supply chain, create a scientific research community, and cultivate skills and potential talent for future generations.
2022.04	India, U.S.	-	India and the United States have decided to advance their collaboration in emerging technologies such as communications, artificial intelligence, quantum science, semiconductor, and biotechnology. They are also urging private companies from both countries to jointly develop and manufacture defense equipment.
2022.06	U.S., Denmark	Joint Statement of the United States of America and Denmark on Cooperation in QIST	Drawing on the strengths of both nations in QIST, this collaborative statement will strengthen supply chains, develop industrial foundations, and cultivate the next generation of quantum talent.
2022.10	U.S., Switzerland	-	Switzerland is set to sign an agreement with the United States to facilitate closer collaboration in the field of quantum computing.
2022.12	France, U.S.	-	This cooperation declaration is built upon the agreement signed in Paris in October 2018 and the joint declaration on scientific cooperation in 2021, which clearly identifies quantum information science as an area of mutual recognition for continuing research cooperation.
2022.11	India, EU	-	On the basis of the established trade and technology committee, the two countries have signed cooperation agreements in areas such as climate modeling and quantum technology.
2022.11	Finland, India	-	The two countries will take the lead in exploring the complex fusion between quantum computing and supercomputing, and use it as a breakthrough to address future industrial solutions based on high-efficiency hardware.
2022.12	France, U.S., Germany	Joint Statement of the United States of America and France on Cooperation in QIST	To address the strategic autonomy challenge facing Europe in the field of quantum technology and lay the groundwork for future European quantum leadership.

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2022.01	China	Development Plan for Metrology (2021-2035)	The document proposes to establish by 2035 a national modern advanced measurement system with quantum metrology as its core, first-class scientific and technological level, in line with the needs of the times and the trend of international development.
2022.02	European Union	European Chip Act	The announcement of a 43 billion euro chip package to support the development of quantum chips. The package states that the EU plans to invest over 43 billion euros (approximately 49 billion US dollars) by 2030.
2022.02	United Kingdom	Spring Declaration of 2022	Supporting artificial intelligence, quantum computing, and robotics technology.
2022.04	Australia	National Research Infrastructure (NRI) Roadmap for 2021	Prioritizing quantum research as a key focus area in the new roadmap.
2022.04	United States	Quantum Computing Network Security Prevention Act	To ensure that the federal government can protect federal IT systems and assets from future cyber attacks by quantum computers.
2022.04	United States	Executive Order Strengthening the National Quantum Initiative Advisory Committee; National Security Memorandum on Promoting United States Leadership in Quantum Computing while Reducing Risks to Vulnerable Cryptographic Systems	President Biden has signed two executive orders to accelerate the development of quantum information science. The first order aims to strengthen the National Quantum Initiative Advisory Committee's executive order. The committee is an independent expert advisory body on government quantum information science and technology. This order places the advisory committee directly under the power of the White House, helping to ensure that the President and other key decision-makers can get the latest information. The second order aims to promote the development of American quantum information technology and establish a plan to address the risks posed by quantum computers to US cybersecurity.
2022.06	United Kingdom	SparQ Quantum Application Discovery Program	To help UK companies and researchers explore the early applications of quantum computing, accelerate innovation in the use of quantum computing in the UK. The program provides four key elements: access to quantum computers, technical support and application expertise, workshops and networking opportunities, and learning resources. The program aims to provide potential users with early practical experience in using quantum hardware and algorithms to address industry-related challenges.
2022.06	Germany	Quantum Systems Research Program	Their mission is to lead Germany into a leading position in the European fields of quantum computing and quantum sensing over the next decade, and to increase Germany's competitiveness in the field of quantum systems.
2022.07	United States	Chip Act	In addition to providing subsidies to the semiconductor industry, the bill will also allocate a large sum of funds to research and development in cutting-edge fields such as quantum computing. This includes injecting new funding into energy department national laboratories such as Brookhaven National Laboratory, which will drive research and development in key technological fields such as quantum computing and artificial intelligence.
2022.08	United States	Chip and Science Act	In the second part of the bill, entitled "Research and Innovation," there are four initiatives that will benefit the field of quantum technology. The first involves conducting research into quantum network equipment and methods, and developing a "quantum network infrastructure" plan to support the supply chain for quantum network technology, which will receive $500 million in funding. The second initiative, the "Quantum User Expansion for Science and Technology" program, will provide US-based researchers with access to American quantum computing resources, with funding set at $165 million. The final initiative is the "Next-Generation Quantum Leaders Pilot Program," which aims to educate the next generation of students and teachers on the fundamental principles of quantum mechanics, and is allocated $32 million in funding.

Date	Government	Document	Main Contents
2022.05	United States	National Security Memorandum on Promoting United States Leadership in Quantum Computing while Reducing Risks to Vulnerable Cryptographic Systems	The memorandum provides an overview of the current government's policies and measures related to quantum computing. It outlines the key steps necessary to maintain the nation's competitive edge in quantum information science (QIS), while also mitigating the risks posed by quantum computing to national networks, the economy, and national security.
2022.07	United States	Quantum Computing Network Security Prevention Act	The passage of the bill coincides with the US federal government's increasing efforts to actively support and address the cybersecurity threats posed by quantum computing. Experts in the field of quantum technology anticipate that these threats will become an increasingly frequent risk factor for governments and businesses around the world in the coming years.
2022.12	United States	Quantum Computing Network Security Prevention Act	The formal enactment of this bill encourages federal government agencies to adopt encryption technologies that are immune to the effects of quantum computing. The bill was passed by the House of Representatives in July of this year, and was passed by the Senate on December 9th, thus becoming law.

5250 Fairwind Dr. Mississauga, Ontario, L5R 3H4, Canada

(+1) 929 530 5901

infer@icvtank.com