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2024

Global Quantum Precision Measurement Industry Development Prospect

February 2024

Quantum Information Annual Report Series

Foreward

As the second year of publishing the Quantum Precision Measurement industry report, the 2024 edition of the report covers technologies and products such as Quantum Clocks, Quantum Magnetometers, Quantum Gravimeters, and Quantum Radar, etc. As we have already covered these major technologies in the 2023 edition of the Quantum Precision Measurement report, in this report, we are focusing on the major advances in Quantum Precision Measurement technologies and their impacts on the various sectors in the past year.

Our aim in producing industry research reports is to provide policy makers, research developers, business people and others with key informational references, as well as our viewpoints, to support them in making informed decisions in this rapidly changing technological and business environment.

This report presents a multidimensional view of the current state of the quantum precision measurement field, as well as future trends, through in-depth technology assessment and market analysis. We systematically introduce the specific progress of different quantum measurement technologies or products and their upstream fields in 2023 from the perspective of the whole system, and give corresponding forecasts of future development directions for their different progress. At the same time, this report gives specific application scenarios for the current as well as future development of different quantum precision measurement devices based on the perspective of industrial development. The wide application in the downstream market not only signifies the great utility of quantum for precision measurement and metrology science, but also heralds new business opportunities and challenges for suppliers in the industry.

Foreward

With the advancement of technology and the development of the industry, in this report, we focus more on the commercialization of quantum precision measurement technology, including market potential, outlook on industry applications, and major challenges and opportunities.

We believe that the development of quantum precision measurement technology will not only be a scientific breakthrough, but also an important force that will gradually change the way of life in our society. We look forward to witnessing with all readers the changes and achievements of quantum technology in the coming years, and thank you for your attention and support to our research work.

ICV Frontier Technology Consulting Director, Senior Vice President

Jude Green

Declaration

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

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

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

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AOSense	国盛量子 CHINAPROSP QUANTUM	mugaltech
中科酷原 CAS COLD ATOM	Genetesis	iXblue
M SQUARED	MICROCHIP Microsemi Product Portfolio	OSCILLOQUARTZ An ADVA Company
QUSPIN	Twinleaf	Infleqtion

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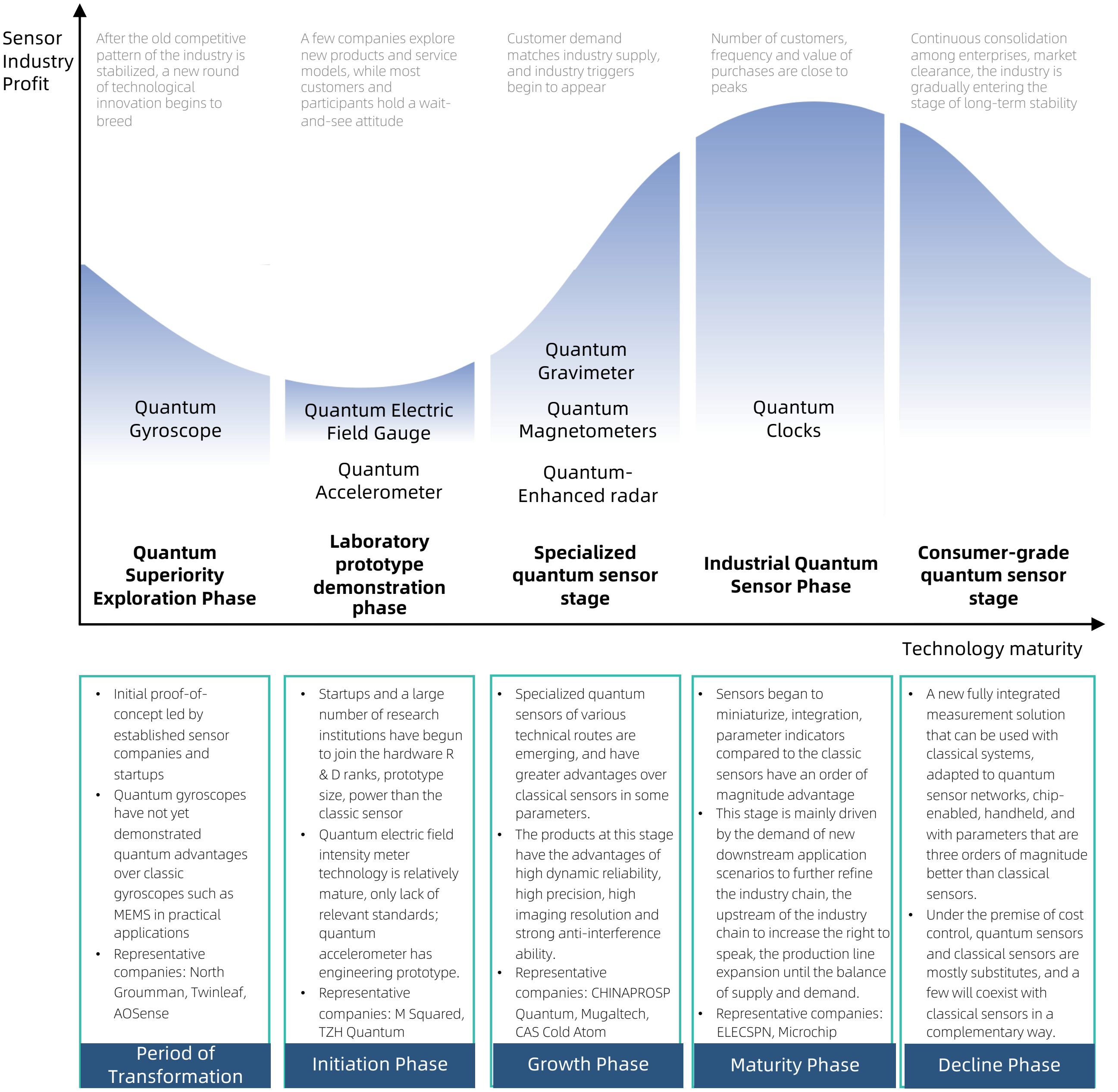
Overview of Industrial Development in 2023

01 Development Cycle in the Industry

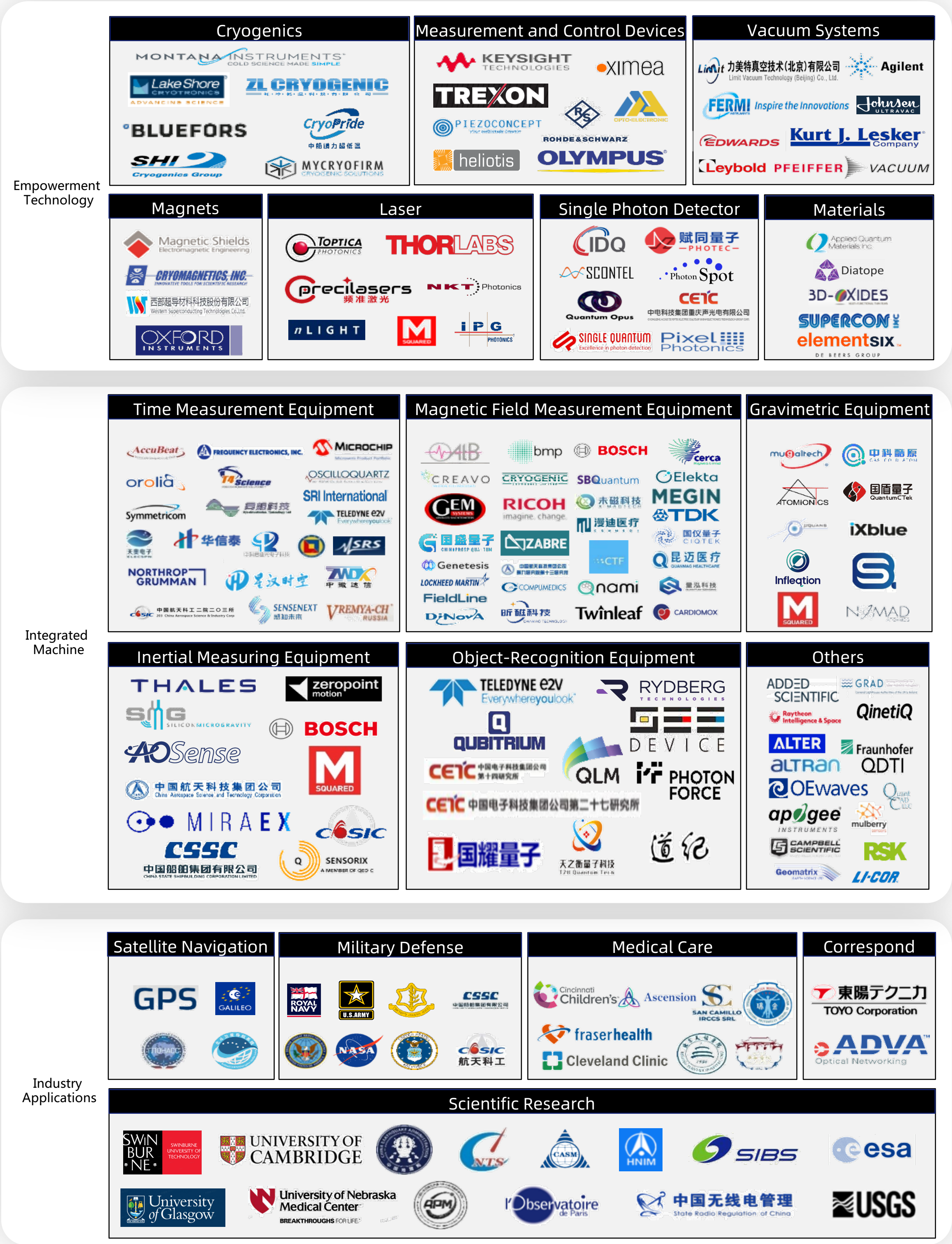
In 2023, the field of quantum precision measurement shows diversity and decentralization. The development routes of various fields are diversified, from quantum gyroscopes to quantum electric field intensity meters to quantum accelerometers, each at a different stage, reflecting the diversity of scientific progress and application needs. There are differences in the maturity of quantum sensors for different physical quantities, with quantum gyroscopes yet to show their advantages, and quantum electric field intensity meters relatively mature, with gaps reflecting different technical challenges and commercial applications.

Figure: Development cycle of the precision measurement industry in 2023



02 Industry Ecology Overview

Figure: Quantum Precision Measurement Industry Ecology Overview



03 Industry Application Market

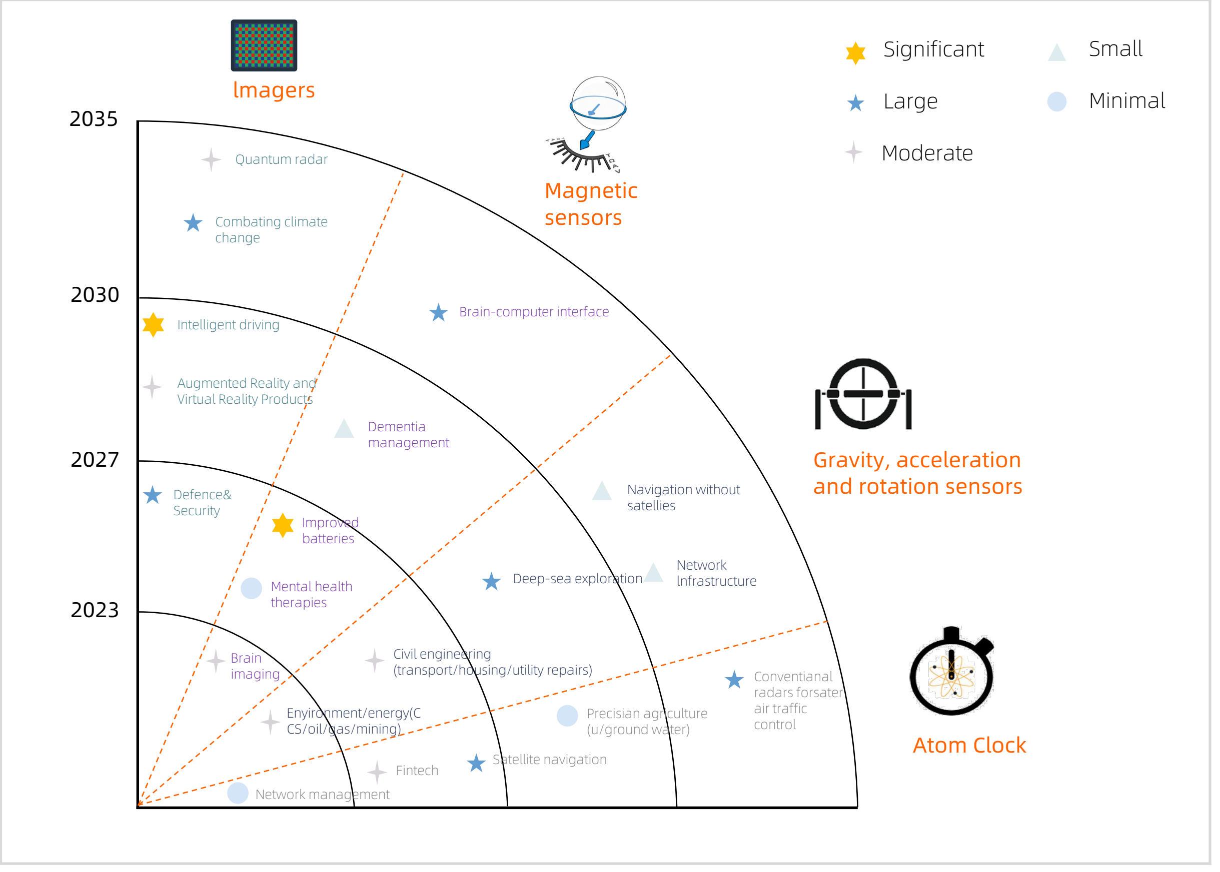
The downstream application market of quantum precision measurement technology in various fields shows a broad prospect. From 2023 to 2035, the demand for quantum precision measurement in different fields grows gradually, showing diversified application scenarios.

Firstly, for some low-market-scale applications, such as network time and frequency management and mental health treatment, although the market size is relatively small, the high accuracy and sensitivity of quantum precision measurement brings more accurate data and solutions to these fields, providing an opportunity for the gradual commercialization of the technology. Especially in areas such as Alzheimer's disease treatment and climate change fighting, the precise diagnosis and data collection capability of quantum precision measurement will become a key technology in the future, driving innovation and development in these areas.

Second, as the technology continues to mature, areas of large-scale commercialization will also gradually rise in the coming years. For example, the demand for high-precision measurements in the fields of air traffic control radar, satellite-less navigation, satellite navigation, etc. is gradually increasing, and quantum precision measurement technology will play a more important role in these fields. And in the field of deep sea exploration, battery improvement, intelligent driving, etc., the high sensitivity and high precision of quantum precision measurement will become a booster for technological breakthroughs, providing impetus for the continuous upgrading of the industry.

Finally, between 2023 and 2030, the application of quantum radar technology will also gradually expand. Quantum radar's high resolution and high sensitivity give it a unique advantage in areas such as defense and security, environmental/energy monitoring, and air traffic management radar. It is expected that with further development of the technology, quantum radar will become an important part of next-generation radar technology in the future.

Figure: Overview of Precision Measurement Industry Application Timeline and Market Size



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Integrated Quantum Hardware

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Integrated Quantum Hardware

01 Quantum Clock

Advances in quantum clock measurements in 2023

As a relatively mature quantum precision measurement product, atomic clocks offer highly accurate and stable time measurement capabilities. Currently, optical atomic clock technology is rapidly expanding its application areas, covering a wide range of industries such as railroad mobile communications, data centers, defense and scientific measurements. This trend shows that optical atomic clocks are not only excelling in scientific laboratories, but are also moving towards practical applications, providing accurate time measurement and synchronization services for different industries.

Quantum Clock

Rubidium/Cesium/Hydrogen Clocks

- Microchip Releases Model 5071B Cesium Atomic Clock That Provides 100 ns Accurate Time Maintenance for Months After Loss of Satellite Signal;
- Adtran Oscilloquartz introduces a new synchronization solution using satellite time and positioning technology that ensures restoration of functionality even when satellite signals are lost.

CPT Atom Clock

- China's first chip-scale atomic clock production line was inaugurated in HXT with an annual production capacity of up to 30,000 units.

Cold Atomic Clock

- Infleqtion's atomic clock, Tiqker, has won the Military + Aerospace Electronics Innovator Platinum Award. The product is an atomic frequency reference with the potential for a wide range of applications in several fields, including smart grids, financial time-stamping, scientific testing, and more.

Optical Lattice Clock

- A research team from the University of Science and Technology of China (USTC) has successfully developed a strontium-atom optical lattice clock with 10,000-second stability and uncertainty better than 5×10^{-18} (equivalent to billions of years with an error of no more than one second). This achievement lays an important technical foundation for the future realization of long-distance optical clock comparison, the establishment of ultra-high-precision optical frequency scale benchmarks and global optical clock networks.

In the development of atomic clocks, continuous performance improvement is one of the key trends. For optical atomic clocks, continuous improvement of frequency stability and longer hold time are the main directions of research and development. This performance enhancement aims to meet the demand for higher precision and longer synchronization in different application areas, providing users with more reliable time references.

The reliability and security of atomic clock technology in the face of GNSS vulnerabilities and cyber-attacks have become the focus of industry attention. As reliance on the Global Navigation Satellite System (GNSS) increases, concerns about interference and attacks on it are on the rise. As a result, developments in atomic clock technology have not only worked to provide better performance, but have also emphasized securing the system in the face of potential threats. This has prompted researchers and companies to invest more in technology upgrades and innovations to address the increasingly complex cybersecurity challenges.

Overview of technical routes

Rubidium and cesium clocks are currently the most mature and widely used atomic clock technology, mainly used in satellite navigation, military, communications and other fields, with a large market size, but because of its frequency stability and accuracy are limited by physical limits, it is difficult to meet the future demand for higher timekeeping. Optical clock is currently the most advanced and highest precision atomic clock technology, mainly used in scientific research, national timing, quantum information and other fields, the market size is smaller, but because of its frequency stability and accuracy is much higher than rubidium, cesium atomic clock, is expected to become the basis of the future redefinition of the second.

At present, the development direction of the atomic clock market is mainly affected by a number of factors, among which technological innovation is the main driving force to promote the development of the market. In terms of technological innovation, atomic clock technology has continuously made breakthroughs, reflected in the following key aspects.

First of all, improving the frequency stability and accuracy of atomic clocks is a core goal of technological innovation. By constantly breaking through the physical limit, atomic clocks can meet the demand for higher precision timekeeping, so that they can be more widely used in various fields.

Secondly, reducing the volume, power consumption and cost of atomic clocks is another important direction of technological innovation. Realizing the miniaturization, integration and commercialization of atomic clocks will expand their application areas, making them more suitable for diversified scenarios such as portable and handheld devices, and at the same time increasing the market scale.

Figure: Quantum Clock Industrialization Development Status

Category	Laboratory Stability*	Technical Advantages and Disadvantages	Examples of Representative	Product Parameters	
Rubidium Clock	9×10^{-14} (Mei Ganghua, Institute of Precision Measurement, Chinese Academy of Sciences, 2024)	Mature technology base; Relatively low frequency stability, large size	AccuBeat (Accurate Frequency & Time) Israel	Model: AR133-3 Stability: 5×10^{-11}	
Cesium Clock	7×10^{-15} (Xuan He, Peking University, 2021)	Mature technology base; Relatively low frequency stability, large size	Microchip USA	Model: 5071B Stability: 8.5×10^{-13}	
Hydrogen Clock	6.69×10^{-16} (Alexandr A. Belyaev, Vremya-CH, Russia, 2019)	Mature technology base; relatively low frequency stability, large size	T4Science (Precision Maser Solutions) Switzerland	Model: iMaser3000™ Stability: 2×10^{-16}	
Cold Atomic Clock	6.69×10^{-16} (Xinwen Wang, Shanghai Institute of Optical Precision Machinery, Chinese Academy of Sciences, 2019)	High frequency stability, reduced coherent detuning; Complex low-temperature environments	AOSense USA	Model: AOS-CAFS-1-X Stability: 2×10^{-14}	
Optical Lattice Clock	6.69×10^{-16} (Pan Jianwei, CSU, 2022)	Very high precision; Relatively complex and costly to build and maintain	RIKEN Japan	Model: Transportable Sr Optical Lattice Atomic Clock Stability: 5.5×10^{-18}	
CPT Atom Clock	2×10^{-13} (Zhang Shougang, National Timing Center, Chinese Academy of Sciences, 2021)	Miniaturization and low power consumption; Lower in terms of long-term accuracy	天奥电子 ELECSPN China	Model: XHTF1045 Stability: 3×10^{-11}	

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Note: * is the stability under laboratory conditions, see references for source papers.

At the same time, the development of new types of atomic clocks is also an important direction of technological innovation. This includes the research and development of chip-scale optical atomic clocks, molecular clocks, etc., and the exploration of new physical principles and technological pathways. These new types of atomic clocks are expected to provide brand new possibilities for the future development of atomic clocks and drive the market forward.

02 Quantum Magnetometer

Advances in Quantum Magnetometry in 2023

At present, the field of quantum magnetometer presents a diversified development status. different types of magnetometer technologies, such as SQUID, OPM, SERF, NV color centers, etc., have made remarkable progress in the fields of medicine, quantum navigation, and materials research.

Quantum Magnetometers

SQUID Magnetometer

- Somfit's SQUID magnetoencephalograph has been approved by the U.S. Food and Drug Administration and is now on the market in the U.S.;
- CSHMEDI released MANDI Shimei's high sensitivity magnetoencephalograph with a sensitivity of 5 fT/Hz½, combined with high stability and high dynamic range; and through the development of an AI intelligent analysis model, the diagnostic accuracy of magnetoencephalography analysis has reached 87.8 percent.

OPM Magnetometer

- Genetesis Introduces CardioFlux Noninvasive Cardiac Magnetometer to Identify Myocardial Ischemia in the Heart, Important for Noninvasive Diagnosis of Coronary Microvascular Disease

SERF Magnetometer

- CHINMAG Technology for myocardial ischemia diagnostic aids has been approved by the Medical Device Registry and is now officially available on the market. The sensitivity of the device can reach up to one ten millionth of the earth's magnetic field strength, and it can sense the weak magnetic field signals generated by myocardial electrical activity without contact, which can be used to detect the weak changes of myocardial electrical activity in both physiological and pathological states.

NV Center Magnetometer

- The CSU and National Synchrotron Radiation Laboratory team used NV color centers as quantum sensors to probe the dynamic connectivity of neuronal synapses;
- The Boston College team used the NV Chromocentric Magnetic Field Sensor to image the local magnetic field generated by photocurrents and to reconstruct the complete flow of photocurrents;
- Bosch Quantum Sensing (NV color-centered magnetometers and quantum gyroscopes) has partnered with Messe Stuttgart to provide a forum for exhibitors to present demonstrations and application examples, and the company is currently involved in eight quantum sensing projects.

In the future, quantum magnetometer technology will continue to evolve in a number of directions to promote its widespread use in various fields. First, the sensitivity and resolution of magnetometers will be the focus of attention to meet specific application requirements. This includes more precise detection of weak magnetic field signals, especially in physiological and pathological states, to provide more accurate tools for scientific research and medical diagnosis. On the other hand, multimodal integration will be one of the trends for future development. Quantum magnetometers are likely to focus more on integrating different types of magnetometer technologies so that they can be adapted to a wider range of application scenarios. This integration is expected to provide more comprehensive information, offering researchers and physicians more perspectives and further enriching the way to understand changes in magnetic fields.

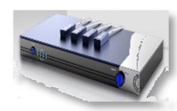
As the technology matures, portability and utility will be another key direction in the development of quantum magnetometers. Portable magnetometer devices will be easier to use in a wide range of applications such as medical care and navigation. Such development is expected to make quantum magnetometers a practical tool in real-world scenarios, supporting mobile diagnosis and real-time monitoring. Intelligent analytics and applications will also be used throughout the future. With the continuous development of artificial intelligence technology, quantum magnetometer devices will focus more on the development of intelligent analysis models. This trend will improve data processing efficiency and diagnostic accuracy, making magnetometers more practical in scientific research and medical practice.

Overview of technical routes

Technological diversity is a notable feature in the current quantum magnetometer market. Various technologies, including proton magnetometers, SQUID magnetometers, OPM magnetometers, SERF magnetometers, NV color-centered magnetometers, and others, offer unique advantages in different application scenarios. This has resulted in a technologically diverse and wide range of choices in the market.

The applications are broad and diverse, including military defense, scientific research, medicine, industrial inspection, navigation, and other fields. Companies are involved in diverse fields such as military defense, biomedicine, geophysical exploration, and navigation systems, reflecting the importance and adaptability of quantum magnetometers in different fields.

Figure: Quantum Magnetometer Industrialization Development Status

Category	Laboratory Sensitivity*	Technical Advantages and Disadvantages	Examples of Representative	Product Parameters	
SQUID	3×10^{-3} pT/√Hz (Antonio Vettoliere, Institute of Applied Science and Intelligent Systems, Italy, 2023)	Higher temperature magnetic field range, higher sensitivity; Requires cryogenic refrigeration, larger size	Quantum Design NORTH AMERICA USA	Model：MPMS3 Sensitivity：10^{-2} pT/√Hz Dynamic Range：1×10^{-5} nT~ 8×10^{-5} nT	
OPM	1×10^{-2} pT/√Hz (Orang Alem, University of Colorado, USA 2023)	No zero drift, fast response and high accuracy; Subject to environmental influences such as light intensity and air pressure	QUSPIN USA	Model：QTFM Gen-2 Sensitivity：3 pT/√Hz Dynamic Range：1000 nT~150,000 nT	
SERF	8.9×10^{-5} pT/√Hz Academician Fang Jiancheng, Beihang; Academician Chu Junhao, East China Normal, 2020)	Extremely sensitive and easy to miniaturize; Requires high temperature and low magnetic field conditions	未磁科技 X-MAGTECH China	Model：SERF Magnetometer Sensitivity：10^{-2} pT/√Hz Dynamic Range：±5nT	
NV Center	8.9 pT/√Hz (Du Jiangfeng's team, CSU, Zhejiang University 2022)	High frequency stability, reduced coherent detuning; Complex low-temperature environments	国盛量子 GUOSHENG QUANTUM China	Model：Quantum Magnetometers Sensitivity：4.2pT/√Hz Dynamic Range：10nT ~ 50mT	

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Due to the differentiated needs for accuracy, stability, weight, and price in different application scenarios, the quantum magnetometer market will be driven to further diversify in the future, gradually replacing the classical magnetometers, and to meet the needs of more levels of users.

Future developments will focus on technological innovations to improve the sensitivity and resolution of magnetometers and increase multimodal integration capabilities to meet a wider range of applications. Portability and practicality will be the future trend, and magnetometer devices will be more portable to facilitate real-time monitoring and mobile diagnosis in medical and navigation fields.

With the continuous development of artificial intelligence technology, future magnetometer devices will pay more attention to the development of intelligent analysis models to improve data processing efficiency and diagnostic accuracy. The introduction of new materials, such as silicon carbide, will improve the performance of magnetometers, thereby expanding applications in the field of quantum sensing. Medical applications will see deeper development, and quantum magnetometers are expected to make more breakthroughs in neuroscience, cardiovascular diseases and other fields.

It is expected that SERF magnetometers and NV color-centered magnetometers will gradually gain more market share and gradually replace SQUID magnetometers as the mainstream technology route. The magnetometer market will continue to be segmented along each technology route to meet the needs of different application scenarios, resulting in more specialized and differentiated products and solutions. This diversified market segmentation will promote the quantum magnetometer technology to penetrate into various industries in a more comprehensive and in-depth manner.

03 Quantum Gravimeter

Advances in Quantum Gravimeter 2023

Quantum gravimeters and quantum gravity gradiometers show a wide range of development prospects in both technological innovation and application fields, and are expected to bring more possibilities for scientific research and practical applications. With the continuous development of cold atom interference technology, quantum gravimeter has made remarkable progress in the field of precision measurement.

Quantum Gravimeter

Quantum Absolute Gravity Meter

- Q-CTRL demonstrates the latest prototype of the Quantum Gravity Instrument. The company establishes an entirely new way of observing the Earth through gravity and magnetism, utilizing small, low-cost satellites to develop a persistent near-Earth observation capability. The company has received support from the CRC-P program and will deliver future prototypes for use in the air and space.
- The "High Precision Quantum Absolute Gravity Measurement System" of Mugaltech was purchased by the Zhejiang Institute of Metrology, marking that the company's gravity measurement equipment is ready for use in metrology systems.
- CAS Cold Atom participated in the 11th International Comparison of Absolute Gravity Instruments ICAG 2023 held in the U.S. The company's quantum gravity instrument WAG-H5-2 has reached the international advanced level in terms of volume, weight, power consumption, gravity measurement accuracy and other indicators.

Quantum Gravity Gradiometer

- UK start-up Delta g has received an innovation grant of around £500,000 from Innovate UK to accelerate commercial product delivery and begin development of a quantum gravity gradiometer platform. It can create "underground Google maps" of "complex underground and unseen locations" and has already produced the world's first field-proven quantum sensor for gravity gradient measurement.
- Delta-g, in conjunction with the University of Birmingham, has successfully tested gravity gradient measurements on a ship in the North Sea. In the future, the technology could provide new capabilities for mapping the ocean and resilient long-term navigation.

As for quantum gravity instruments, with the advancement of technology, quantum gravity instruments continue to improve the precision and resolution of their measurements. Through cold atom interference technology, the instrument is able to realize high signal-to-noise ratio signal detection and effectively solve key problems such as gradient signal extraction, making the static measurement sensitivity close to the quantum projection noise limit. And with the further maturation of the technology, the quantum gravimeter is developing towards miniaturization and mobility. This makes quantum gravimeters more flexible in different scenarios and provides a wider range of possibilities for various applications.

Gravity gradiometers usually consist of two gravimeters with the aim of eliminating instrument drift. However, quantum gravimeters are already significant in improving accuracy, and combining two high-precision absolute gravimeters into a gravity gradiometer may increase the cost without demonstrating a significant metric advantage. Therefore, future trends may require a balance between system optimization and cost-effectiveness.

Currently, the quantum gravity gradiometry technique has been shown to be superior for urban subsurface space detection. Through the simulation and actual measurement of quantum gravity gradient data, it has shown certain advantages especially in the identification of shallow anomaly boundaries. Therefore, the cold atom-based interferometric gravity gradiometer is expected to be more widely used in urban underground space detection.

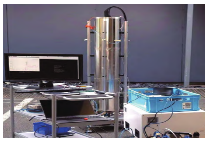
Overview of technical routes

With the further maturation of the technology, quantum gravity gauges are developing in the direction of miniaturization and mobility, providing a wider range of possibilities for various applications. The development of high-precision dynamic cold atom gravity gradiometers is still facing a series of technical difficulties. Improving the scale factor through large momentum transfer techniques such as Bragg diffraction and Bloch oscillation, and solving the problem of transverse atomic jitter by using light-guided interferometry are technical challenges that need to be overcome continuously in order to achieve a higher level of performance.

To realize more compact, low-power, high-precision and stable quantum gravity sensors through micro- and nanofabrication and integrated circuit technologies. In response to the challenges of external-field dynamic measurement technology, future efforts will be devoted to solving the performance problems of atomic interferometers in high dynamic ranges in order to increase the bandwidth and extend the dynamic measurement range. In terms of systematic integration scheme and process exploration, the future will further improve the systematic integration scheme and explore the innovation of micro-nano process in order to realize a more compact and stable convenient high-performance laser system.

In terms of technology level, we will continue to improve the research level in spin noise mechanism, magnetic shielding technology, long relaxation time atomic gas chamber preparation technology, atomic polarization and stability control technology in the future. At the same time, basic research will be strengthened in the areas of micro-small high-performance atomic gas chamber preparation, micro-small magnetic shielding preparation, and high-performance semiconductor laser development.

Figure: Current Status of Industrialization of Quantum Gravimeter

Category	Laboratory Sensitivity*	Technical Advantages and Disadvantages	Examples of Representative	Product Parameters	Product Sample Image
Quantum Absolute Gravity Meter	Sensitivity：4.2 μGal/√Hz Stability：3μGal （HUST, 2022）	High accuracy, no drift, long-term continuous operation, suitable for dynamic scenarios; Accuracy, and repeatability have no advantage over classic*	mugaltech China	Model：MGAG-LH Sensitivity：surpass 25μGal/√Hz Long-term stability*：≤1 uGal Accuracy: 5-10μGal	
			μQUANS iXblue France*	Model：Absolute Quantum Gravimeter Sensitivity：50μGal/√Hz Long-term stability：2μGal Accuracy: ≤10 uGal	
			中科酷原 CAS COLD ATOM China	Model：WAG-H5-2 Sensitivity：＜15μGal/√Hz Long-term stability：<1μGal Accuracy: <10 uGal	
Quantum Gravity Gradient Meter	Sensitivity：28E /√Hz Resolution 7E （Stanford University, 2015）	High accuracy, no bias, Low drift, self-calibrating; Expensive, unable to measure full tensor	iXblue France	Model： Prototype quantum gravity gradiometer Gravity gradient resolution：0.15E Sensitivity：50E /√Hz	
			中科酷原 CAS COLD ATOM China	Model： WAGG-H5-1 Gravity gradient resolution： 3.3E Sensitivity： 350E/VHz	

Note: * Denotes sensitivity under laboratory conditions, source is in the reference; Muquans was acquired by iXblue in May 2021;
Due to the complexity of cold atom technology, short development time, and diverse solutions, the overall accuracy and repeatability are not as good as classical instruments such as FG5X. FG5X is a leading instrument among classical instruments; 1E= 10^{-9} s^{-2}

It is expected that SERF magnetometers and NV color-centered magnetometers will gradually gain more market share and gradually replace SQUID magnetometers as the mainstream technology route. The magnetometer market will continue to be segmented along each technology route to meet the needs of different application scenarios, resulting in more specialized and differentiated products and solutions. This diversified market segmentation will promote the quantum magnetometer technology to penetrate into various industries in a more comprehensive and in-depth manner.

04 Quantum Accelerometer & Gyroscope

Advances in Quantum Inertial Measurements in 2023

In 2023, the field of quantum precision measurement made significant progress in the development of quantum accelerometers and quantum gyroscopes. Infleqtion introduced the world's first software-configurable, high-performance quantum accelerometers designed for localization, navigation, and timing applications in high-acceleration environments. Meanwhile, nuclear magnetic resonance gyroscopes improved bias stability through self-calibration methods, the diamond nano-cone structure of NV color-centered gyroscopes promises to influence micro- and nano-optical designs, and SERF gyroscopes improved long-term stability by tuning the pump power density. Three-axis accelerometry has become a key direction in the development of cold-atom interferometric accelerometers, and improving the overall system performance has become a research priority.

Quantum Accelerometer & Gyroscope

Cold Atom Interference Accelerometer

- Infleqtion demonstrated the world's first software-configurable, quantum-enabled, high-performance accelerometer by combining machine learning with quantum sensing. Designed for positioning, navigation and timing applications, it operates at accelerations tens of times Earth's gravity

Nuclear Magnetic Resonance Gyroscope

- A self-calibration method was proposed and implemented at the Institute of Systems Engineering, Chinese Academy of Engineering Physics (CAEP) to compensate for the NMR phase drift during Rb-PM measurements. By self-calibrating Rb-PM, it is demonstrated that the bias stability of NMRG is significantly improved

Diamond NV-Centered Gyroscope

- Xi'an Jiaotong University team obtains diamond nano-cone structure by thermal annealing method, which could positively affect the design and fabrication of future NV-center-based micro-nano optics such as NV color-centered gyroscopes

SERF Gyroscope

- The BUAA team found that the main source of noise in SERF gyroscopes is Markov noise introduced due to the slow convergence rate of the spin-coupled ensemble, which affects their long-term stability. The team varied the correlation time by adjusting the pump power density to suppress the Markov noise

Atomic Interference Gyroscope

- The BUAA team found that the main source of noise in SERF gyroscopes is Markov noise introduced due to the slow convergence rate of the spin-coupled ensemble, which affects their long-term stability. The team varied the correlation time by adjusting the pump power density to suppress the Markov noise

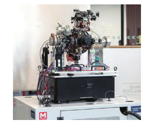
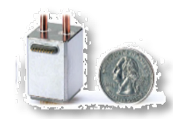
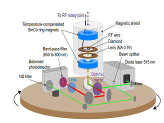
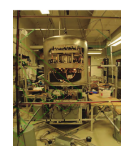
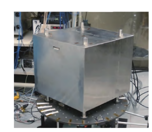
Quantum accelerometers and quantum gyroscopes have demonstrated high accuracy and stability in practical applications, but challenges remain in areas such as bandwidth and dynamic range. Regarding the assessment of technology routes, different research institutes and countries have made certain breakthroughs in their respective areas of specialization, but overall, there are some challenges to be overcome. For cold-atom interferometric accelerometers, solving the "dead time" problem and improving measurement availability are important development directions. For quantum gyroscopes, three-axis acceleration measurement, engineering applications and improving overall system performance are key tasks for the future.

With international cooperation and national support, the field of quantum precision measurement is expected to further promote innovation in quantum accelerometer and quantum gyroscope technologies. Future trends include improved performance, miniaturization, and cost reduction to better meet the needs of navigation, timing, national defense, and other fields. Taken together, quantum precision measurement technology will continue to play an important role in practical applications, bringing new breakthroughs in the fields of navigation and high-precision measurement.

Overview of technical routes

In recent years, with the rapid development of quantum precision measurement technology, quantum inertial sensors represented by atomic gyroscopes and atomic accelerometers can provide absolute measurements of angular velocity and acceleration with higher sensitivity and long-term stability. By replacing the traditional inertial sensors, the positioning accuracy of INS can be guaranteed for a long period of time without frequent recalibration. In addition, when navigating over long distances, a composite inertial guidance scheme for gravity-field-matched navigation can be realized by using high-precision atomic gravimeters or atomic gravity gradiometers mounted on carriers, limiting the accumulation of INS errors over time and prolonging the system's recalibration cycle.

Figure: Quantum Accelerometer & Gyroscope Industrialization Development Status

Category	Laboratory Sensitivity*	Technical Advantages and Disadvantages	Examples of Representative	Product Parameters	Product Sample Image
Cold Atom Interference Accelerometer	10^{-8} g	High sensitivity, good stability, strong anti-interference ability; Large volume, high power consumption, high cost	M SQUARED UK	Model：Prototype Accuracy: 10-8g	
Nuclear Magnetic Resonance Gyroscope	10^{-2} °/h	Early development, large dynamic range, has entered the chip product development stage; Requires an applied magnetic field	NORTHROP GRUMMAN USA	Model：Prototype zero-article stability：10-2 °/h	
Diamond NV-Centered Gyroscope	10^{3} °/h	Small size and fast start-up; Requires high quality diamond samples and precise nanofabrication	Berkeley UNIVERSITY OF CALIFORNIA USA	Model：Academic Research zero-article stability：0.4 °/s	
SERF Gyroscope	10^{-4} °/h	High precision and small bandwidth; Technically difficult, in the laboratory prototype stage	Twinleaf USA	Model：Laboratory prototype zero-article stability：10-3 °/h	
Atomic Interference Gyroscope	10^{-5} °/h	Extremely high precision, good stability, strong anti-interference ability; Large volume, high power consumption, high cost	AOSense USA	Model：Laboratory prototype zero-article stability：10-4 °/h	

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Note: * is the accuracy under theoretical conditions, see references for source papers.

Compared with classical inertial sensors, theoretically quantum gyroscopes and accelerometers have the advantages of higher precision, lower drift, and stronger anti-jamming ability. However, whether these advantages can be reflected in the actual engineering applications will be affected by many factors, including the design of the equipment, manufacturing process, the use of the environment, etc. At this stage, as most of the products are in the prototype stage, facing the challenges of large size, high cost, and lack of stability, the superiority has not yet been reflected.

At present, the research and development in the field of quantum inertia is led by universities, and the top teams in Europe and the United States are Stanford, Princeton, Paris Observatory, Sandia National Laboratories, etc. The Chinese teams, such as Beihang University, Southeast University, and Precision Measurement Institute of the Chinese Academy of Sciences are also advancing their research, but at present, the overall performance index of the products is about 2-3 orders of magnitude lower than that of the international advanced level. Among the various types of products, the nuclear magnetic resonance gyroscope is the most expected product to be popularized and applied in the short term, and the cold atom interferometric accelerometers and gyroscopes show extremely high precision, have great application prospects, and may become the mainstream technology in the field of high-precision inertial navigation in the future.

05 Quantum Radar

Advances in Quantum Radar in 2023

Quantum radar can be classified into three main categories based on the types of transmission and reception: interferometric quantum radar, quantum-enhanced radar, and quantum illumination radar. Among them, quantum-enhanced radar is advancing most rapidly in industrialization and has been applied in military and environmental protection fields. This approach significantly improves radar accuracy and sensitivity by transmitting classical signals and receiving quantum signals. Depending on the type of signal transmission (laser or microwave), the receiving end can be further divided into two categories: single-photon detectors and atomic antennas.

The quantum-enhanced radar based on single-photon detectors utilizes the high sensitivity and quantum properties of single-photon detectors to enhance radar system performance. This technology's advantage lies in its extremely high sensitivity to weak signals, enabling high-resolution detection of distant targets. By combining advanced technologies such as deep learning, single-photon detectors can also improve the adaptability of radar systems in complex environments, making them more robust against noise and interference.

In contrast, quantum-enhanced radar based on atomic antennas focuses on detecting signals in the microwave frequency range. This technology utilizes the sensitivity of atomic antennas to microwave signals, achieving high-sensitivity detection of microwave signals through quantum control and readout. Due to the widespread application of microwave frequencies in communication, radar, and remote sensing, quantum-enhanced radar based on atomic antennas has broad potential applications in these fields. The uniqueness of this technology lies in its high resolution and sensitivity to microwave signals, making it potentially important in areas such as electronic warfare, communication systems, and astronomical observations.

Quantum Radar

Quantum-Enhanced Radar Based on SPD

- QCI supports NASA's climate change monitoring with a quantum sensing solution that uses radar systems to remotely measure the physical properties of different types of snow and calculate how much water can be released when the snow melts.
- QLM's novel quantum gas laser radar has been validated as industry-leading in testing at METEC. This technology has highly precise capabilities for detecting, locating, and quantifying natural gas leaks, making it the gold standard in continuous methane monitoring technology.
- QI Solutions has launched a quantum photon vibration meter for remote vibration detection, sensing, and inspection. This device has made significant advancements in sensitivity, speed, and resolution, offering efficient remote vibration detection solutions for military and commercial applications.
- A quantum radar detected by an embedded microwave photon counter developed by the ENS Paris research team has achieved a significant improvement in ranging resolution, increasing detection speed by 209% compared to traditional radar.

Quantum-Enhanced Radar Based on Atomic Antennas

- Inflegtion and L3Harris have made significant breakthroughs in quantum radio frequency (RF) technology, overcoming the limitations of traditional technologies based on highly excited Rydberg states of atoms. This technology offers advantages such as continuous tuning, interference resistance, and high sensitivity in the RF sensing field, opening up new possibilities for RF applications.
- Inflegtion's quantum RF aperture/receiver system, SqyWire, demonstrated outstanding capabilities in the Army NetModX23 evaluation, which is significant for the development of RF network management.
- Rydberg recently launched a small, lightweight, low-power atomic receiver in the US Army's Combat Capabilities Development Command Center Network Modernization Experiment, demonstrating remote radio communication using atomic quantum sensors.

Quantum Radar Product Overview

Quantum radar technology is poised to achieve remote target detection and high-resolution imaging in complex noise environments in the near future, with wide applications in both military and civilian sectors. Global collaboration and continuous innovation will drive the advancement of quantum radar technology, providing more precise and efficient solutions for target detection and identification in the future. Enhanced quantum radar at the receiver end, achieved by incorporating squeezed light and phase-sensitive amplifiers to reduce standard quantum noise at the receiver, is a development direction that has attracted much attention in recent years.

Figure: Quantum Radar Industrialization Development Status

Category	Field of Application*	Technical Advantages and Disadvantages	Examples of Representative	Product Parameters	Product Sample Image
Quantum-Enhanced Radar Based on SPD	Atmospheric wind field, wake current measurement	High radial signal-to-noise ratio, near-infrared optical band; Requires low temperature environment, higher cost	国耀量子 China	Model: High-resolution wind measurement lidar Wind speed measurement accuracy: Perpendicular <0.3m/s@3km Wind speed range: ±50m/s	
	Greenhouse gas leakage detection	Continuous, real-time monitoring, small size, low power consumption; Need to maintain coherence and suppress noise	QLM UK	Model: Quantum Gas Detection distance: 200 m Detectable methane leakage rate: 0.012 g/s	
	Remote monitoring and detection	Remotely and accurately recognizes material intrinsic frequencies with high fidelity and low power consumption; Some performance metrics are still being tested	QCi USA	Model: Quantum Photonic Vibrometer Accuracy: 110 nm Frequency ranges: DC to 4 kHz	
Quantum-Enhanced Radar Based on Atomic Antennas	Radio communication	High sensitivity, wide bandwidth; Large size and complex laser system	天之衡量子科技 TZH Quantum Tech China	Model: Atomic Receiver Response frequency: 100kHz~40GHz Resolution: 0.1~1mm	

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Note: * Quantum radar products can be involved in a variety of application scenarios, and many companies' product lines also involve a variety of quantum radar, so this part of the selection of a typical product and application to do analysis.

The current quantum radar technology is facing challenges in detecting diverse targets, as the varying sizes and structural characteristics of different targets pose significant challenges to detection. To address this issue, in recent years, interferometric quantum radar technology has become an important means to optimize the design of long-range airborne target detection systems. By combining quantum entangled states with interferometers, this technology enhances the visibility of interference fringes, achieving ultra-sensitive detection and high-resolution target identification. Meanwhile, through techniques such as aerodynamic shaping and electromagnetic absorbent materials, the backward scattering of electromagnetic waves is minimized, thereby reducing the system's energy consumption and improving data collection time or transmission power.

Future trends will place greater emphasis on considering the overall factors such as radar dynamic range, sensitivity, and bandwidth, to ensure the system's application effectiveness in various environmental conditions. Quantum radar systems will gradually adopt a "classical-quantum dual-channel" system configuration, integrating quantum channels with classical radars. This integration can fully leverage the high precision and sensitivity of quantum channels while maintaining the current application scenarios and technological capabilities of classical radars, thereby enhancing the overall radar performance. In the medium to short term, this dual-channel system configuration is expected to become mainstream, better coping with various complex environments and extreme weather conditions.

06 Quantum Field Strength Meter

Advances in Quantum Field Strength Meter in 2023

The field of quantum electric field measurement has made significant progress, with measurement techniques using Rydberg atoms and diamond NV centers demonstrating superiority. Atomic systems have advantages such as repeatability, precision, and stability. Gaseous atoms are minimally perturbed by the applied electric field, enabling high-precision measurement of spectral frequencies.

In measuring ultra-weak electric fields, these techniques have significant advantages over existing microwave sensors. Diamond NV centers can achieve 10-nanometer-level electric field imaging and precise control of charge states, also exhibiting high sensitivity to weak electric fields

Future development of quantum field strength meters will focus on improving the precision of quantum electric field measurements, including high-sensitivity measurements of tiny electric fields. Research teams may explore more advanced quantum technologies to achieve more accurate field strength meter measurements to meet the needs of scientific research and applications. As quantum electric field measurement technology matures, the establishment of relevant standards will become crucial. The formulation of standards can ensure the comparability and credibility of measurement results among different laboratories and research teams. Organizations such as the International Organization for Standardization (ISO) may need to be involved in the development of these standards.

Future development will pay more attention to the multimodal integration of quantum precision measurement technologies, that is, integrating different types of measurement technologies. In electric field measurements, this may involve combining different atomic systems and different optical technologies to provide more comprehensive and comprehensive measurement solutions.

Quantum Field Strength Meter

Rydberg Atomic Electric Field Strength Meter

- A team from the University of Science and Technology of China (USTC) has successfully expanded the bandwidth sensitivity of microwave electric field measurements based on Rydberg atoms using an auxiliary microwave field. This advancement enables the detection of microwave fields with a detuning of up to 100 MHz, achieving a sensitivity improvement of 10 times compared to measurements without the auxiliary microwave field.
- The Beijing Wireless Measurement Research Institute and the Qingdao Key Laboratory of Terahertz Technology have collaborated on a scheme for measuring microwave electric fields based on Rydberg atoms using dual-color electromagnetically induced transparency (EIT). Simulation results show that compared to conventional EIT schemes, the spectral resolution can be improved by approximately 4 times, and the minimum detectable intensity of the microwave electric field can be improved by approximately 3 times. After Doppler averaging, the minimum detectable intensity of the microwave electric field is approximately 5 times greater than without the Doppler effect.

Diamond NV-Center Field Strength Meter

- A research team at the University of Illinois at Urbana-Champaign is developing a sensor based on nitrogen vacancy (NV) centers in diamond, which has unique quantum properties and can be used to measure the electric dipole moment of neutrons, potentially finding applications in quantum information science. They are studying a quantum technology called dynamic decoupling to improve the accuracy of electric field measurements.

With the continuous advancement of technology, quantum electric field measurement technology will be more widely used in practical scenarios, such as communications, medicine, and environmental monitoring. This will require the technology to better adapt to complex environments and provide practical solutions.

07 Algorithm & Software & Platform

Advances in Quantum Software Algorithm Platform in 2023

In 2023, there were significant advancements in the field of quantum precision measurement software, algorithms, and platforms. Innovations in software configuration and algorithms have enabled quantum sensors to adapt more flexibly to different environments, particularly performing well in resource-constrained situations. The development of platforms has provided more tools and resources, promoting the widespread application of quantum technology in research and practical applications.

Software
Algorithm
Platform

Software

- Infleqtion demonstrated a software-configurable, high-performance quantum-accelerated accelerometer by combining machine learning with quantum sensing.
- Sandbox AQ and the US Air Force successfully tested a magnetic anomaly navigation system based on quantum sensors. This system, a composite of artificial intelligence and quantum (AQ) technology, provides an alternative for environments where GPS is unavailable or denied.

Algorithm

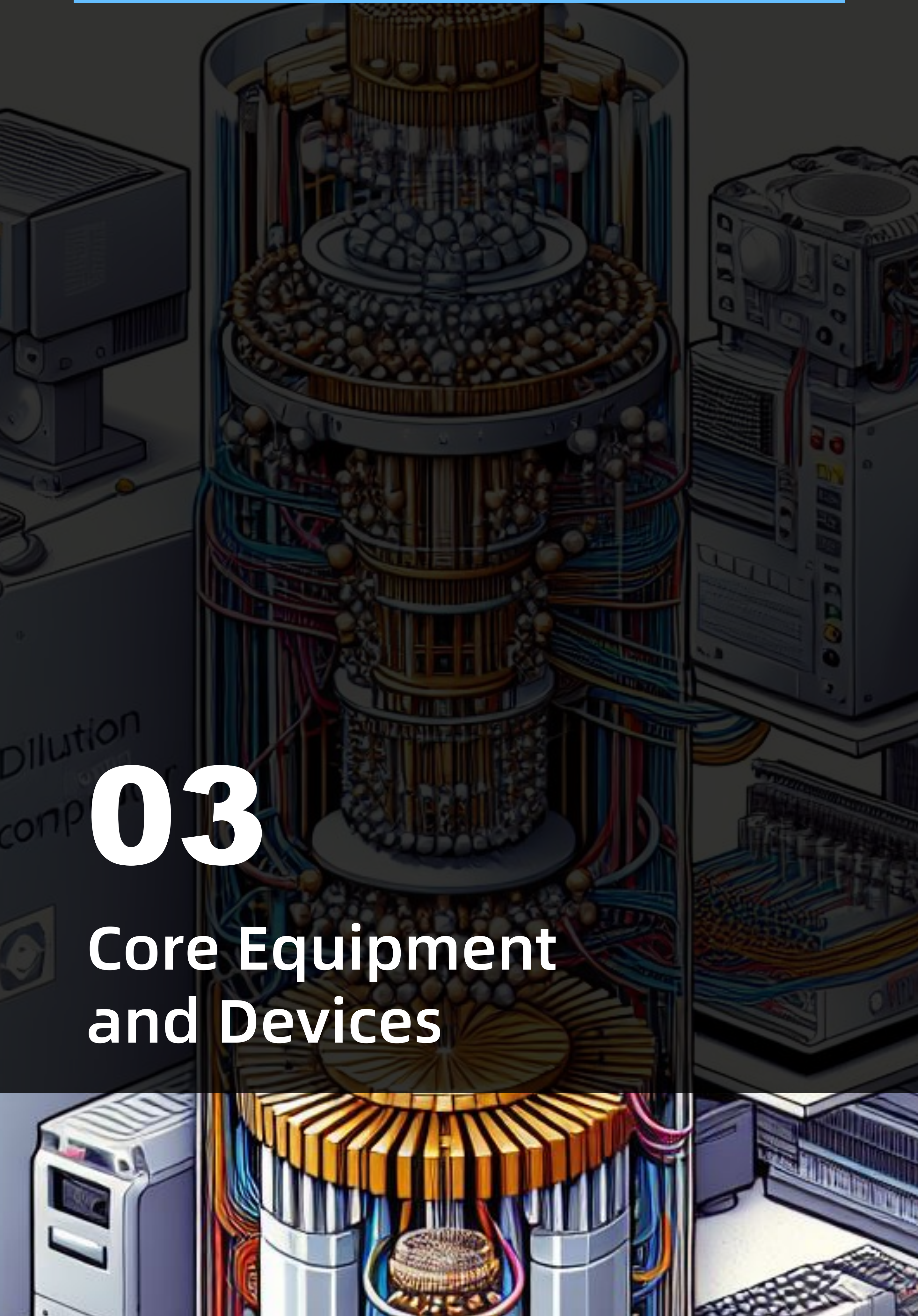
- The team from the University of Rome has proposed a model-free method that optimizes multi-parameter estimation by combining reinforcement learning algorithms with deep neural networks. This method can be widely applied to optimize the performance of quantum sensors.
- The Beijing Computational Science Research Center has proposed a universal, efficient, and simple method for implementing positive operator measurements (quantum random walk algorithm), and successfully demonstrated it in physical applications.

Platform

- Infleqtion has announced the launch of Oqtant, the world's first Quantum Innovation Platform as a Service, providing researchers and innovators with access to quantum materials.
- QLM Technology has commercially launched its Quantum Gas Laser Radar and QLM Cloud, offering superior performance and accuracy, along with cloud-based analysis and data management.
- Adtran's enhanced Oscilloquartz synchronization product portfolio now offers the aPNT+™ platform, which includes intelligent threat detection and mitigation capabilities.
- The Electric Power Research Institute of China's Quantum Power Measurement Platform was officially put into operation in May 2023. The platform aims to establish a quantum electrical measurement standard system, characterized by high stability and unaffected by changes in time, space, and environmental conditions.

Future developments will focus on the integrated fusion of software, algorithms, and platforms to construct more complete and efficient quantum measurement systems. With continuous technological advancements, there will be a growing concern for security and stability, especially in environments prone to frequent cyberattacks. The application of cloud services may be further emphasized, providing users with more advanced data analysis, management, and security features.

Furthermore, the expansion of quantum technology into broader application areas, especially in navigation, measurement, and security, will be a key direction for future development. Overall, the field of precision measurement will continue to benefit from the innovation of quantum technology, providing more precise and reliable solutions for scientific and industrial fields.



03

Core Equipment and Devices

Contents

03
Core Equipment and Devices

01 Major Progress

As quantum technology continues to advance, the demand for its upstream hardware is increasing, driving continuous improvement in performance and reliability. The upstream of quantum precision measurement covers various aspects such as peripheral support systems, core hardware, and auxiliary hardware, providing necessary foundational support for achieving highly precise quantum measurements.

Peripheral support systems include magnetic shielding systems, vibration isolation systems, cooling systems, and vacuum systems. These systems are crucial for improving the stability, accuracy, and reliability of quantum measurements. Core hardware includes single-photon detectors, microwave sources, lasers, and atomic chambers. As the core components of quantum sensors, they can provide highly sensitive signal detection, precise micro-adjustment control, and stable signal sources, thereby bringing higher sensitivity, faster response times, and lower noise levels to quantum measurements. Auxiliary hardware includes RF devices, electro-optic modulators, acousto-optic modulators, and cryogenic cables, which mainly play a role in auxiliary control and signal transmission in quantum measurement experiments.

Figure: 2023 Quantum Precision Measurement Core Component Advances

Perimeter Support Systems	Core Hardware	Auxiliary Hardware
• The Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, in collaboration with partners, has successfully developed a portable superconducting single-photon detection system based on small liquid-helium dewars. • A research group at the Swiss Federal Institute of Technology in Zurich has detected a new type of ferromagnetism in artificially produced materials, with a magnetic moment alignment different from traditional materials. It may be used in the future to produce new superconducting magnets, potentially leading to new applications in magnetic storage and quantum precision measurement.	• QCi has established a new factory for manufacturing quantum photonics chips, which can be used for quantum sensing and imaging products. • iXblue's neodymium-doped fiber lasers are widely used in two-photon fluorescence excitation microscopy techniques. • A research team from the University of California, Berkeley, and Lawrence Berkeley National Laboratory has successfully developed the first quantum light source using silicon. • Tianjin University has demonstrated for the first time the use of superconducting nanowire single-photon detectors for non-line-of-sight imaging. • Researchers at the Massachusetts Institute of Technology have discovered a method to manipulate the spin density of diamond, opening up new possibilities for advanced quantum measurement devices.	• iXblue's ILS laser system features a complete production chain, providing specialty optical fibers, Bragg gratings, high-speed modulation solutions, and micro-optical components. • iXblue has released the COH 90° optical mixing solution, which enables signal demodulation. This solution, based on four 90° phase steps, can extract phase, amplitude, and polarization information, with wide applications in medical imaging and other fields.

02 Peripheral Support Systems

Figure： Quantum Precision Measurement Upstream Peripheral Safeguard System Overview

Type	Cryogenic System	Magnetic Shielding System	Vacuum System
Representative companies	**Finland**: BLUE FORS **Japan**: SHI Cryogenics Group **China**: ZL CRYOGENIC; CryoPride 中船鹏力超低温	**UK**: Magnetic Shields Electromagnetic Engineering; OXFORD INSTRUMENTS **USA**: Twinleaf **China**: 北京翠海佳诚磁电科技有限责任公司	**USA**: Agilent **Germany**: Leybold; PFEIFFER VACUUM **UK**: EDWARDS **China**: KYKY 中科科仪
Role and its market landscape	• Low-temperature systems can reduce atomic thermal motion, thereby improving the precision and stability of the system. • The main suppliers of global pulse tube cryocoolers are Sumitomo in Japan and Cryomech (acquired by Bluefors). Chinese companies currently can only supply GM cryocoolers.	• Excluding external magnetic field factors, it is technically feasible to achieve this through alloy material coating or geomagnetic field compensation. • All major technology countries worldwide can supply. In addition, low-temperature system manufacturers can also purchase magnetic shielding housings and supply them downstream to customers along with the low-temperature system.	• The vacuum chamber and flange require a vacuum level of around 10^-9 Torr, which is technically easy to achieve. • Currently, only a few companies supply high-performance molecular pumps, with Pfeiffer Vacuum having the best performance and a high market share, followed by Edwards and Agilent.

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The peripheral support system is an important part of quantum precision measurement, and its performance and quality directly affect the precision and stability of quantum precision measurement.

In terms of technological innovation, future peripheral support systems will continue to drive performance and quality improvements. The increase in magnetic shielding efficiency will be achieved through the use of new materials, improved designs, and manufacturing processes. Vibration isolation systems will seek lower levels of vibration noise, and refrigeration systems will be continuously optimized to reduce temperature and improve cooling efficiency. The introduction of new materials and innovative structural designs will further enhance the reliability and performance of peripheral support systems. The direction of miniaturization and integration will make peripheral support systems more compact, portable, and efficient through the use of advanced manufacturing techniques and intelligent control systems.

In terms of application requirements, future peripheral support systems will more accurately meet the needs of specific fields. The rapid development of quantum navigation will drive the demand for higher-precision and more stable peripheral support systems. Future quantum sensors will continue to pursue higher sensitivity and accuracy. This, in turn, will prompt peripheral support systems to provide more advanced and customizable solutions to meet the needs of different fields of quantum technology applications.

03 Core Hardware

Figure: 2023 Quantum Precision Measurement Core Hardware Overview

Type	Laser	SPD	Microwave Sources	Atomic Chamber
Representative companies	UK: M SQUARED Germany: TOPTICA USA: Vixar China: precilasers 频准激光	Switzerland: IDQ FROM VISION TO TECHNOLOGY Netherland: SINGLE QUANTUM Excellence in photon detection China: 赋同量子 PHOTEC; CETC 中电科技集团重庆声光电有限公司	Germany: ROHDE&SCHWARZ USA: KEYSIGHT TECHNOLOGIES China: RIGOL	Germany: ROSATOM USA: AMERICAN ELEMENTS THE ADVANCED MATERIALS MANUFACTURER China: 中核集团 CNNC
Role and its market landscape	• High-quality, coherent, and monochromatic laser beams provide the light source for key processes such as quantum state preparation, precision manipulation, and interference measurement. • The main suppliers of lasers for quantum precision measurement worldwide are Toptica from Germany, M Squared from the UK, and Vixar from the US. Chinese companies currently lag behind in performance indicators, and most of the gain chips and light sources still rely on imports.	• Efficient and precise measurement and counting of quantum states are achieved by detecting the presence of photons, mainly used in devices such as quantum radar and optical clocks. • The main suppliers of single-photon detectors globally include IDQ from Switzerland and Single Quantum from the Netherlands. In China, PHOTEC is the first company to industrialize superconducting nanowire single-photon detectors, with a domestic market share of approximately 70%.	• Used to generate microwave signals and interact resonantly with quantum systems (such as atoms or molecules) to achieve precise control over their states. • The main suppliers worldwide are Rohde & Schwarz from Germany and Keysight Technologies from the United States. RIGOL in China currently offers a variety of arbitrary waveform generator products, with performance indicators reaching international advanced levels, available for supply to manufacturers related to quantum precision measurement.	• Used to provide an independent device for placing atoms such as rubidium and cesium required for atomic clocks. After inflation, it can calculate time based on the specific atomic energy level transition frequency. • The main suppliers of atoms for quantum precision measurement globally are the Russian State Atomic Energy Corporation and American Elements. China National Nuclear Corporation is the only manufacturer in China that sells by-products of nuclear industry such as thulium atoms, but it cannot sell in small doses.

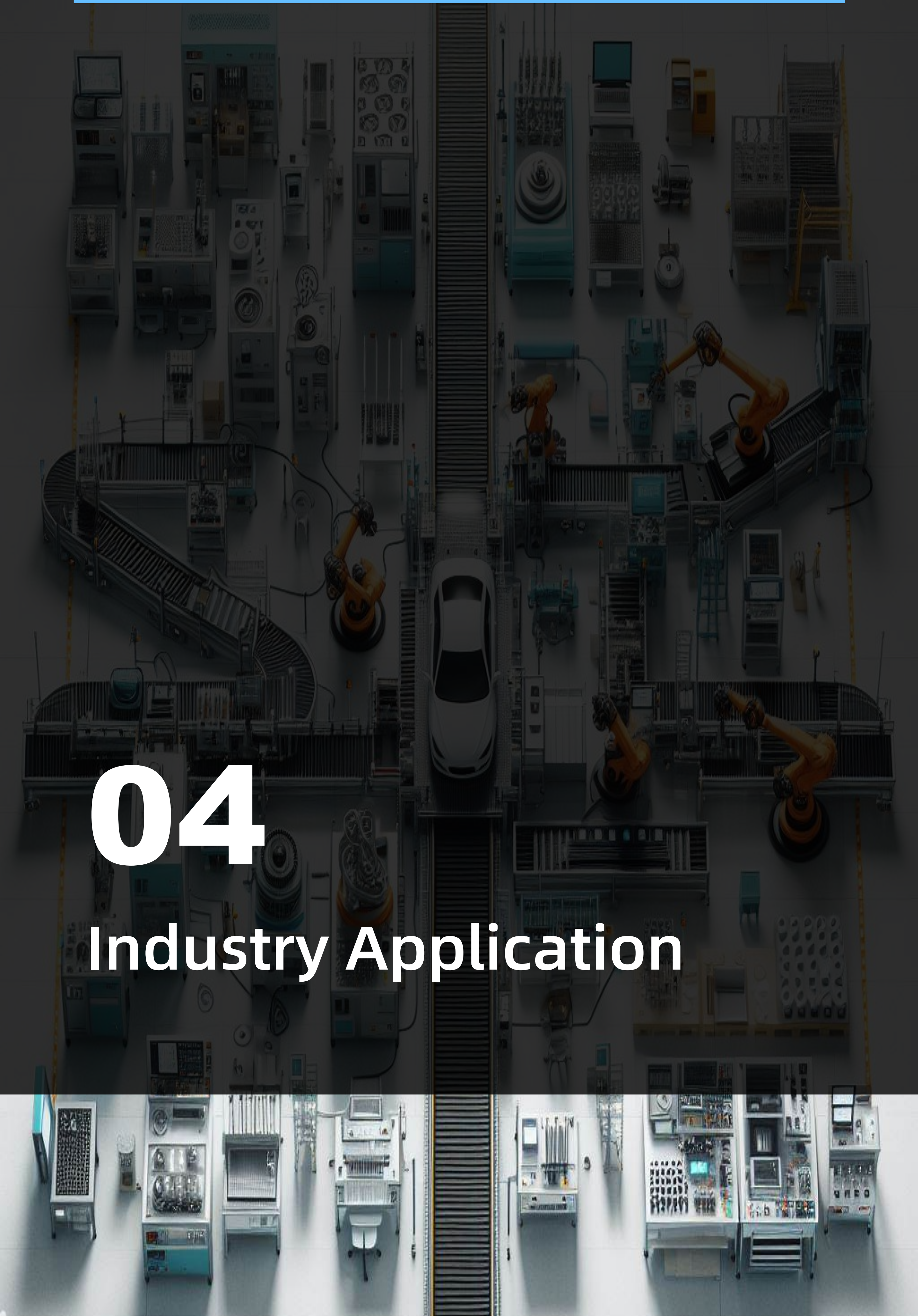
In the future, laser sources will undergo improvements in stability, power, and frequency control to meet the demand for higher precision in quantum measurements. Additionally, Chinese companies may increase their research and development efforts in the field of quantum light sources to bridge the performance gap and reduce dependence on imports. Trends in single-photon detectors may include larger arrays, longer response wavelengths, improved photon-number resolution, higher operating temperatures, larger photosensitive areas, and higher yield rates. Furthermore, quantum state measurement devices will become more diverse to meet the requirements of various application fields.

04 Auxiliary Hardware

Figure: 2023 Auxiliary Hardware for Quantum Precision Measurement Overview

Type	Low Temperature Cable	Modulator	Radio Frequency Device
Representative companies	**France** Radiall	**France** OPTO-ELECTRONIC	**USA** Mini-Circuits
	Japan KEYCOM Characteristic Technologies	**UK** G&H	**Germany** attocube WITTENSTEIN group
	China 西部超导	**China** CETC 中国电科	**China** ZWDX 中微达信
Role and its market landscape	• Some quantum precision measurement devices need to operate in extremely low-temperature environments, where traditional cables exhibit significant scattering noise, which is detrimental to measurements. Therefore, specialized low-temperature cables are required. • Global suppliers of low-temperature cables for quantum precision measurement include Keycom from Japan and Radiall from France. Western Superconductor is one of the few companies in China capable of producing ultra-low-temperature cables.	• Modulation technology can generate high-frequency electrical oscillations, which, through transducers, can form mechanical waves. By quickly controlling the waves, this modulation technique can modulate laser beams in devices, improving the sensitivity or precision of quantum measurements. • Acoustic-optic and electro-optic modulators are available from major technology countries worldwide. CETC offers electro-optic modulators suitable for ion traps and neutral atom systems.	• The operation and control of quantum states require various fields and waves. Radiofrequency microwave devices can be used to adjust the interaction and operation between quantum states and to accurately read them out. • Global suppliers of RF devices include Mini-Circuits from the United States and attocube from Germany. In China, Zhongweidaxin offers general components such as low-temperature, low-noise amplifiers for quantum precision measurement.

In the future, the research and production of low-temperature cables will be increasingly important to reduce scattering noise and improve the performance of measurement devices operating in extremely low-temperature environments. Major technology countries worldwide may strengthen their investments in low-temperature cable technology to meet the requirements of quantum precision measurement devices for extreme environments. The application of acousto-optic modulation technology in quantum measurements will further develop. By using high-frequency electrical oscillations and transducers for mechanical wave conversion, rapid modulation of laser beams can be achieved to enhance the sensitivity or precision of quantum measurements. Innovations in this area may involve the design and manufacture of new types of modulators. The development and application of radiofrequency microwave devices will be crucial for the operation and control of quantum states. In the future, there will be a trend towards higher processing precision, higher signal-to-noise ratio, and miniaturization and chipification at low temperatures to meet the requirements of quantum precision measurement systems.



04

Industry Application

Contents

04
Industry Application

01 Defense and Military

In terms of quantum precision measurement types, it covers various aspects such as time, measurement, gravity, inertia, target identification, reflecting the widespread application of quantum precision measurement technology in the military industry. From global navigation satellite systems and global positioning systems to magnetic anomaly navigation and near-Earth observation, it provides comprehensive support for military tasks. Due to the importance of military applications for national security, countries tend to focus more on research and development in the military industry, leading to a relatively closed research environment in this field.

The following figures mainly focus on the representative progress of quantum precision measurement in the defense and military industry in 2023. The selection criteria include collaborations between mid-tier quantum precision measurement companies and well-known enterprises or institutions in the defense and military industry, with priority given to those that produce actual or quantitative results, and only a few are exploratory collaborations.

Figure: Examples of Quantum Precision Measurement in the Defense Industry

Partner	Technology	Applications	Core Development
USA	Cold Atom Clock	Global Navigation Satellite System (GNSS) and Global Positioning System (GPS)	Developing next-generation quantum atomic clocks, quantum sensors, and component technologies is necessary to create better clocks, high-performance sensors, and related technologies, which are more resilient in the space domain.
SANDBOXAQ USA	Optically Pumped Magnetometer	Magnetic anomaly navigation refers to providing uninterrupted navigation in situations where GPS is unavailable, intentionally denied, or spoofed.	The company's quantum navigation prototype is installed on a U.S. Air Force C-17 Globe Master III military transport aircraft and has successfully received geomagnetic navigation data during ground and multiple flight tests.
Q-CTRL Austrailia	Cold Atom Absolute Gravimeter	Near-Earth observations based on low-cost satellites	The company has received support for collaborative research center projects and plans to deliver a quantum gravity meter for aerospace applications in the future. It aims to predict or even prevent the impact of drought or mining activities on water resources and agriculture.
UK	Cold Atom Accelerometer	Inertial navigation systems without GPS	Using ultracold atoms for acceleration measurement has the potential to provide high-precision position data in environments without global positioning systems (GPS) and global navigation satellite systems (GNSS).
QCi USA	Quantum-enhanced Radar	Quantum sensing solutions for satellite and airborne missions to test and monitor climate change	Supporting NASA in testing its proprietary quantum photonics system, which is used for remote sensing applications to monitor climate change, such as measuring the physical properties of various types of snow, including density, particle size, and depth.

In the future, three main development trends will emerge: improving technical performance, expanding application areas, and strengthening international cooperation. Firstly, by conducting research and development on next-generation quantum sensors and their core components, superior high-performance sensors can be created to meet the more complex task requirements in the military industry. Secondly, countries will continue to expand the application areas of quantum technology beyond applications such as inertial navigation systems without GPS, monitoring climate change, and testing magnetic anomaly navigation. Finally, strengthening international cooperation will be crucial for future development, encouraging countries to collectively address the complex demands of the defense and military industry, share technological achievements, and further promote progress in the entire field.

02 Healthcare and Medicine

Quantum precision measurement in the healthcare sector demonstrates a clear trend of international collaboration on a global scale. Countries such as the United States, China, Germany, Switzerland, and Finland have all provided advanced quantum magnetometry solutions for the global healthcare sector.

The following figrure primarily discusses and analyzes representative advancements of quantum precision measurement in the healthcare sector in 2023. The selection criteria include collaborations between mid-tier quantum precision measurement companies and well-known enterprises or institutions in the healthcare sector, with a priority on generating tangible or quantifiable results, with a few instances focusing on exploratory collaborations.

Figure: Examples of Progress in Quantum Precision Measurement in the Healthcare Field

Partner	Technical roadmap	Application directions	Core Development
MEGIN campus biotech Fondation Campus Biotech Geneva Finland, Switzerland	SQUID	Non-invasive methods for detecting and measuring brain activity, brain-machine interfaces, and research on neural feedback.	The latest generation MEG (Magnetoencephalography) system equipped with helium recovery and state-of-the-art magnetic sensors was delivered in Geneva, Switzerland. After installation and commissioning, it was used to provide precise and comprehensive images of brain activity.
Genetesis The Christ Hospital Health Network USA	OPM	Non-invasive diagnosis of coronary microvascular disease	The company's magnetocardiography device (CardioFlux MCG) has obtained breakthrough device certification, enabling its use in identifying myocardial ischemia in patients who may have coronary microvascular disease.
未磁科技 X-MAGTECH 安贞医院 ANZHEN HOSPITAL China	SERF	magnetocardiogrA-phy (MCG)	The company's 64-channel cryogen-free magnetocardiograph (MCG) was successfully installed at the Anzhen Hospital in Beijing. A ceremony was held to unveil the plaque designating it as the "Training Base for Magnetocardiography Equipment Technology and Clinical Application" by the Chinese Medical Equipment Association, along with a signing ceremony.
Universität Stuttgart BACEI Germany, China	NV centers	Magnetoencephalography (MEG) and magnetocardiograp-hy (MCG)	The demonstration includes simulating action potential signal detection using a muscle model and showcasing the potential application of NV magnetometers in measuring magnetocardiograms (MCGs) and magnetomyograms (MMGs) in unshielded biological magnetic fields.

In the field of healthcare, quantum precision measurement is primarily applied in specialized areas such as magnetocardiography (MCG) and magnetoencephalography (MEG). Quantum magnetometers, with their advantages of being non-invasive, radiation-free, contrast agent-free, and resistant to electromagnetic interference, have become important tools in medical diagnostics.

With technological advancements, quantum precision measurement technology will further expand into various medical fields. In addition to the already established areas of cardiology and neuroscience, innovations may be seen in cancer diagnosis, treatment of neurological disorders, and other medical applications in the future. Quantum precision measurement holds the promise of providing more comprehensive and accurate data for medical diagnostics, helping doctors better understand and treat diseases. Additionally, personalized medicine will emerge as a key trend. With more precise measurement data, doctors can tailor personalized treatment plans for each patient, improving treatment effectiveness and reducing unnecessary medication and procedures. Innovations in quantum magnetometry technology will drive the innovation of medical research and treatment methods, potentially improving the quality of life for patients and opening doors for the development of novel disease treatment methods.

In terms of equipment, future developments will focus on improving measurement accuracy, reducing costs, enhancing device portability, and usability. This will encourage more healthcare institutions and clinical laboratories to adopt quantum precision measurement technology, promoting its widespread application in the medical field. Furthermore, if SERF magnetometers achieve further breakthroughs in performance, sensitivity, and cost, they may become the dominant tools in magnetic measurement technology in the medical field in the future. This could lead to more precise and cost-effective magnetic measurement solutions, driving rapid development in the field of medical magnetometry.

03 Energy and Environmental Protection

In the field of energy and environmental protection, Western countries, particularly Europe and the United States, are the main drivers, while the Asia-Pacific region lags behind in this area. From a technological perspective, quantum precision measurement technology provides important support for the efficient operation of smart grids, climate change monitoring and understanding, formulation of environmental protection decisions, and understanding of dynamic changes in the atmosphere through the provision of high-precision synchronization solutions, gravity gradient measurements, meteorological monitoring, and radiofrequency sensing. The application of these technologies contributes to the innovation and development of the energy and environmental protection sector.

The following figure mainly describes and analyzes the representative progress of quantum precision measurement in the energy and environmental protection field in 2023. The selection criteria prioritize collaborations between mid-level quantum precision measurement companies and well-known companies or institutions in the energy and environmental protection sector, with an emphasis on generating tangible or quantitative results, with few exploratory collaborations.

Figure: Examples of Quantum Precision Measurement Progress in the Energy and Environmental Protection Sector

Partner	Technical roadmap	Application directions	Core Development
OSCILLOQUARTZ (An ADVA Optical Networking Company), OCP ACCEPTED USA、Switezerland	Rubidium atomic clock	Smart Grids	The new synchronization solution utilizes satellite timing and positioning technology to address the vulnerabilities in GPS and other GNSS systems, which are increasingly susceptible to interference and spoofing attacks. This solution can be applied in industries such as smart grids.
TEXAS (The University of Texas at Austin), NASA USA	Cold Atom Absolute Gravimeter	Readings of important climate factors include sea level rise, rate of ice melt, changes in terrestrial water resources, and variations in ocean heat storage.	Developing Photonic Integrated Circuits (PICs) to detect minute variations in Earth's gravity from space. This device utilizes numerous lasers and optical components to cool and trap atoms, enabling highly sensitive measurements of gravity gradients.
REPSOL, QLM UK	Quantum-Enhanced Radar	Near-Earth observations based on low-cost satellites.	The experimental images, while not showing hotspots of methane concentration, still allow for the precise quantification of the exact flow rate of emissions from the open sewage tank diffusion.
WORLD VIEW, Infleqtion USA	Rydberg Atom Antenna	Stratospheric Balloon System	Testing RF Sensing Technologies for Next-Generation Quantum and Stratospheric Exploration in Environments from Near-Earth to Atmospheric Edge

In the future, quantum precision measurement technology will extensively penetrate the energy and environmental protection sector, demonstrating diverse application scenarios. Optimization of smart grids will be achieved through the enhancement of temporal and spatial synchronization accuracy using quantum synchronization solutions, thereby improving the operational efficiency of power systems, reducing energy wastage, and enhancing energy utilization. Additionally, climate monitoring and response efforts will benefit from the high sensitivity monitoring provided by quantum-enhanced radar systems, enabling accurate monitoring of key climate factors and supporting more targeted environmental initiatives. The application of cold-atom absolute gravimeters in the study of gravitational variations on Earth holds the promise of providing precise data for disciplines such as geology and geophysics, advancing our understanding of the Earth's interior structure and dynamics.

In terms of technological innovation, future developments will continuously pursue the goals of improving measurement accuracy, expanding application domains, and reducing costs. The design of novel sensors will focus on sensitivity, compactness, and reliability to adapt to various environments and application scenarios, thereby enhancing measurement accuracy. The formulation of efficient data processing algorithms will ensure the more effective processing of quantum measurement data, improving real-time performance and accuracy. The design and manufacture of advanced experimental devices will ensure reliable quantum precision measurements under various conditions.

04 Synchronous Communication

In the field of synchronous communication, quantum precision measurement technology has been widely applied and collaborated upon globally, with a predominant presence in Europe and North America. The technological pathways in this domain mainly involve atomic clocks and their sub-technological products. These enterprises have propelled the development of applications such as critical communications between synchronous aircraft and control towers, 5G base stations and data centers, and railway mobile communication systems through the research and application of technology pathway products like rubidium atomic clocks, cesium atomic clocks, optical clocks, and cold atomic clocks.

The following chart mainly selects representative advancements of quantum precision measurement in the field of synchronous communication in 2023 for discussion and analysis. The selection criteria prioritize collaborations between mid-tier quantum precision measurement enterprises and well-known enterprises or institutions in the synchronous communication field, focusing primarily on producing tangible or quantitative results, with a smaller portion exploring collaborative endeavors.

Figure: Examples of Quantum Precision Measurement Progress in the Synchronous Communication Sector

Partner	Technical roadmap	Application directions	Core Development
MICROCHIP Federal Aviation Administration USA	Cesium atomic clock	Critical communication between synchronized aircraft and control towers	The new generation of cesium atomic clocks can assist the air traffic control in the United States by utilizing broadcast automatic dependent surveillance-broadcast (ADS-B) and wide-area multilateration (WAM) to accurately locate aircraft positions in the national airspace.
OSCILLOQUARTZ USA Communications USA, Switzerland	Rubidium atomic clock	5G base stations and data centers	Utilizing low Earth orbit satellites as a unique time source not only provides an effective alternative to GNSS but also enhances the reliability and security of GNSS. This dual-source approach aligns with the principle of zero trust.
OSCILLOQUARTZ DB USA, Switzerland	Optical atomic clock	Railway mobile communication systems	Deutsche Bahn utilizes the company's optical cesium atomic clock technology to provide precise timing for its nationwide railway network. The enhanced primary reference clock solution will enable Deutsche Bahn to implement predictive maintenance and other technological advancements across the entire network.
Infleqtion 2023 Military+Aerospace Electronics Innovators Awards USA	Cold atomic clock	Wireless broadband, network synchronization, autonomous vehicles, sensor networks	The company's Tiqker cold atomic clock product won the Platinum Award in the 2023 Military + Aerospace Electronics (MAE) Innovators Awards.

In the future, chip-scale atomic clocks are poised to replace the existing crystal oscillator technology in 5G base stations. The miniaturized design of chip-scale atomic clocks makes them easier to embed into communication equipment, providing higher frequency stability and time synchronization performance, which will help improve the efficiency and performance of communication systems. This is particularly significant for scenarios such as mobile communication base stations, especially for 5G networks requiring highly precise time synchronization, playing a crucial role in driving advancements in these fields.

Optical clock technology will become one of the key technologies in synchronous communication. With its outstanding frequency stability and accuracy, optical clocks will become the ideal choice for fields such as financial transactions and network communications. In the future, as optical technology continues to advance, the performance of optical clocks is expected to further improve, meeting the high demands for time synchronization and promoting more precise data transmission and processing in synchronous communication systems.

In clock ensembles, averaging multiple measurements is a common strategy to mitigate external interference and improve measurement accuracy and stability. This approach positively impacts the reliability and robustness of synchronous communication systems. Future developments will focus more on the multimodal integration of quantum precision measurement technology, integrating different types of measurement techniques to provide more comprehensive and versatile measurement solutions.

05 Scientific Research

In the field of scientific research, quantum precision measurement technology has demonstrated broad and profound application prospects. From a regional perspective, European and American countries play important roles in promoting the development of quantum precision measurement technology in scientific research. In global collaboration, countries such as Germany, Switzerland, and India collaborate with research institutions to jointly promote innovation in quantum precision measurement technology.

The following chart primarily selects representative advancements of quantum precision measurement in the scientific research field in 2023, discussing and analyzing collaborations between medium-sized enterprises in quantum precision measurement and renowned research institutions. The selection criteria prioritize tangible or quantitative results, with a few collaborations explored for potential outcomes.

Figure: Examples of Progress in Quantum Precision Measurement in Scientific Research

Partner	Technical roadmap	Application directions	Core Development
OSCILLOQUARTZ, PTB Germany, Switzerland	Cesium atomic clock	Astronomical research	The company conducted a three-month evaluation of its latest OSA 3300-HP high-performance optical cesium atomic clock, and the results far exceeded the product specifications. This technology will play a crucial role in astronomical research.
ZABRE, Indian Institute of Technology Madras Switzerland, India	Diamond NV center	Research on quantum technology based on spin and photons	The device can provide quantitative data on surface magnetic fields, electric currents, and electric fields with nanometer resolution and high sensitivity. Currently, the equipment has been installed in Professor Vidya Praveen Bhallamudi's laboratory.
iXblue, CARIOQA-PMP EU*	Cold atom absolute gravimeter	Cold atom rubidium interferometer for quantum acceleration measurement in orbit - Pathfinder mission preparation.	It is used to study satellite-based observations of changes in Earth's mass distribution, such as glacier melting or groundwater loss. Independent development and operation of space missions based on quantum sensors can be achieved, assisting in the completion of a series of related experiments.
QCi, Oklahoma State University USA	Quantum-enhanced radar	Landmine detection and validation	Simulating the conditions and environments experienced during global demining work involves validating a comprehensive range of 143 different items, including landmines, bullets, unexploded ordnance, and improvised explosive devices (IEDs).

Note: *The cold atom rubidium interferometer for quantum acceleration measurement in orbit - Pathfinder mission preparation is an EU-wide project, and iXblue is also a French company, so the country position here is listed as "EU".

In the future, the alternative value of quantum precision measurement technology in the scientific research field will become more prominent. Quantum precision measurement technology not only offers higher precision but also demonstrates superior performance in scientific experiments. Additionally, its widespread application in research is evident in providing quantitative data on surface magnetic fields, currents, and electric fields. The nanometer resolution and high sensitivity of these quantum sensors make them indispensable tools in laboratory environments, facilitating scientists to delve into the study of phenomena at the microscopic scale.

Furthermore, the application of quantum precision measurement technology in simulating global demining efforts highlights its practical significance in the research field. This technology can verify conditions and environments across various domains in the laboratory and can also be applied in satellite observations to assist in a series of related experiments, thereby advancing a deeper understanding of complex issues in scientific research. In the realm of scientific research, quantum precision measurement technology is continuously innovating to provide scientists with more powerful tools, driving continuous breakthroughs in scientific research.

05

Investment and Financing

Contents

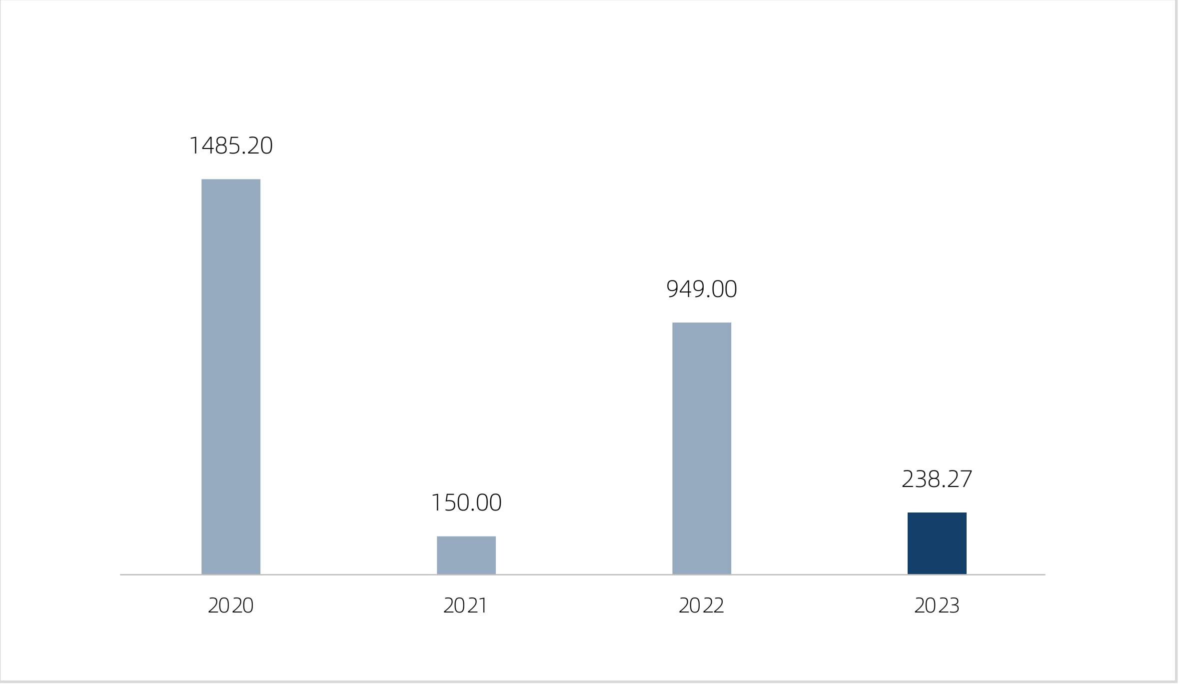
05
Investment and Financing

01 Overview of Financing

In the field of quantum precision measurement in 2023, financing enterprises are mainly divided into three categories: trapped atoms/ions, solid-state spins (NV centers), and others. According to public information, a total of 17 companies worldwide raised approximately $238 million in financing. For companies that have not disclosed specific financing amounts, including China's Ruilun Technology (Beijing), Benewake (Beijing) Photonics, Suzhou Guoshun Laser, Ningbo Yuanxin Optoelectronics, Suzhou Shiguangxin Science and Technology (China), Lingming Photonics, Fushi Technology, Germany's N Vision Imaging Technologies (Series A), Germany's N Vision Imaging Technologies (government grant), Quantum Diamonds, UK's Skylark Lasers, and US-based Source Photonics, estimated amounts were provided.

Compared to 2022 (approximately $949 million), the total financing scale in 2023 has decreased. The instability of the global economic situation and potential changes in policies and regulations may have led investors to adopt a conservative approach in emerging technology sectors, thereby impacting the scale of investment and financing. Additionally, the data collection process is based on company announcements, which may result in a lag between the reported financing rounds and the actual occurrences.

Figure: Total Financing Amount in the Global Quantum Precision Measurement Sector from 2020 to 2023 (Unit: $M)



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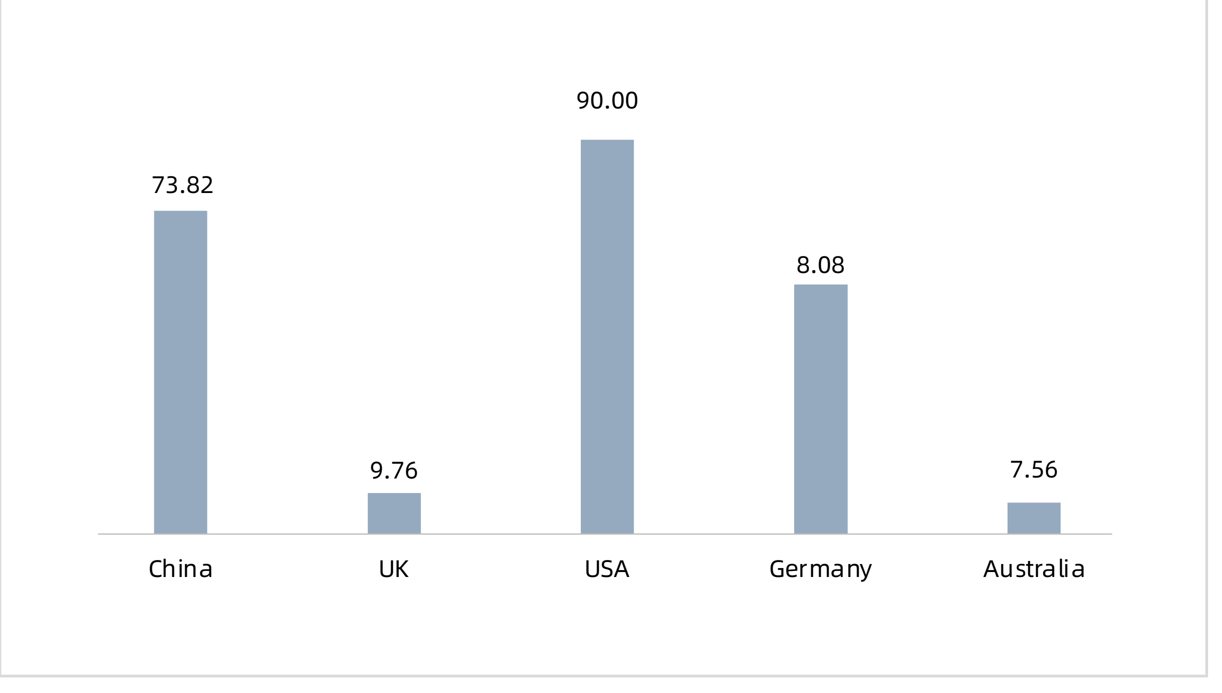
02 Regional Distribution of Financing

The majority of funding goes to companies in the United States, followed by China and Germany.

In 2023, funded companies are from five countries (United States, China, Australia, Germany, United Kingdom). Based on disclosed financing amounts (Source Photonics from the United States, N Vision Imaging Technologies (Series: A) from Germany, N Vision Imaging Technologies (Series: Grant) from Germany, Benewake from China, Adaps Photonics from Shenzhen), the highest amount of funding goes to companies in the United States (approximately $90 million, 1 company), followed by China (approximately $74 million, 9 companies), Germany (approximately $57 million, 3 companies), the United Kingdom (approximately $10 million, 3 companies), and Australia (approximately $8 million, 1 company).

Figure: Global Quantum Precision Measurement Financing Amounts in 2023 (Unit: $M)



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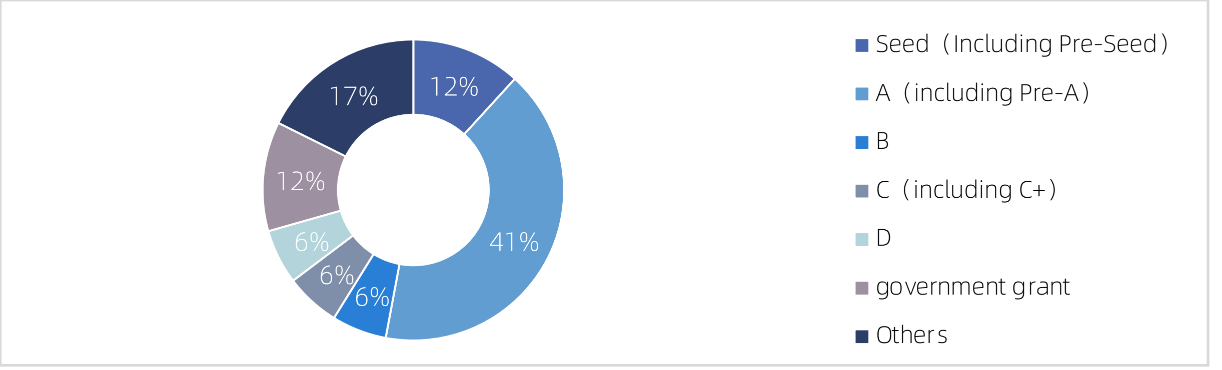
03 Types of Financing

The main type of financing is Series A investment. This financing survey is categorized into several types: Seed Round (including Pre-seed), Series A (including Pre-A), Series B, Series C (including C+), Series D, Government Grants, and Others (Strategic Investment, undisclosed). From the perspective of financing types, Series A financing is the most common (7 rounds, accounting for 41.67% of the total), indicating that companies in the quantum precision measurement sector are still in the early stages of development and require early-stage financing as well as government investment.

Figure: Financing situation of global quantum precision measurement companies in 2023



Financing rounds situation

Round	Trapped atoms/ions	Solid-state spin	Others
Seed (including Pre-Seed)	Delta.g	QUANTUM DIAMONDS SENSOR TECHNOLOGY	
A(including Pre-A)	NOMAD ATOMICS; 國測量子	NVISION	Skylark Lasers; 国顺激光 GLIGHT; SOPHOTON; RAYZ
B			ORI CHIP
C(including C+)			adaps ADAPS PHOTONICS
D		NVISION	source PHOTONICS
Government Grants	Skylark Lasers		
Others	星汉时空		Benewake

04 Funding Direction

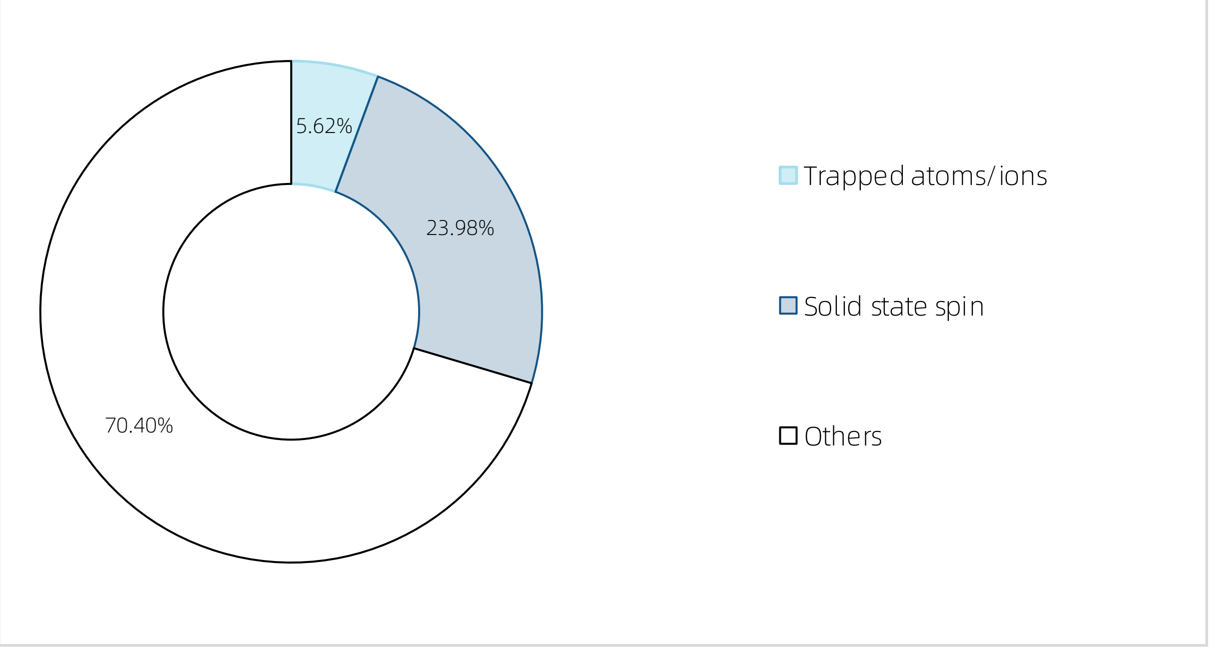
In 2023, financing enterprises in the field of quantum precision measurement are mainly categorized into three major technological paths: trapped atoms/ions, solid-state spins, and others.

From the compiled data, it is observed that in 2023, a total of 5 companies received funding to advance neutral atom development, including Xhtime, Guoce, Skylark Lasers, Delta g, and Source Photonics, collectively raising approximately $13 million.

In the solid-state spin industry sector, 3 companies secured financing, namely Germany's N Vision Imaging Technologies (Series A), Germany's N Vision Imaging Technologies (government grant), and Quantum Diamonds (Germany), with a combined funding of $57 million.

In other directions, 9 companies received investments, primarily focused on upstream laser technologies. These include Suzhou Guoshun Laser (China), Ningbo Yuanxin Optoelectronics (China), Skylark Lasers (UK), Source Photonics (US), Ruilun Technology (Beijing) (China), Benewake (Beijing) Photonics (China), Suzhou Shiguangxin Science and Technology (China), Lingming Photonics (China), and Fushi Technology (China), collectively raising $168 million in funding.

Figure: Distribution of Investment Technologies in the Quantum Precision Measurement Field in 2023



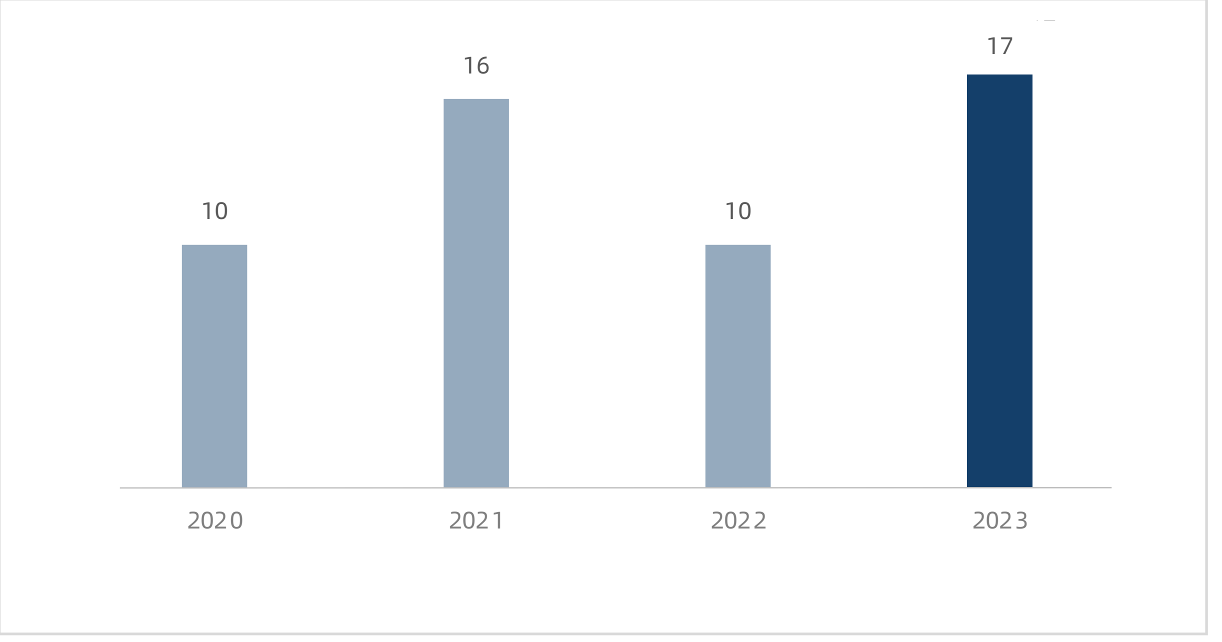
05 Financing Rounds

In 2023, a total of 17 financing events occurred in the quantum precision measurement sector, representing an increase compared to the number of financing events in 2022 and roughly consistent with the number in 2021.

The increased financing activity in the quantum precision measurement sector in 2023 can be attributed to several factors. Firstly, continuous breakthroughs and advancements in technology within this field have sparked strong interest from investors in related startups and projects. Additionally, government policy support and the overall market environment have provided a favorable backdrop for the development of quantum precision measurement, bolstering investor confidence in this sector.

In 2023, the German National Metrology Institute (PTB) released its "Tasks and Goals for the Period 2023-2025" plan, which includes research and development efforts in utilizing quantum metrology techniques for representing and preserving electrical units, developing high-sensitivity quantum-based electrical measurement methods and sensors, and optimizing integrated quantum circuits for semiconductor single-electron sources and broadband single-electron detectors (RF ensemble detectors). Similarly, China has issued several documents outlining development plans for metrology, promoting research in quantum precision measurement and quantum sensing technologies, and strengthening the original innovation of metrology's fundamental theories and core technologies. Investors hold a more optimistic outlook for the future of the quantum precision measurement sector, leading to increased willingness to invest.

Figure: Number of Quantum Precision Measurement Financing Rounds (2020-2023)



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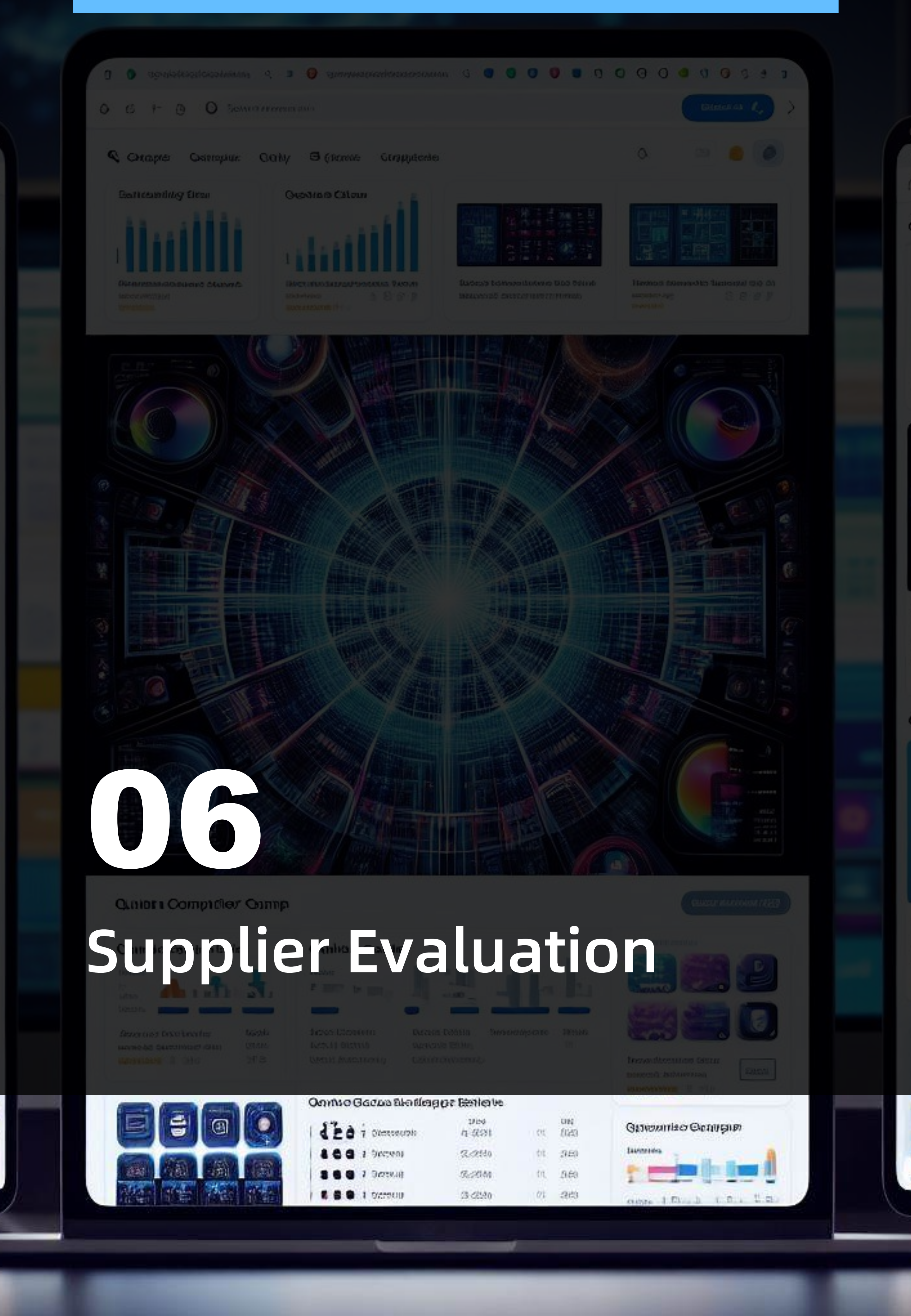

06

Supplier Evaluation

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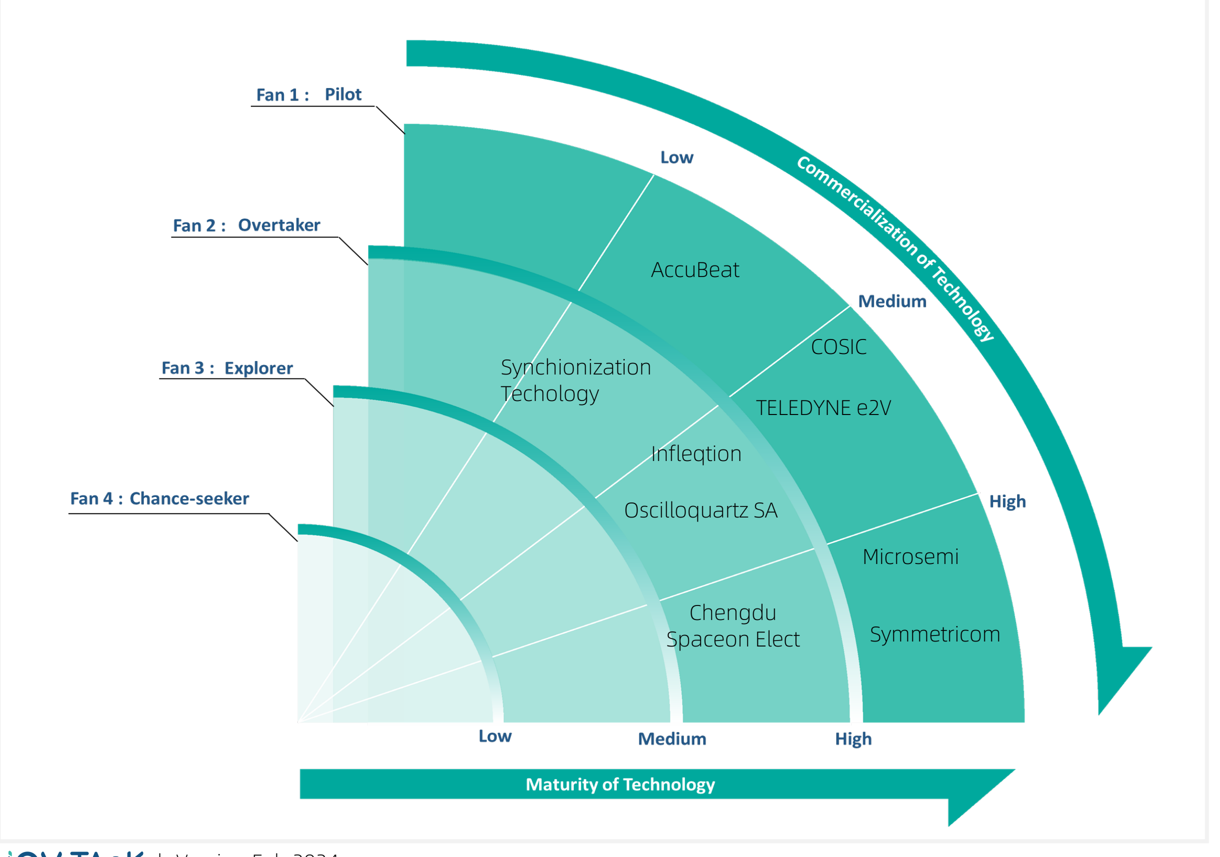
06
Supplier Evaluation

01 CTF Model - Quantum Clock

Quantum precision measurement scientific instruments mainly provide high-end laboratory or industrial equipment for fields such as biomedicine, materials science, and nanotechnology. Currently commercialized products primarily include various types of microwave atomic clocks (rubidium clocks, hydrogen clocks, cesium clocks), microwave chip-scale atomic clocks, optical clocks, chip-scale molecular clocks, and time-frequency synchronization products (protocols).

Figure: CTF Model in the Quantum Clock Field



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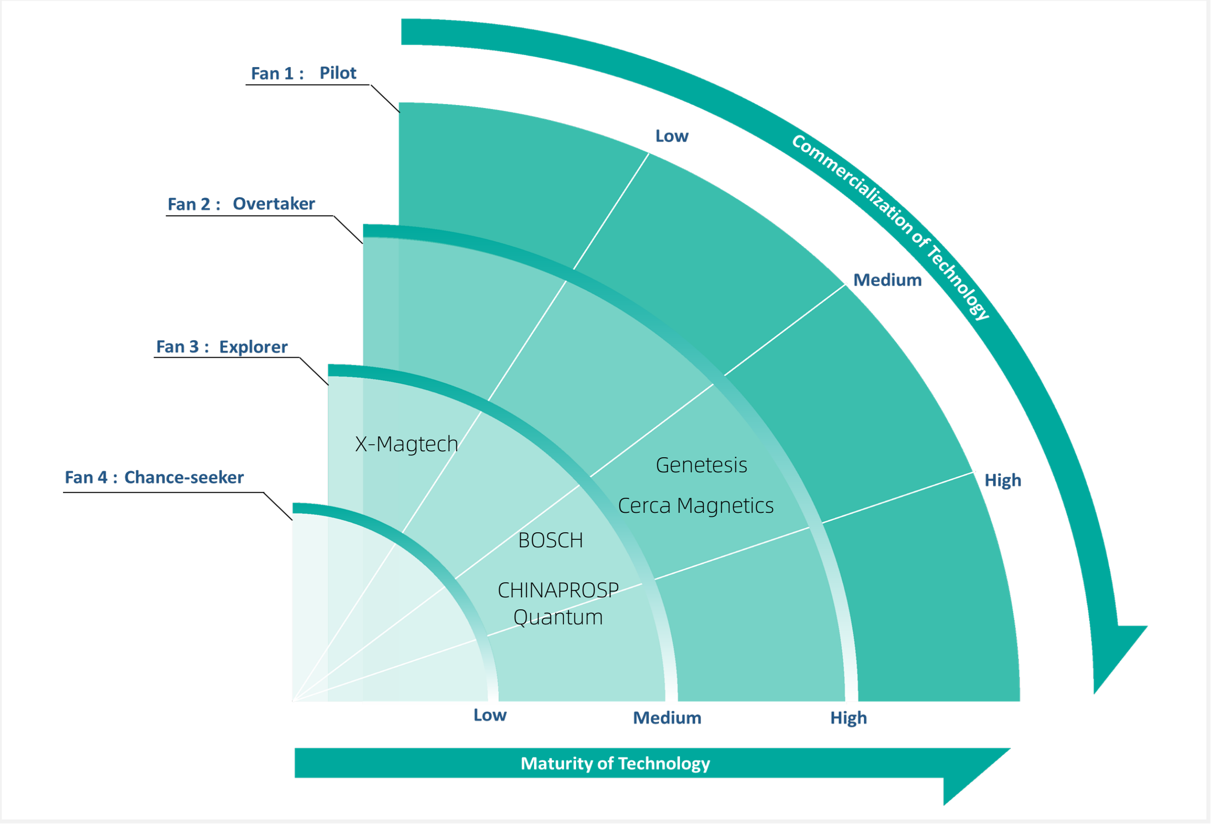
In the field of quantum clocks, organizations like Microsemi and Symmetricom are leading in optical clocks. Molecular clocks are currently only publicly pursued by companies like Zhongweidaxin. In the realm of microwave clocks, the global market is mature, with key players being companies like Oscilloquartz and the 203 Institute in China.

Among countries with atomic clock technology, the United States and Europe have numerous commercialized companies. Few other regions have commercialized companies, with most of the technology being held by national metrology standards-setting institutions and research institutes. Symmetricom in the United States is a leading technology provider in atomic clocks. Additionally, according to public reports, the European Union and Japan have also developed prototype chip-scale atomic clocks.

02 CTF Model - Quantum Magnetic Field Measurement

Figure: CTF Model in the Quantum Magnetic Field Measurement Field



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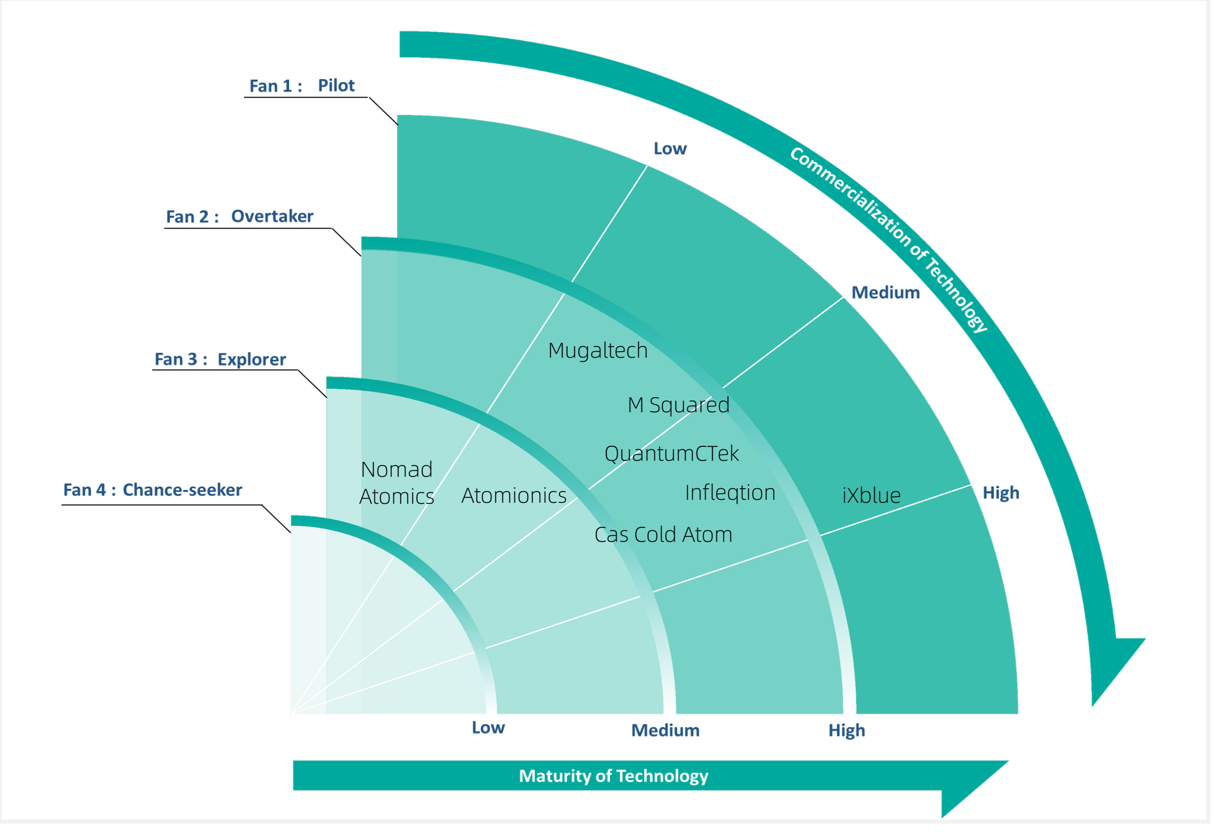
In the realm of quantum magnetic field measurement, instruments can be applied in various fields such as geology, biology, and healthcare for life sciences. Quantum magnetometers (SQUID/OPM/SERF/NV centers) primarily serve for detecting weak magnetic fields, finding applications in military defense, geology, and biomedical fields.

Currently, there are several technological paths for quantum magnetic field measurement. Optical-pumped magnetometers and SQUIDs dominate the market presently, but in the future, SERF and NV center magnetometers may compete for market share, potentially expanding quantum commercialization through cost advantages.

Magnetometers are commercially mature in fields such as biomedical applications, geomagnetic exploration, and physics research globally.

03 CTF Model - Quantum Gravity Measurement

Figure: Quantum Gravity Measurement (Quantum Gravity Meter & Quantum Gravity Gradient Meter) Field CTF Model



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In the field of quantum gravity measurement, there are currently only technologies based on cold atom interferometers, all of which are absolute measurement instruments. This category of instruments is monopolized by foreign countries and the market is mature, often used in conjunction with relative gravity meters. Currently, there are 2 companies in the United States, 1 in the United Kingdom, 1 in Australia, and 2 in China involved in quantum gravity measurement instruments. The main participants in quantum gravity measurement instruments include AOSense (USA), M Squared (UK), Atomionics (Singapore), iXblue (France), Muquans (France, acquired by iXblue), Microquake Quantum (China), CAS Cold Atom (China), QuantumCteK (China), and Nomad Atomics (Australia).

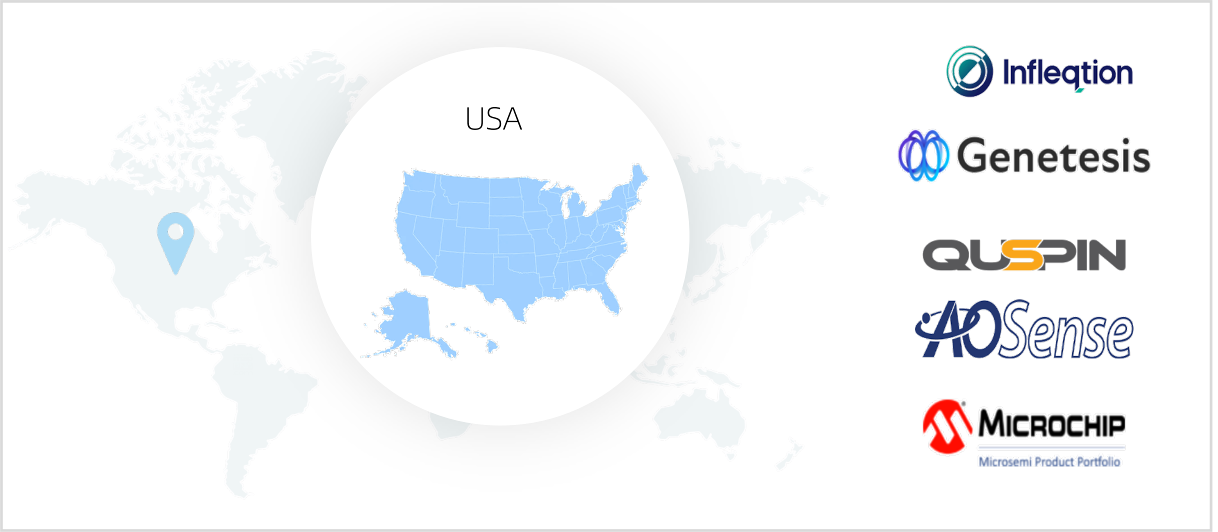
Currently, quantum gravity measurement instruments are completing the transition from the laboratory to commercialization. Among them, major research institutions of quantum gravity meters have completed the transition from the laboratory to commercialization, and companies in the United States, France, China, and Singapore have launched various models of commercial quantum gravity meters. They mainly provide products and technologies to research institutes, universities, relevant government agencies, and enterprises engaged in geological research, marine research, offshore operations, inertial navigation, and aircraft research.

The quantum gravity meter market is not yet fully mature, and downstream users have limited understanding of the advantages of quantum gravity meters, so trial use and promotion need to be strengthened. Compared with high-end products in classical gravity meters, quantum gravity meters have not shown absolute advantages in accuracy, sensitivity, and other indicators, coupled with high prices, resulting in fewer purchases.

04 Typical Enterprise Analysis

Assessment of American Suppliers

Figure: American Quantum Precision Measurement System Suppliers



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In 2023, Infleqtion achieved significant milestones through collaboration with the University of Colorado, leveraging machine learning and quantum sensing to realize software-configured quantum accelerometers. These accelerometers demonstrated outstanding accuracy in positioning, navigation, and timing applications. The company's accomplishments include driving the transition of quantum radio frequency sensing technology to field applications, developing the first optical atomic clock surpassing the accuracy and reliability of current global navigation satellite system equipment, and introducing the world's first quantum innovation platform, Oqtant.

Genetesis, a leader in the field of biomagnetic cardiac imaging, announced in April 2023 that its flagship imaging solution, CardioFlux MCG, received FDA breakthrough device designation. This solution can identify myocardial ischemia in the heart, particularly in patients at risk of coronary microvascular disease (CMD). This achievement marks a significant step forward in cardiac health, offering the potential for earlier treatment and diagnostic options, particularly for CMD patients, and bringing positive impact to the field.

Quspin focuses on OPM manufacturing and produces optical atomic magnetometers for biomedical and geophysical applications. The company aims to develop fundamental science by using quantum entities, such as electron spins, as carriers of information, enabling information transmission in fundamentally different ways. Quspin's products, including zero-field and full-field magnetometers, are currently widely used in various fields, including quantum sensing and intelligent sensing technology innovation centers in major scientific infrastructure research institutes with extremely weak magnetic fields, as well as in epilepsy research in the medical field.

Founded in 2004, the company designs, manufactures, and tests high-performance cold atom sensors for inertial navigation, time and frequency standards, and gravity measurement. Its product offerings mainly include gyroscopes, accelerometers, inertial measurement units (IMUs), gravimeters, gravity gradiometers, and atomic frequency standards, providing a comprehensive product portfolio. The company collaborates closely with NASA's Goddard Space Flight Center to develop quantum sensors for precise navigation.

Founded in 1989, this US-based company is a leading supplier of intelligent, interconnected, and secure embedded control solutions. With a rich product portfolio, one of its notable offerings is in the Clock & Timing domain. In 2011, the company launched the Chip-Scale Atomic Clock (CSAC), the world's first commercial chip-scale atomic clock. In June 2023, the company introduced the 5071B cesium atomic clock, the next-generation commercial cesium clock following the 5071A model. This cesium clock provides long-term, precise timing and frequency solutions for multiple industries and can maintain system synchronization for over two months when global navigation satellite system (GNSS) signals are denied.

Figure: Chinese Quantum Precision Measurement System Suppliers

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Established in 2018, the company specializes in the research, development, manufacturing, and servicing of high-precision quantum gravimeters. Its products are widely used in seismic research, resource exploration, geological surveys, and other fields. The company independently controls core technologies, holds multiple invention patents, and collaborates closely with universities. With stable business growth, in 2023, the company won the bid for the project at the Zhejiang Institute of Metrology, marking industry-wide recognition of its technological strength and product quality.

Established in 2019, the company is committed to integrating quantum measurement technology with industrial practical needs, focusing on the research and application of quantum sensors to achieve the industrialization of high-end quantum sensing equipment. The company's long-term goal is to empower various industries through quantum measurement technology and contribute to the popularization and development of quantum science and technology education. In November 2013, Quantum Future donated the "Quantum Magnetic Sensing Teaching Machine" product to the Quantum Science Popularization Exhibition Hall established in Baizi Township, Quanzhou City, Fujian Province. In addition, the first provincial local standard in the field of quantum measurement in China, led by the company, was officially implemented on November 7, 2023.

Established in 2020, the company operates in both the quantum precision measurement and quantum computing fields. It has undertaken several national-level projects related to quantum precision measurement and quantum computing, including major national research programs and projects under the Chinese Academy of Sciences' strategic priority research program. In 2023, the company participated in the signing of the Chu Tian Feng Ming Science and Technology Angel Fund in Hubei Province, China, and established an internship base with the School of Mathematics and Physics at China University of Geosciences (Wuhan). The company's equipment achieved international leading standards in the International Comparison of Absolute Gravimeters (ICAG) 2023 held in the United States.

Established in 2020, the company offers comprehensive solutions for weak magnetic field measurements and is a leading provider of SERF magnetometer technology in China. Its products can be widely used in areas such as security inspection, biomedicine, military defense (underwater target detection, high-precision quantum gyro navigation), and geophysics. In 2023, Unimagnet Technology officially launched the world's first 64-channel liquid-helium-free magnetocardiograph, the Miracle MCG® Pro34, following the approval of China's first 36-channel liquid-helium-free magnetocardiograph, which was the second such device globally, obtained by the company the previous year.

Founded in 2004 and listed in 2015, the company is the only publicly listed company in the field of quantum clocks and is controlled by the 10th Institute of China Electronics Technology Group Corporation (CETC). As a leading time and frequency enterprise in China, the company has a complete product line in time and frequency and possesses integrated capabilities in time and frequency systems, offering customers comprehensive time and frequency solutions. In 2023, Tianao Electronics signed a significant order with institutional clients for rubidium clock modules, totaling approximately 100 million yuan. Currently, the company's projects for industrializing atomic clocks and time synchronization products are in the final stages, with production lines undergoing debugging and small-scale trial production.

Figure: European Quantum Precision Measurement Equipment Suppliers

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Cerca Company designs, manufactures, and tests high-performance cold atom sensors for inertial navigation, time and frequency standards, and gravity measurement. In 2023, the company successfully developed the world's first wearable electroencephalogram (EEG) scanner, which can measure brain function in both healthy and diseased states. Additionally, Cerca Magnetics was honored with the inaugural award from the Quantum Business Innovation and Growth (qBIG) group of the Physics Institute, aimed at supporting innovation and commercialization of quantum technologies.

M Squared's product range includes lasers, microscopes, quantum devices, and instruments. As a global leader in the fields of quantum sensing, timing, and computing, M Squared has achieved milestones such as the UK's first commercial quantum gravimeter and accelerometer. In 2023, the company developed a universal laser system for cold atom sensors.

In 2023, the company collaborated with CIMAP laboratory to successfully develop a laser source based on neodymium-doped fiber for two-photon fluorescence excitation microscopy techniques. Additionally, iXblue provided erbium-doped fibers to enhance laser radar applications and introduced all-glass Er/Yb-doped fibers to improve system reliability. The company's COH 90° optical hybrid solution can be applied in metrology and medical fields. Furthermore, iXblue will develop quantum sensors for space applications, which will be used in the European Quantum Accelerometer (EQAccelerometer) mission preparation project for cold atom rubidium interferometers in orbit.

Oscilloquartz specializes in providing high-precision and reliable timing and synchronization solutions to address vulnerabilities in GPS and other GNSS systems caused by interference and attacks. The company's technology includes novel timing solutions utilizing Satellite Time and Location (STL) technology, enhancing security and reliability through dual-source approaches. Currently, the company's products cover various fields, including biomedical imaging, laser radar applications, quantum sensing, national operator SDH networks, railway mobile communication systems, and data center operators.

07

Industry Analysis and Forecast

Contents

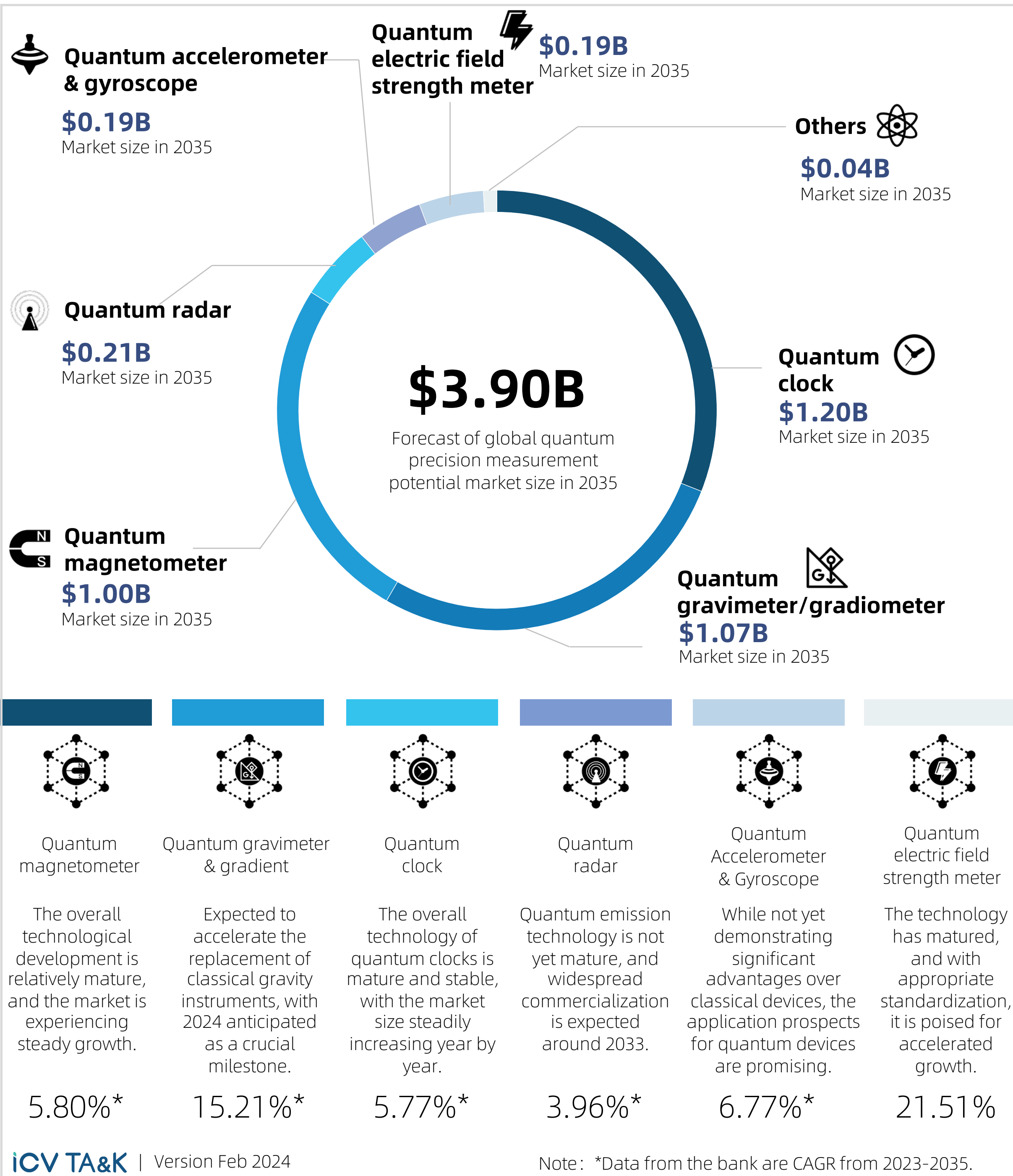
07
Industry Analysis and Forecast

01 Quantum Precision Measurement

Increased Market Expectations

Anticipating an upward adjustment in market expectations for segmented areas such as quantum clocks and quantum gravity sensors & gradients, the global quantum precision market is projected to grow from $1.47 billion in 2023 to $3.90 billion in 2035. This trajectory indicates a continuous upward trend with a compound annual growth rate (CAGR) of 7.79%.

Figure: Forecast of Global Market Size for Quantum Precision Measurement (Unit: $B)

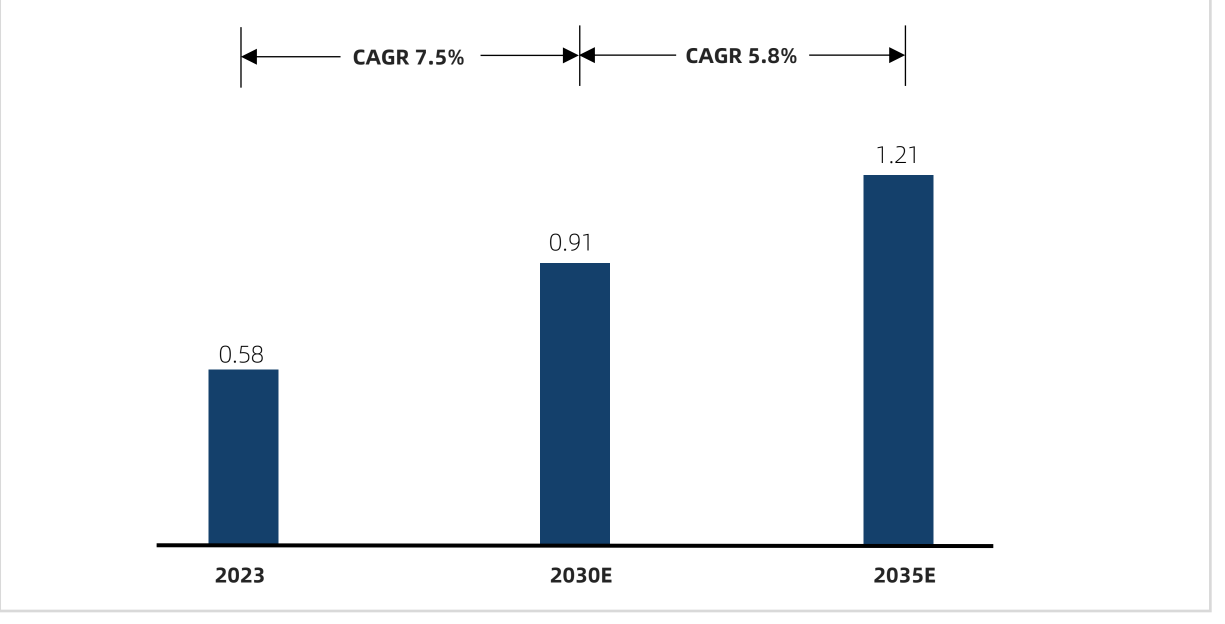


02 Quantum Clocks

Global Quantum Cock Market Size

Between 2023 and 2035, the quantum clock market has shown a steady growth trend, with the market size increasing from $580 million in 2023 to $1.21 billion, representing a compound annual growth rate (CAGR) of 5.77%.

Figure: Global Quantum Clock Market Size (2021-2035, Unit: $B)



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Quantum clocks, as crucial tools for high-precision time measurement, are experiencing increasing demand across various fields. The development of communication technologies, especially emerging technologies like 5G, is driving the need for high-precision synchronization and time standards. Quantum clocks provide critical support for data transmission and network synchronization in the communication sector.

Global satellite navigation systems and other navigation and positioning systems are increasingly relying on high-precision time measurements, where the stability and accuracy of quantum clocks make them key components in these systems.

In the field of scientific research, the demand for precise time measurements is also increasing with deeper research into environmental changes and climate. Quantum clocks' applications in meteorology and earth sciences provide scientists with accurate time benchmarks.

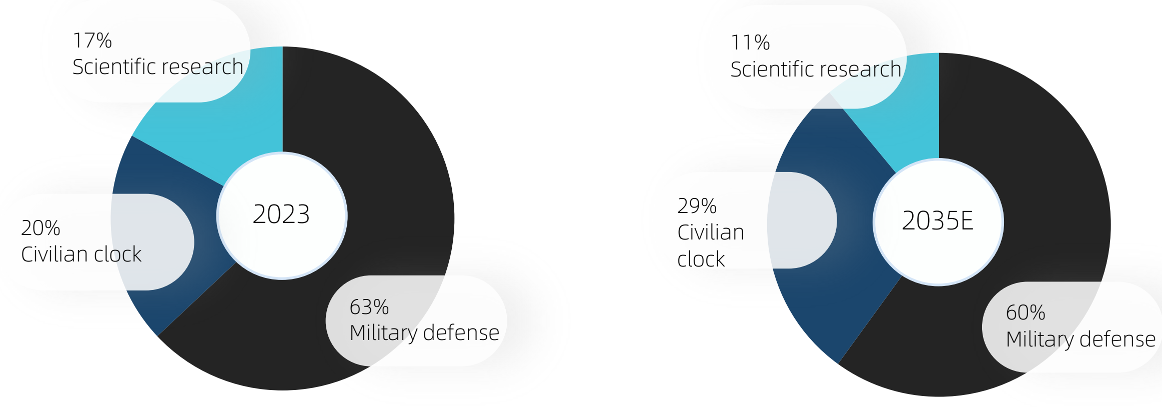
In extreme environments such as space exploration and deep-sea exploration, the stability and reliability of quantum clocks are highly valued, providing reliable time support for research and engineering.

The demands in these various sectors are driving the continuous expansion of the quantum clock market. In the future, quantum clock technology will continue to evolve, improving its precision and performance, further stimulating market demand and driving market growth. New application scenarios may continue to emerge, such as in finance, healthcare, energy, and other fields, bringing more growth opportunities to the market.

Market Size of Global Quantum Clock Segments

The global demand for quantum clocks is primarily driven by the defense industry, with aerospace being the main downstream application. In recent years, the maritime sector has witnessed an increase in scale, and the civilian sector has experienced rapid market share growth, thanks to the development of mobile communication technologies. This has led to significant growth in the overall market size.

Figure: Quantum Clock's Main Application Field Share and Private Field Subdivision Share (Unit: %)



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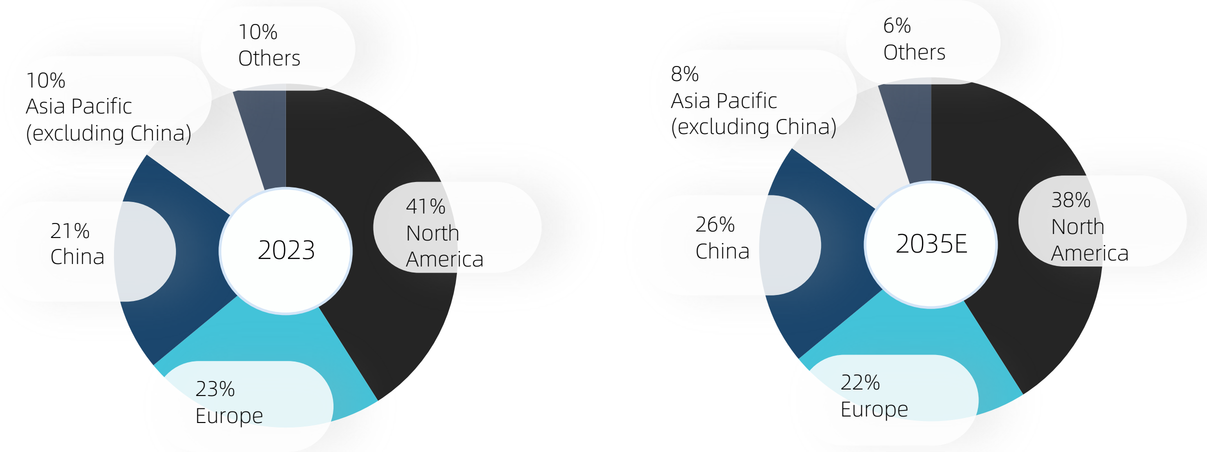
In 2023, the application of quantum clocks is mainly concentrated in the military field, accounting for about 63% of the market share. However, according to ICV's predictions, with further research on technologies such as optical clocks and molecular clocks, as well as the advancement of 5G and information society infrastructure construction, the application of quantum clocks in the civilian field will grow rapidly. It is expected that by 2035, the market share in the civilian field will reach 29%.

In addition, as quantum clock technology matures, its applications in finance, therapy, energy and other fields will gradually increase. In the financial field, high-precision time measurement can be used to synchronize global trading systems and improve the efficiency and security of transactions. In the medical field, precise time measurement can be used to synchronize medical equipment, improving the accuracy of diagnosis and treatment. In the energy field, precise time measurement can be used to optimize energy distribution and use and improve energy efficiency.

Quantum clocks in North America may be the largest application area for quantum clocks due to their relatively early development and mature market; Europe and China have similar market shares and are currently the main areas of use; the Asia-Pacific region (excluding China) accounts for about 10% and other regions 5% is relatively small, and there is still great potential for development. Currently, all countries are vigorously developing quantum clocks, and by 2035, the share will not change much.

Figure: Quantum Clock's Main Application Field Share and Private Field Subdivision Share (Unit: %)



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03 Quantum Gravimeter & Gravity Gradiometer

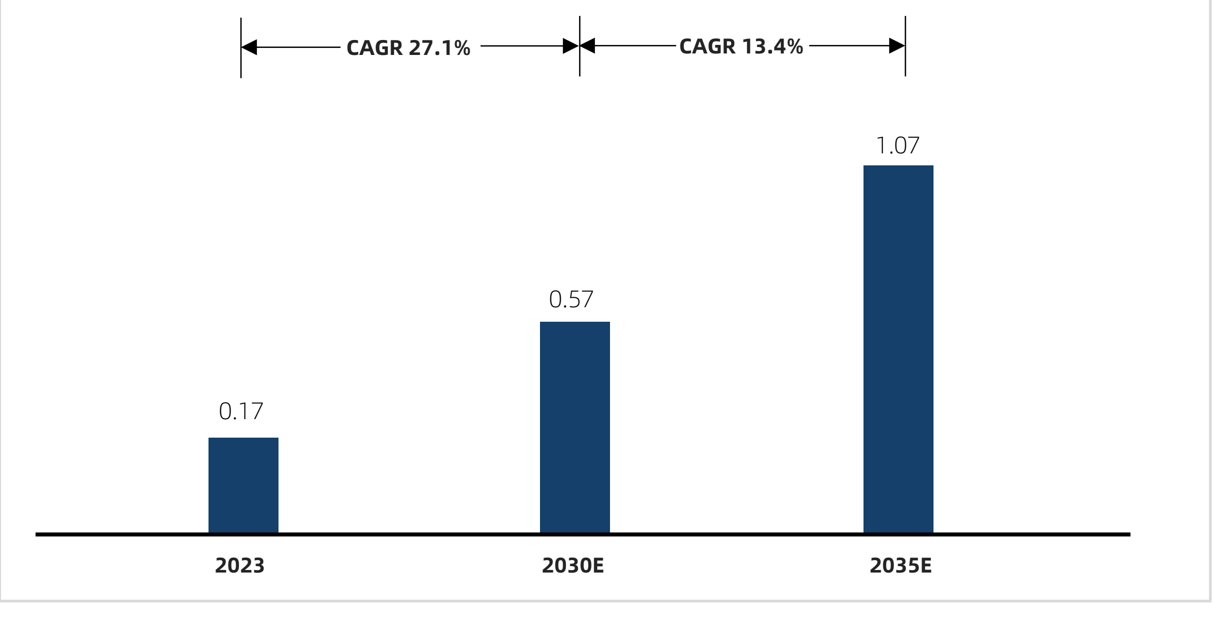
Global Quantum Gravimeter & Gravity Gradiometer Market Size

As the demand for precise measurements of gravity fields and gradients in scientific research and engineering applications continues to increase, quantum gravity meters and quantum gravity gradient meters have been widely used in geological exploration, oil and gas exploration, and other fields due to their advantages such as high reliability in dynamic environments and drift-free operation.

With the continuous improvement in the performance of quantum gravity measurement devices, the market is gradually seeing their potential to replace traditional classical gravity meters. Their higher sensitivity and anti-interference ability give them advantages in complex geological environments. In addition, highly integrated quantum sensor systems not only improve measurement accuracy but also expand the range of applicable working environments, including applications in extreme conditions. It is expected that in the coming years, they will further replace classical relative gravity meter equipment.

According to ICV, the market for quantum gravity meters and quantum gravity gradient meters is expected to show strong growth. The market size is projected to increase rapidly from $170 million in 2023 to $1.07 billion in 2035, with a compound annual growth rate of 15.21%, highlighting the huge potential in this field.

Figure: Quantum Gravimeter & Gradiometer Market Size (2023-2035, Unit: $B)



Driven by technological innovation, increased market awareness, and growing demand for high-precision measurements across various industries, ICV anticipates that 2027 will be a pivotal year for the quantum gravimeter and quantum gravity gradiometer market. In this year, the market size is expected to witness significant growth, surpassing traditional instruments and accelerating the replacement of classical gravimeters.

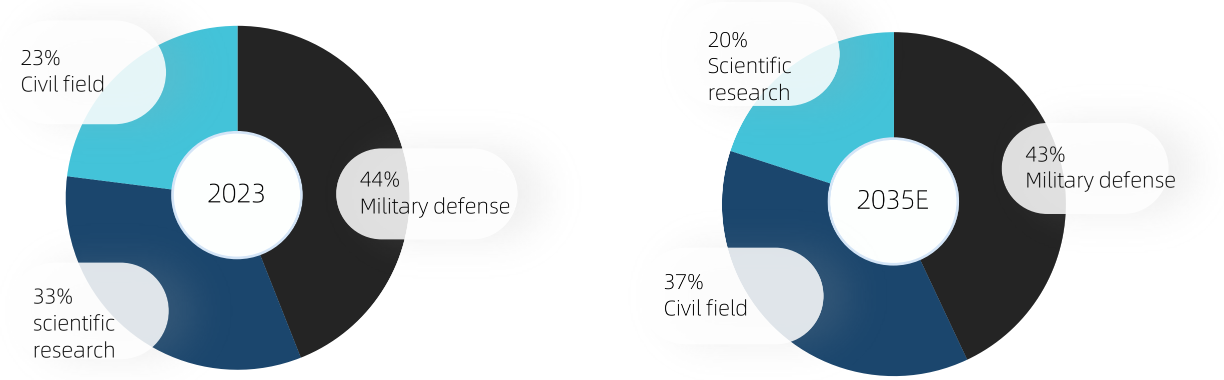
Looking ahead, as the technology of quantum gravimeters and quantum gravity gradiometers matures, their applications in fields such as Earth sciences, resource exploration, and environmental monitoring are poised to expand further, injecting new growth momentum into the market.

With continuous innovation in quantum technology, the coming years may see the emergence of more advanced and higher-performance quantum gravimeters and quantum gravity gradiometers, further propelling the market's development.

Global Quantum Gravimeter & Gravity Gradiometer Market Size

In the future, the quantum gravity measurement instrument market is expected to shift more towards civil applications, especially in the field of oil and gas exploration. The competition will be intense, and companies will need to maintain competitiveness in areas such as technological innovation, market promotion, and cost-effectiveness to seize future growth opportunities.

Figure: Share of Main Application Fields of Quantum Gravimeter & Gradiometer and Share of Subdivided Fields in Private Sector (Unit: %)



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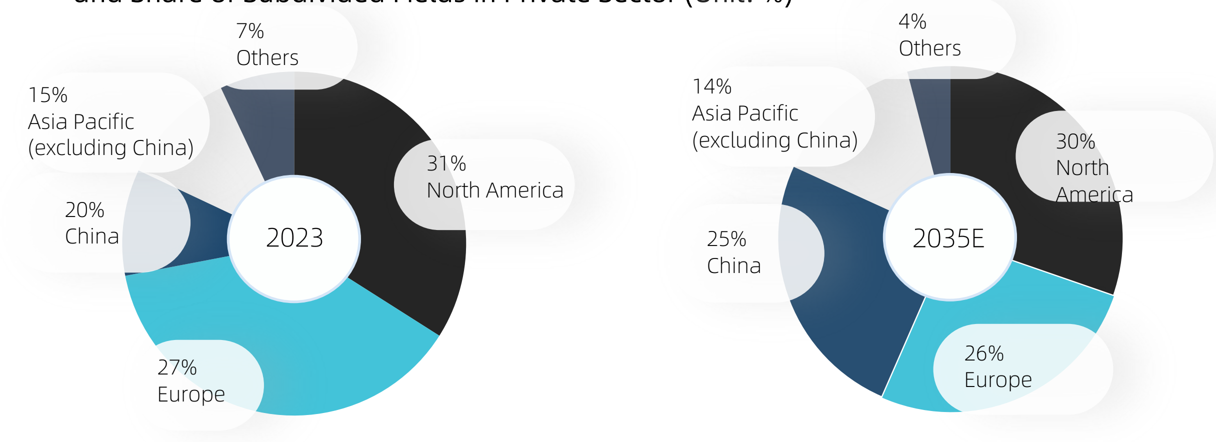
Quantum gravimeters and gradient meters are primarily utilized in the military sector, with ICV predicting that the military defense sector will hold a 44% market share in 2023. Following closely is the research sector, accounting for a 33% share, while the civil market associated with oil and gas exploration holds a 23% share. This indicates that in the early stages, quantum gravity measurement instruments were primarily concentrated in military and research applications, with a relatively smaller share in the civil market. However, as technology matures and downstream application markets expand, the pricing and performance of products will play a crucial role, especially in the civil market. In the future, civil applications of quantum gravity/gravity gradient meters are expected to capture a 37% market share.

The current market share is predominantly concentrated in the United States and the Asia-Pacific region, holding 31% and 35% shares, respectively. Applications mainly include geological exploration and scientific research. ICV anticipates that by 2035, China's share will rise to 25%, indicating that in the coming years, China is poised to become a primary growth driver in the quantum gravity measurement instrument market.

Figure: Share of Main Application Fields of Quantum Gravimeter & Gradiometer and Share of Subdivided Fields in Private Sector (Unit: %)



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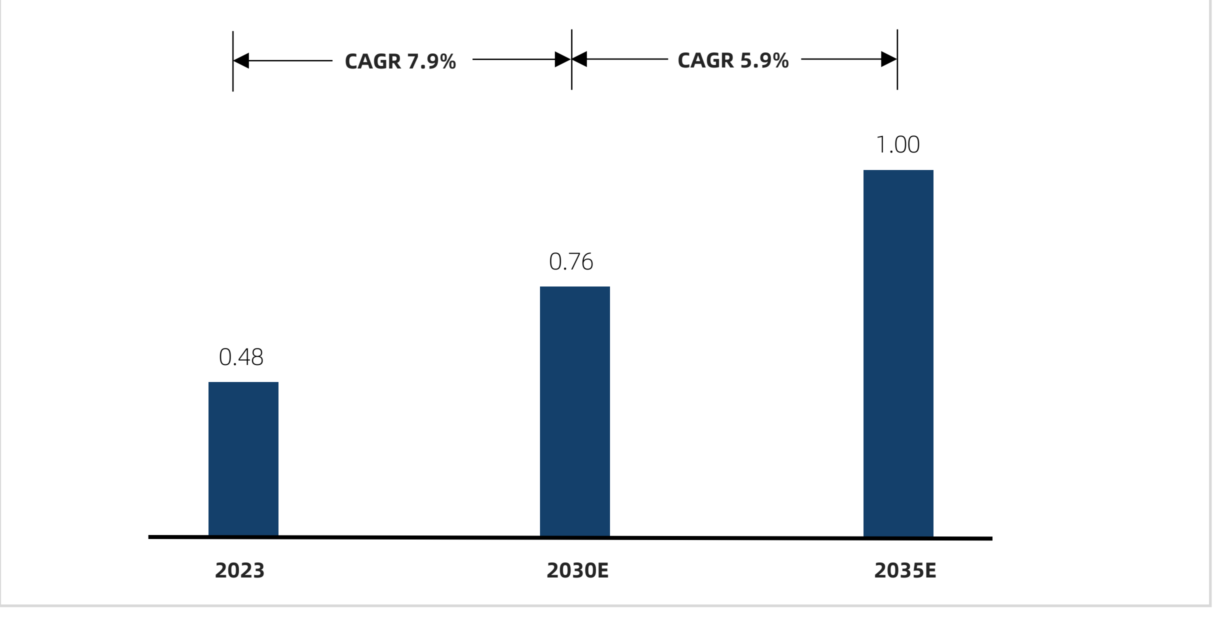
04 Quantum Magnetometer

Global Quantum Magnetometer Market Size

The application of quantum magnetometers in scientific research is increasingly widespread, especially in the fields of physics, earth sciences, and biomedical research. Simultaneously, in the industrial sector, quantum magnetometers find extensive use in magnetic material testing, electronic manufacturing, and other areas, providing high-precision magnetic information for industrial processes. The expansion of these applications further propels the growth of the market.

The quantum magnetometer market exhibits robust growth from 2023 to 2035, rising from $480 million in 2023 to $1.0 billion in 2035. This growth trend is primarily driven by the continuous demand for high-precision magnetic measurements in scientific research, the industrial sector, and other fields during this period.

Figure: Quantum Magnetometer Market Size (2023-2035, Unit: $B)



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The high precision and sensitivity of quantum magnetometers make them crucial tools in the field of new material research. In areas such as new energy materials and magnetic materials, scientists require accurate measurements of magnetic field characteristics to drive innovation and development in new materials. With the increasing demand for new materials, quantum magnetometers are poised to play a key role in this domain.

Geological exploration stands out as a significant application of quantum magnetometers in the civilian sector. Their use in detecting mineral resources, petroleum, and natural gas reserves will be a major driver of future growth. The high sensitivity and resolution of quantum magnetometers relative to traditional instruments make them excel in underground resource exploration.

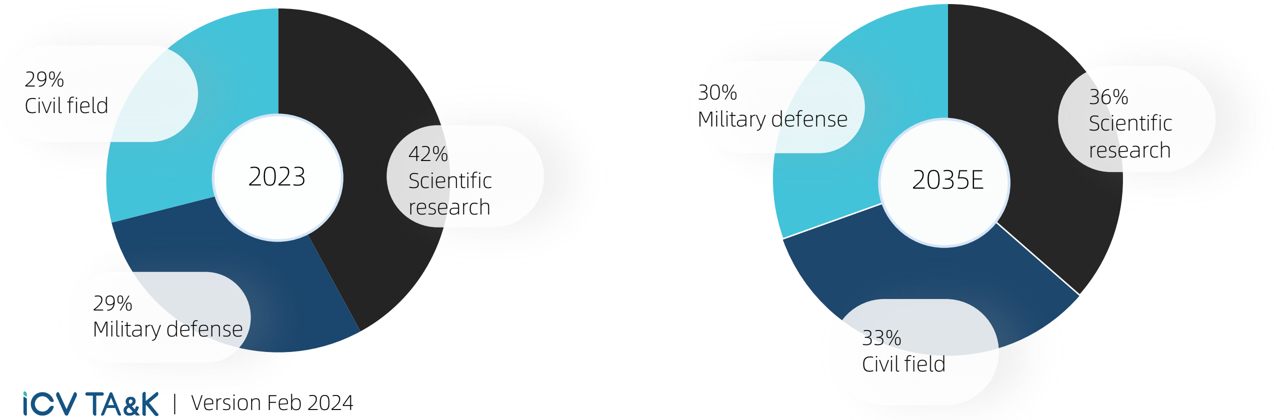
In the field of medical imaging, the application of quantum magnetometers is expected to expand further. Their high-precision magnetic field measurement capabilities can be used for biomagnetic field imaging, providing more detailed data for neuroscience and brain research. This advancement will propel medical imaging technology to higher levels, offering more accurate diagnostic tools for clinical medicine.

With continuous innovation in quantum technology, future quantum magnetometers are expected to introduce more advanced, portable, and efficient products. This will further expand their application areas, including drone-based magnetic field measurements, mobile magnetic field monitoring, and other fields, providing users with more convenient solutions.

Market size of Global Quantum Magnetometer Segments

The competitive landscape of the global magnetometer market is influenced by regional scientific research strength and technological innovation. Mature technologies and industrial chains in Europe and the United States have driven market concentration. The Asia-Pacific region is expected to gain a larger market share in the future by increasing its research and development efforts on new magnetometers.

Figure: Quantum Magnetometer's Main Application Field Share and Private Field Subdivision Share (Unit: %)



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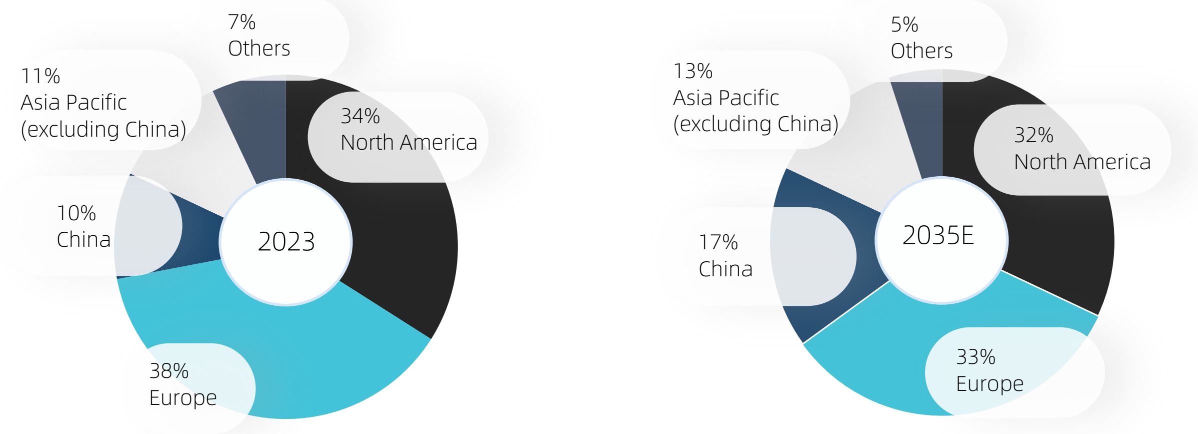
In terms of future trends, further research on optical clocks and molecular clocks will increase the market for basic research. However, the infrastructure construction of civilian 5G and information society will cause the time and frequency market in the civilian field to grow more rapidly. In the future, quantum clocks may have more application areas, such as determining altitude through tiny time differences at different altitudes. Quantum clocks in North America may be relatively weak due to development

Due to the leading position in quantum technology development and the faster industrialization process in Europe and North America, these regions currently account for over two-thirds of the market share. The Asia-Pacific region is expected to increase its efforts in the research and development of new quantum magnetometers in the future. Particularly in areas such as Optical Magnetometers (OPM) and NV Center Magnetometers, the Asia-Pacific region is poised to capture a portion of the market share. By 2035, it is anticipated that the Asia-Pacific market share will expand to approximately 30%, with China accounting for around 17%. This trend reflects the potential and growth momentum of the Asia-Pacific region in the technological research and application promotion of quantum magnetometers.

Figure: Quantum Magnetometer's Main Application Field Share and Private Field Subdivision Share (Unit: %)



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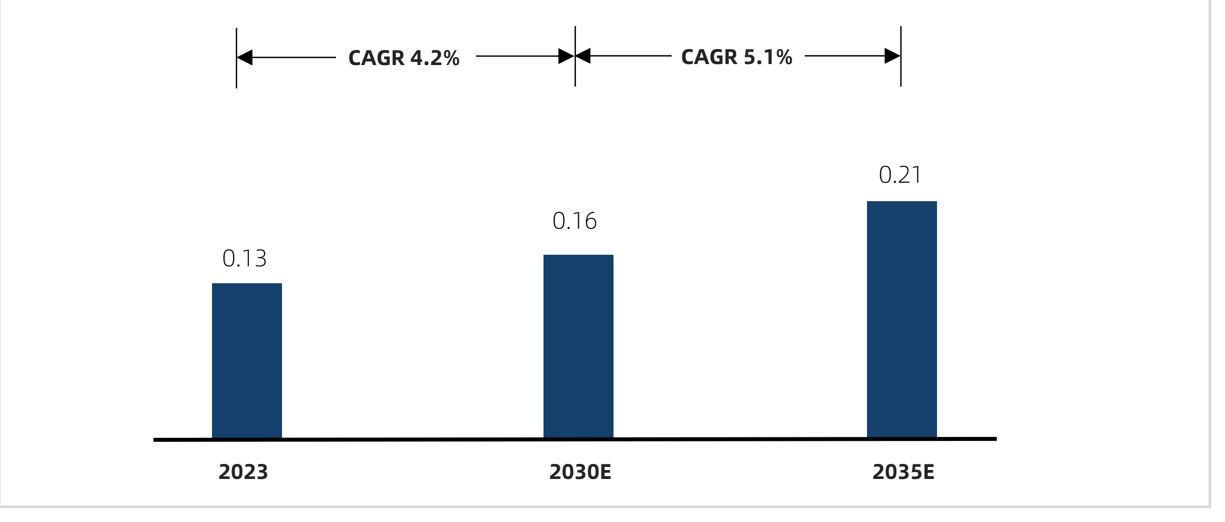
05 Quantum Radar

Global Quantum Radar Market Size

With continuous technological innovation and the growing demand in the market, quantum radar is poised to play a crucial role as an advanced measurement technology in the future market. In the military defense sector, the high sensitivity and resolution of quantum radar make it an ideal choice for monitoring, tracking, and identifying targets. Additionally, the scientific research field has shown keen interest in its unique capabilities for detecting distant objects and subtle changes.

According to the latest market data, ICV anticipates a year-over-year increase in the global market share of quantum radar. It is projected that by 2035, the market size will reach $210 million.

Figure: Quantum Radar Market Size (2023-2035, Unit: $B)



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Some classical radar systems currently in the market have already adopted various enhancement technologies, which to some extent, slow down the market penetration of quantum radar. Traditional radar systems are quite mature in terms of performance, and they may still have a competitive advantage in cost-effectiveness. The comprehensive application of quantum radar technology, especially the difficulty in achieving quantum emission, may require more research and investment. This, in the short term, means that some quantum radars are not significantly cost-effective, limiting their widespread application in the market.

Secondly, the relatively small market share may also be related to the market's acceptance and understanding of quantum technology. As an advanced measurement technology, the principles and advantages of quantum radar may need more time to be widely recognized and accepted. Efforts in education and increasing users' awareness of quantum radar technology may be necessary to better convey its practical application value to the market.

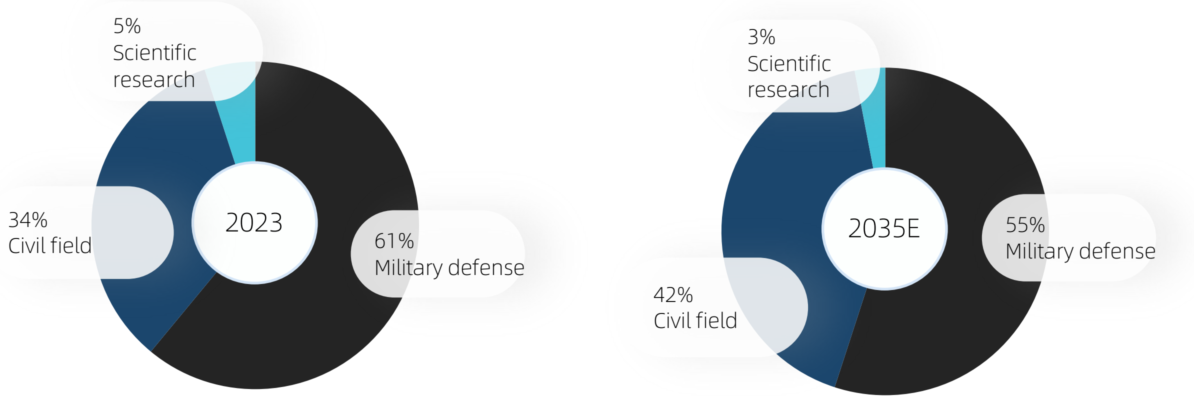
Furthermore, compared to other quantum technologies, quantum radar may face more stringent technical challenges, such as achieving quantum emission. These challenges may require more research and innovation, resulting in a relatively slow process of technological commercialization.

Despite these challenges, the future market outlook remains promising. Through continuous performance optimization, solving technical challenges, increasing awareness, and reducing costs, quantum radar is expected to achieve larger-scale market penetration in the coming years. In this process, technology developers, governments, academia, and various stakeholders in the industry chain will play crucial roles in collectively driving the commercialization and industrialization of quantum radar technology.

Market Size of Global Quantum Radar Segments

The military defense sector has consistently been the primary driving force for quantum radar applications, with its demand for high sensitivity and high resolution leading to rapid advancements in quantum radar technology. North America has maintained a leading position in military technology and innovation, while China has gradually emerged in research and commercial domains, influencing the global distribution of quantum radar to some extent.

Figure: Quantum Radar's Main Application Field Share and Private Field Subdivision Share (Unit: %)



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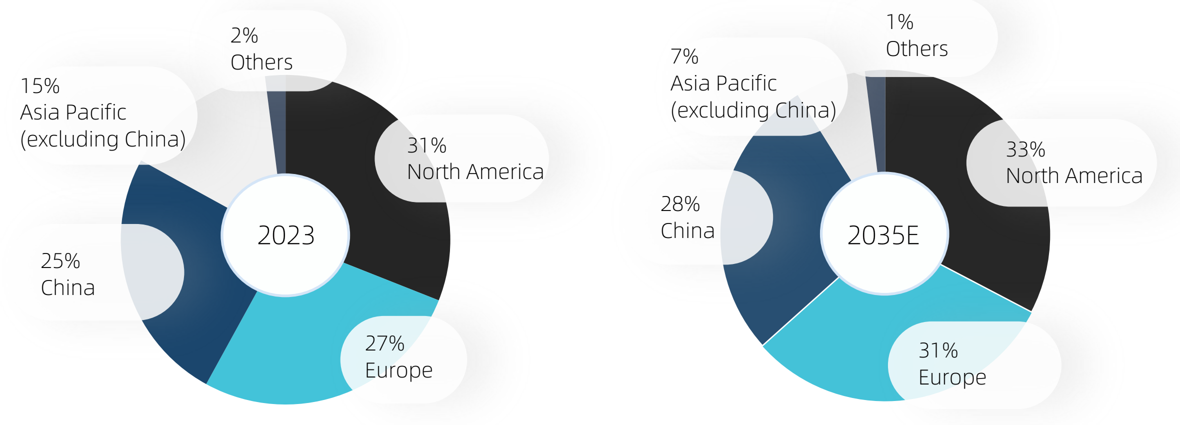
From the perspective of the application market, quantum radar dominates in the military defense sector. In 2023, the market share for military defense is 61% and 55%, respectively. This indicates a high demand and advantage for quantum radar in military applications. In military contexts, the high sensitivity and resolution capabilities of quantum radar make it an ideal choice for target monitoring, tracking, and identification, playing a crucial role at both tactical and strategic levels. The civilian sector is also a leading force in quantum radar innovation, with China gradually emerging in research and commercial domains, influencing the global distribution of quantum radar to some extent.

In terms of regional distribution, North America has consistently been a major region in the quantum radar application market. However, by 2023, its market share has increased from 31% to 33%. This shift may indicate a strong interest in quantum radar from North American defense and research sectors, as well as emerging applications in civilian domains. Concurrently, China's market share has risen from 25% to 28%, highlighting the growth potential of the Asia-Pacific region in the quantum radar market.

Figure: Quantum Radar’s Main Application Field Share and Private Field Subdivision Share (Unit: %)



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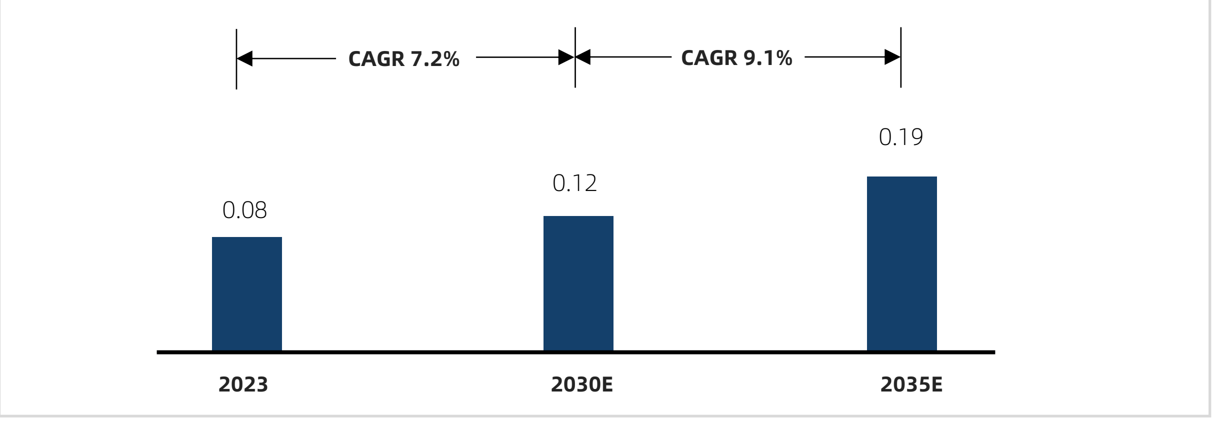
06 Quantum Accelerometer & Gyroscope

Global Quantum Accelerometer & Gyroscope Market Size

With the continuous advancement of technological capabilities, the global market for quantum accelerometer & gyroscope is experiencing robust growth. Looking at the data from 2023 to 2035, the market demonstrates a steady upward trend with a Compound Annual Growth Rate (CAGR) of 6.77%. The market size is projected to increase from $65 million in 2023 to an estimated $187 million in 2035, nearly tripling in overall size.

Figure: Quantum Accelerometer & Gyroscope Market Size (2023-2035, Unit: $B)



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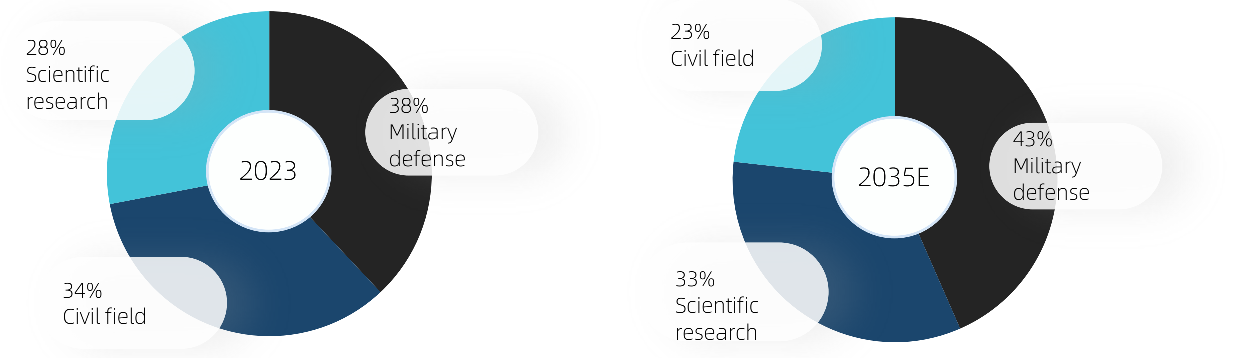
This growth is primarily driven by several factors. Firstly, the increasing demand for high-precision and high-stability sensors in fields such as scientific research, navigation, and industrial automation has led to the widespread application of quantum accelerometer & gyroscope, which are essential components in meeting these requirements. Secondly, continuous technological innovation and upgrades have enabled quantum accelerometer & gyroscope to excel in extreme environments, fulfilling the needs of various specialized scenarios, such as aerospace and military applications.

In the future, with the continuous improvement of the global industrial chain, quantum accelerometer & gyroscope are expected to find applications in a broader range of fields, including but not limited to autonomous driving, intelligent transportation, virtual reality, and more. As market awareness increases and costs decrease, quantum technology will further penetrate various industries, driving the continuous expansion of the market. Therefore, quantum accelerometer & gyroscope, as crucial advanced sensor technologies, will continue to play an irreplaceable role in contributing to global technological advancement and industrial upgrading in the coming years.

Market Size of Global Quantum Accelerometer & Gyroscope Segment

The global market share distribution worldwide reflects variations in demand across regions and sectors in military, civilian, and scientific domains. The diverse demands from different sectors and regions create a multi-layered and diversified market landscape.

Figure: Quantum Accelerometer & Gyroscope Main Application Field Share and Private Field Subdivision Share (Unit: %)



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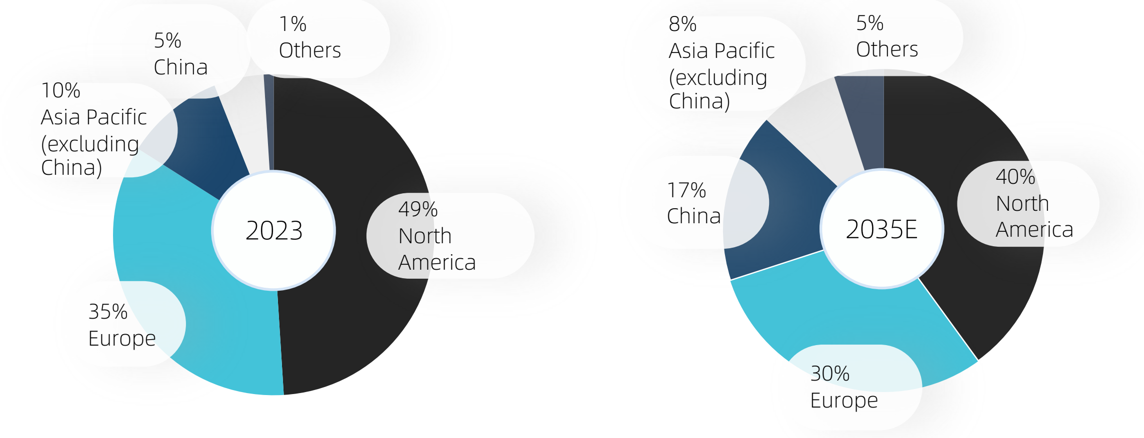
From the perspective of application areas, military defense has consistently been one of the primary application domains for quantum accelerometer & gyroscope, with significant market shares of 38% and 43% in 2023. This is attributed to the outstanding performance of this technology in military applications such as missile guidance and aircraft stabilization. Additionally, civil and scientific sectors each hold market shares of 34% and 33%, as well as 23% and 23%. This indicates that quantum accelerometer & gyroscope have found widespread applications in civil and scientific fields, especially in high-precision navigation, industrial automation, and scientific research.

In terms of regional distribution, North America has consistently been the predominant market, holding market shares of 49% and 40% in 2023. This reflects North America's leading position in high-tech industries and defense technology. Europe follows closely, with market shares of 35% and 30%. China's market share in this field has been gradually increasing, rising from 5% in 2023 to 17%, indicating China's rapid ascent in the application of quantum technology. The Asia-Pacific region (excluding China) and other regions occupy relatively smaller market shares.

Figure: Quantum Accelerometer & Gyroscope Main Application Field Share and Private Field Subdivision Share (Unit: %)



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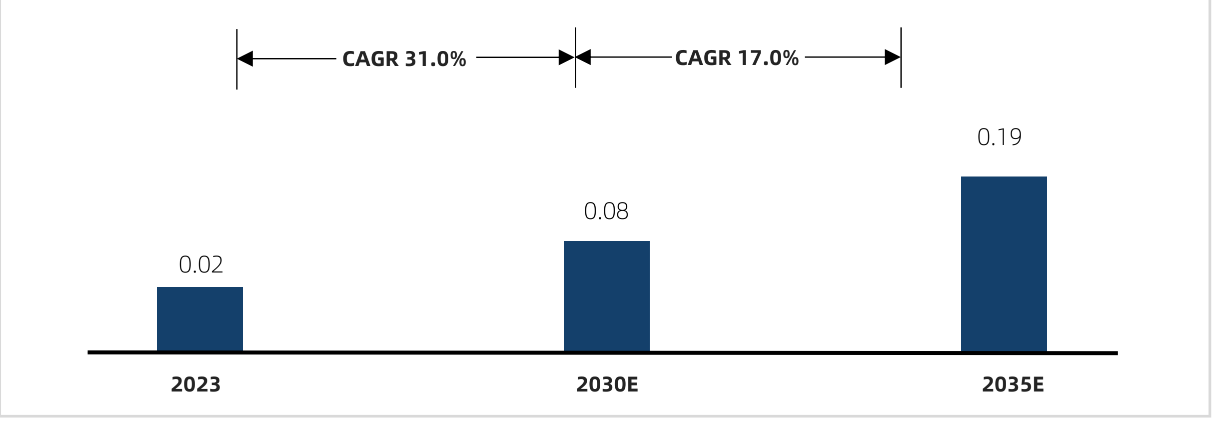
07 Quantum Field Strength Meter

Global Quantum Electric Field Strength Meter Market Size

The quantum electric field meter demonstrates a clear market growth trend and potential. Despite its relatively small market size in 2023, standing at just $0.21 billion, it is projected to reach $1.85 billion by 2035, with an impressive CAGR of 21.51%.

While the current market size is relatively modest, the future holds significant promise for quantum electric field meters, driven by continuous innovation and enhancement in Rydberg atom field strength measurement technology. Quantum electric field meters are expected to find extensive applications in scientific research, material science, and energy and power fields. They are poised to become a pivotal growth factor in the realm of quantum precision measurement technology.

Figure: Global Quantum Electric Field Strength Meter Market Size (2023-2035, Unit: $B)



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From a technical advantage perspective, Rydberg atom field strength meters exhibit characteristics of repeatability, precision, and stability. This uniqueness grants them a competitive edge in the electric field measurement domain. High sensitivity and resolution are notable features of Rydberg atom field strength meters, providing scientists with a powerful tool to delve into the microscopic impact of electric fields on matter. This plays a constructive role in advancing frontier research in fields like material science and quantum information, offering scientists possibilities for breakthroughs under electric field control.

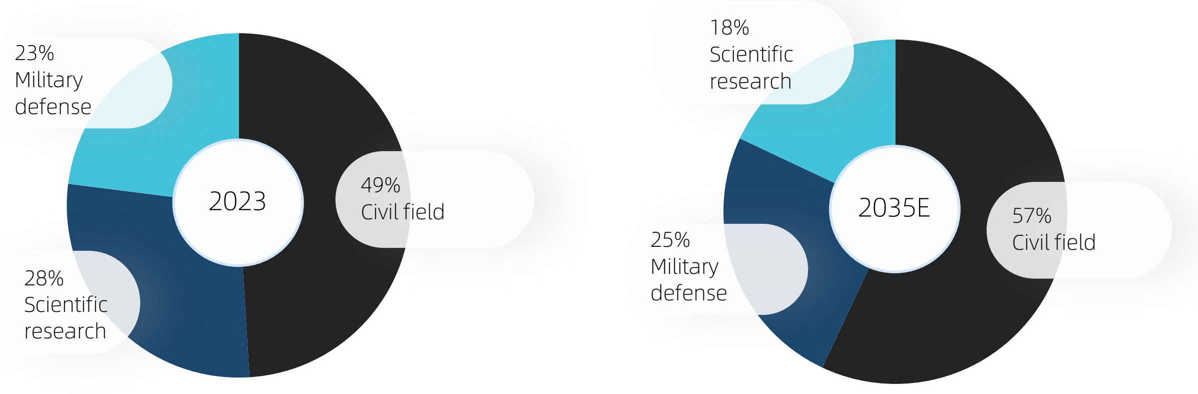
Despite optimistic market prospects, the Rydberg atom electric field strength measurement technology is currently facing a lack of industry standards. This situation may pose challenges to its further market penetration and development. In-depth data analysis reveals that the absence of industry standards may result in varying degrees of market acceptance of new technologies, limiting their application in broader fields. This is why, in the coming decade, Rydberg atom electric field strength measurement technology needs to emphasize collaboration with the industry, standard development, and other means to address this challenge and drive its technological penetration in the market.

By closely collaborating with the industry and actively participating in the process of industry standard development, Rydberg atom technology is poised to enhance its recognition in the market. Simultaneously, standardization will aid in regulating market behaviors, reducing entry barriers, and creating a more stable and predictable development environment for Rydberg atom electric field strength measurement technology. In the future, with gradually improved standards, Rydberg atom technology is expected to more extensively leverage its technological advantages in the quantum electric field measurement field, fostering further prosperity throughout the industry.

Market Size of Global Quantum Electric Field Strength Meter Segments

The market dynamics of quantum electric field strength meters have been influenced by diverse demands from various sectors, including military defense, civilian applications, and scientific research. The distinct requirements from these sectors have driven fluctuations in market share, playing a crucial role in shaping the market dynamics.

Figure: Quantum Electric Field Strength Meter's Main Application Field Share and Private Field Subdivision Share (Unit: %)



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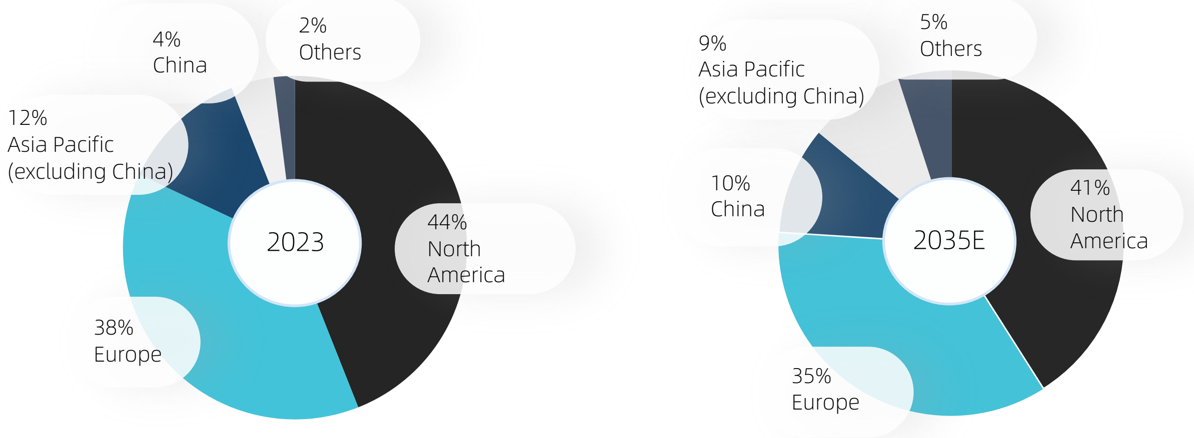
In the military defense sector, the market share for quantum electric field strength meters was 23% in 2023, increasing to 25% by 2035, indicating a relatively moderate overall growth rate. This suggests the relative stability of military demand for quantum electric field strength meters. The high bandwidth and sensitivity of quantum electric field strength meters make them more readily accepted in the civilian sector, driving market share growth. In the same period, the market share in the civilian sector increased from 49% to 57%, while the market share in the scientific sector decreased from 28% to 18%.

In terms of regional distribution, North America has consistently maintained a significant market share, accounting for 44% in 2023 and slightly decreasing to 41% by 2035. This indicates a robust market demand for quantum electric field strength meters in North America, although facing some competition from other regions, notably the impact of the Chinese market. The European market maintains a dominant position with market shares of 38% in 2023 and 35% in 2035, experiencing a slight decrease but retaining its advantage.

Figure: Quantum Electric Field Strength Meter's Main Application Field Share and Private Field Subdivision Share (Unit: %)



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08

Industry Outlook

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Industry Outlook

01 Quantum Clock Measurement

Atomic clocks will evolve towards high performance, autonomy, low power consumption, and portability.

Atomic clock technology has demonstrated excellent performance in both scientific experiments and practical applications. Future trends will focus on continuously improving performance while expanding into a wider range of application areas. With advancing technology, atomic clocks will further enhance frequency stability and extend their holdover time to meet the demands for higher precision and longer-term synchronization in various fields. This will make atomic clocks more suitable for future scientific research, navigation, communication, and other fields, becoming a more widely used tool for time and frequency measurement.

In the face of GNSS vulnerabilities and network attacks, the reliability and security of atomic clock technology will be key development directions. As dependence on the Global Navigation Satellite System (GNSS) increases, concerns about its susceptibility to interference and attacks are also rising. The future development of atomic clock technology will focus on providing better performance while ensuring the security of the system when facing potential threats. This will drive researchers and companies to increase investment in technology upgrades and innovations to ensure that atomic clocks are adequately protected in various applications.

Optical clocks are the next generation of time and frequency measurement products.

Rubidium and cesium clocks, as the most mature and widely used atomic clock technologies, have a large market size but are limited by physical limits. Optical clocks, on the other hand, are the most advanced and highest precision atomic clock technology, with a relatively smaller market size but higher frequency stability and accuracy. In the future, the development of atomic clock technology will focus on overcoming physical limits, further improving precision and stability, while reducing costs to meet different market demands. Optical clocks are expected to redefine the second and gradually replace traditional rubidium and cesium clocks to play a greater role in a wider range of applications.

02 Quantum Magnetic Field Measurement

The development of quantum magnetometer technologies will continue to be diverse, with various approaches showing unique advantages in different fields

Atomic (SERF, etc.), solid-state spin (diamond NV centers, etc.), and superconducting (SQUID, etc.) systems have demonstrated unique advantages in various fields, each suitable for different application scenarios. For example, superconducting quantum sensors excel in measuring extremely weak magnetic fields and are widely used in geological exploration and medical diagnostics. The diamond NV center magnetometer features high sensitivity and good biocompatibility without the need for cryogenic cooling. Its biological signal imaging approaches the theoretical optical diffraction limit, offering excellent spatial resolution and a wide operating temperature range, making it ideal for magnetoencephalography (MEG), magnetocardiography (MCG), and scientific research on biomolecules. The diamond NV center sensor has experienced rapid development in recent years and is being applied in more fields.

Currently, single NV center-based magnetic measurement technology has achieved nanoscale resolution in sensitivity and can detect single nuclear spins. In terms of applications, ensemble NV center-based magnetometers have detected magnetic signals produced by worm neurons, conducted eddy current imaging, and detected minerals in paleomagnetism.

Quantum magnetometers will continue to follow a diverse development trend, providing customized solutions for different industries and scenarios.

Quantum magnetometers will continue to pursue higher sensitivity, bandwidth, and resolution performance metrics

The key performance metrics of quantum magnetic field sensors include sensitivity, bandwidth, and resolution. For example, improving the preparation techniques and measurement methods of quantum states can enhance the sensitivity of sensors, allowing them to detect weaker signals. Simultaneously, optimizing the signal processing algorithms and hardware structure of sensors can improve their bandwidth and resolution, enabling more accurate signal identification and analysis. These efforts will enable quantum sensors to play a more significant role in scientific research, industrial production, and other fields.

In the United States, SandboxAQ uses quantum sensors to measure the Earth's magnetic field with high sensitivity to provide continuous navigation. The system captures signals from the Earth's magnetic field as an unchangeable Earth "fingerprint" and compares the signals with existing map data to improve overall location accuracy. Genetesis in the United States uses the SERF magnetometer in its CardioFlux MCG to identify myocardial ischemia in the heart, especially coronary microvascular disease (CMD).

Miniaturization, low power consumption, and cost-effectiveness are another important development direction for future quantum magnetometers

As technology continues to advance, quantum magnetometers are expected to become smaller, more energy-efficient, and more affordable, moving towards chip-scale integration. Additionally, organizations are placing more emphasis on integrating different types of magnetometer technologies to provide users with more comprehensive information and data from multiple perspectives, thereby expanding their application range. For example, in scientific research, quantum magnetometers can help scientists explore deeper physical laws. In the field of national defense and security, quantum magnetometers can be used for precision navigation and joint positioning. In the field of electric power energy, quantum magnetometers can be used for non-destructive testing and fault location of electric power equipment.

Quantum magnetometers are driving a revolution in metrology traceability, with profound implications for the field of metrology

The key difference between quantum sensors and traditional sensors lies in their ability to be remotely traced. Traditional sensors require a hierarchical measurement approach to ensure the reliability of their readings, whereas quantum sensors can be calibrated through remote tracing. This flat tracing model is expected to become part of the future international quantumization revolution.

Currently, the future development of the international quantumization revolution mainly includes two aspects. First is the quantumization of measurement standards, replacing the first standard with a quantumized approach. Second is the flattening of measurement transfer, with remote tracing being an intermediate transitional mode. In this development process, remote tracing and remote calibration have become directions for exploratory research. For example, quantum voltage and current sensors can ensure the accuracy of measurements through remote calibration based on frequency, opening up new possibilities for the development of metrology.

03 Quantum Gravity Measurement

Gravimeters will trend towards miniaturization or lower cost, and there is a need to further expand their application scenarios to fully leverage their advantages in dynamic measurement.

With the continuous advancement of technology, gravimeters are expected to become more miniaturized. This will make gravimeters more adaptable to different fields and application scenarios, thereby expanding their range of applications. Through miniaturization, gravimeters can be more flexibly integrated into various devices to meet a wider range of dynamic measurement needs, such as applications in industrial automation, building monitoring, and mobile devices.

In addition, cost reduction is also an important direction for the future development of gravimeters. By reducing manufacturing costs, more industries and fields can afford the application of this technology. This will further promote the popularization and application of gravimeters in the market, providing high-quality dynamic measurement solutions for more industries.

Quantum gravimeters are tending towards having natural processing and sensing capabilities, i.e., becoming more intelligent and user-friendly.

In the future, quantum gravimeters are expected to have more natural data processing and sensing capabilities, making them more intelligent. This will help reduce the threshold for use, allowing non-professionals to easily operate and obtain high-quality measurement data.

Quantum gravimeters may adopt advanced data processing algorithms and artificial intelligence technologies to more effectively analyze and interpret measurement data. This will increase the level of automation of the instrument, reduce the operational burden on users, and make the instrument more easily applied in different fields. Furthermore, by simplifying the operation interface of the instrument and providing user-friendly software interfaces, quantum gravimeters will be more easily used widely, not only limited to professional fields, further promoting the expansion of quantum gravimeters in more practical scenarios.

04 Quantum Inertial Measurement

Cold atom interferometric accelerometers and gyroscopes are the core sensors for next-generation inertial navigation.

For cold atom interferometric accelerometers, one of the future development directions is to address the "dead time" issue, where the instrument may fail to respond in cases of rapid acceleration or abrupt changes. Improving measurement availability will be an important goal to ensure efficient and accurate measurements in various real-world application scenarios.

Cold atom interferometric gyroscopes will focus more on achieving measurements of three-axis acceleration. This will not only improve the navigation system's perception of motion states but also help in better understanding the changes in the acceleration field, enhancing overall system performance.

Future development directions also include improving the overall system performance by optimizing various components of the instrument, integrating advanced control algorithms, enhancing anti-interference capability, and stability to meet the demand for high precision and stability in different application scenarios.

Gyroscopes will continue to advance towards high precision, high reliability, and miniaturization, and low cost.

In terms of high precision, nuclear magnetic resonance gyroscopes have improved bias stability through self-calibration methods, and NV center gyroscopes' diamond nanocone structures are expected to impact micro-nano optical designs, improving overall system performance. By improving the control and measurement technology of quantum states, optimizing the core components of gyroscopes, the performance of gyroscopes in navigation, aerospace, and other fields will be significantly improved. In the future, research institutions will continue to focus on improving the accuracy of gyroscopes to meet more refined and complex navigation and timing application requirements.

In terms of high reliability, miniaturization, and low cost, for gyroscopes, technology roadmap assessments suggest that improving the overall system performance is one of the key tasks for the future. Engineering applications and research on three-axis acceleration measurement and other technologies will promote the application of gyroscopes in micro-nano scales, such as drones and mobile devices, while improving their feasibility in commercial applications. To address the bias stability issue, new materials or structural designs may be introduced in the future to make gyroscopes more adaptable to complex and high-acceleration environments, more widely used in practical engineering scenarios, including aerospace navigation, high-speed transportation, precision instruments, etc., and continuously promote the upgrading and improvement of gyroscope technology.

05 Quantum Target Identification

Quantum radar will appear in the medium and short term in a "classic-quantum dual-channel" system form.

While maintaining the application scenarios and technological capabilities of current classic radars, quantum radar enhances radar performance by utilizing the high precision and sensitivity of quantum channels. The dual-channel system form allows quantum radar to better adapt to various complex environments and extreme weather conditions. By combining the robustness provided by classic radar with the high sensitivity of quantum radar, the system can maintain efficient and stable performance even under harsh conditions. The adoption of the dual-channel system form will allow the radar system to achieve comprehensive performance improvements by considering factors such as radar dynamic range, sensitivity, and bandwidth. This will help address the challenges faced by quantum radar technology in detecting diverse targets.

Rydberg atom antennas will develop towards high sensitivity, wide bandwidth, high instantaneous bandwidth, and multi-array detection direction.

The application of Rydberg atom antennas can improve the sensitivity of quantum radar in the microwave frequency range, making it more sensitive to detect weak signals. This is of great significance for applications in military, communication systems, and astronomical observations. Future Rydberg atom antennas will pursue wider bandwidth and higher instantaneous bandwidth to meet the signal detection requirements at different frequencies and time scales. This will enhance the adaptability and flexibility of quantum radar in different application scenarios. To improve the accuracy of target positioning and the overall performance of the system, Rydberg atom antennas are expected to develop structures that support multiple array detection directions. This will enable quantum radar to simultaneously monitor signals from multiple directions, improving the system's omnidirectionality and multi-target detection capability.

06 Quantum Electric Field Measurement

Rydberg atom electric field strength meters will focus on improving bandwidth sensitivity and gradually perfecting related industry standards.

In the field of quantum electric field measurement, Rydberg atoms have already demonstrated their advantages in repeatability, accuracy, and stability. The high sensitivity and resolution of Rydberg atom field strength meters will help scientists deepen their understanding of the microscopic effects of electric fields on matter, promoting new breakthroughs in scientific research under electric field control. This will bring about a deeper understanding in fields such as materials science and quantum information.

Future research will focus more on achieving more accurate results in high-frequency electric field measurements, providing more comprehensive information for scientific research and applications, and promoting their indispensable role in researching microscopic physical phenomena in laboratory environments.

As quantum electric field measurement technology advances, it will become crucial to establish relevant standards. The development of Rydberg atom electric field strength meters will emphasize the necessity of standardization to ensure the comparability and reliability of measurement results across different laboratories and research teams. Organizations such as the International Organization for Standardization (ISO) may need to be involved in the development of these standards to promote the widespread application of this technology in various fields.

Diamond NV center field strength meters will focus on improving their adaptability to complex environments, with greater potential in the medical field.

Diamond NV centers, as a key technology in electric field measurement, have demonstrated superiority in imaging electric fields at the 10-nanometer level and precise control of charge states. Future research will focus on improving the measurement stability and resolution of diamond NV center field strength meters. By optimizing experimental conditions and technical parameters, more accurate electric field measurements are expected, especially in the high-sensitivity detection of small electric field intensities. This will enable their more extensive application in practical scenarios in the future, such as in communications, medicine, environmental monitoring, and other fields.

Future development will focus on improving their adaptability to complex environments to ensure reliable measurement solutions in practical applications. This includes adaptability to different substances and performance stability in complex electric field backgrounds. Additionally, the biocompatibility of diamond NV centers will become a competitive advantage for this technology in medical imaging applications. Future efforts should focus more on the biocompatibility of diamond NV center electric field strength meters, enabling their wide application in fields such as medicine.

07 Software Algorithm Cloud Platform

Software integration with algorithms and platforms enhances system flexibility and adaptability

Future software development will focus on integrating software, algorithms, and platforms in quantum precision measurement systems. This integration will make software and hardware more closely aligned, enabling dynamic adjustment of parameters and configurations to adapt to different application scenarios, providing users with more precise measurement results.

In the United States, Infleqtion has demonstrated software configuration and high-performance quantum-accelerated accelerometers by combining machine learning with quantum sensing. Sandbox AQ, in collaboration with the US Air Force, has successfully tested a magnetic anomaly navigation system based on quantum sensors, which is a composite system of artificial intelligence and quantum (AQ) technology, providing an alternative for GPS-denied or GPS-restricted environments.

In the future, quantum precision measurement software will not only provide basic measurement functions but also integrate more auxiliary functions on the platform, including machine learning, AI data visualization processing, result prediction analysis, and fault diagnosis, further improving user efficiency.

The development of algorithms will focus on enhancing the practicality and applicability of quantum sensors through the combination of reinforcement learning algorithms and deep neural networks.

This integration will optimize the estimation of multiple parameters, providing quantum sensors with more efficient and accurate performance. The design of algorithms will consider the characteristics of different quantum measurement types, achieving more comprehensive performance coverage to meet the needs of various application scenarios.

The model-free approach proposed by the University of Rome team combines reinforcement learning algorithms and deep neural networks to optimize the estimation of multiple parameters, which can be widely applied to optimize the performance of quantum sensors. This approach uses deep neural networks to model complex quantum systems and optimizes measurement strategies through reinforcement learning algorithms, effectively improving the performance of quantum sensors.

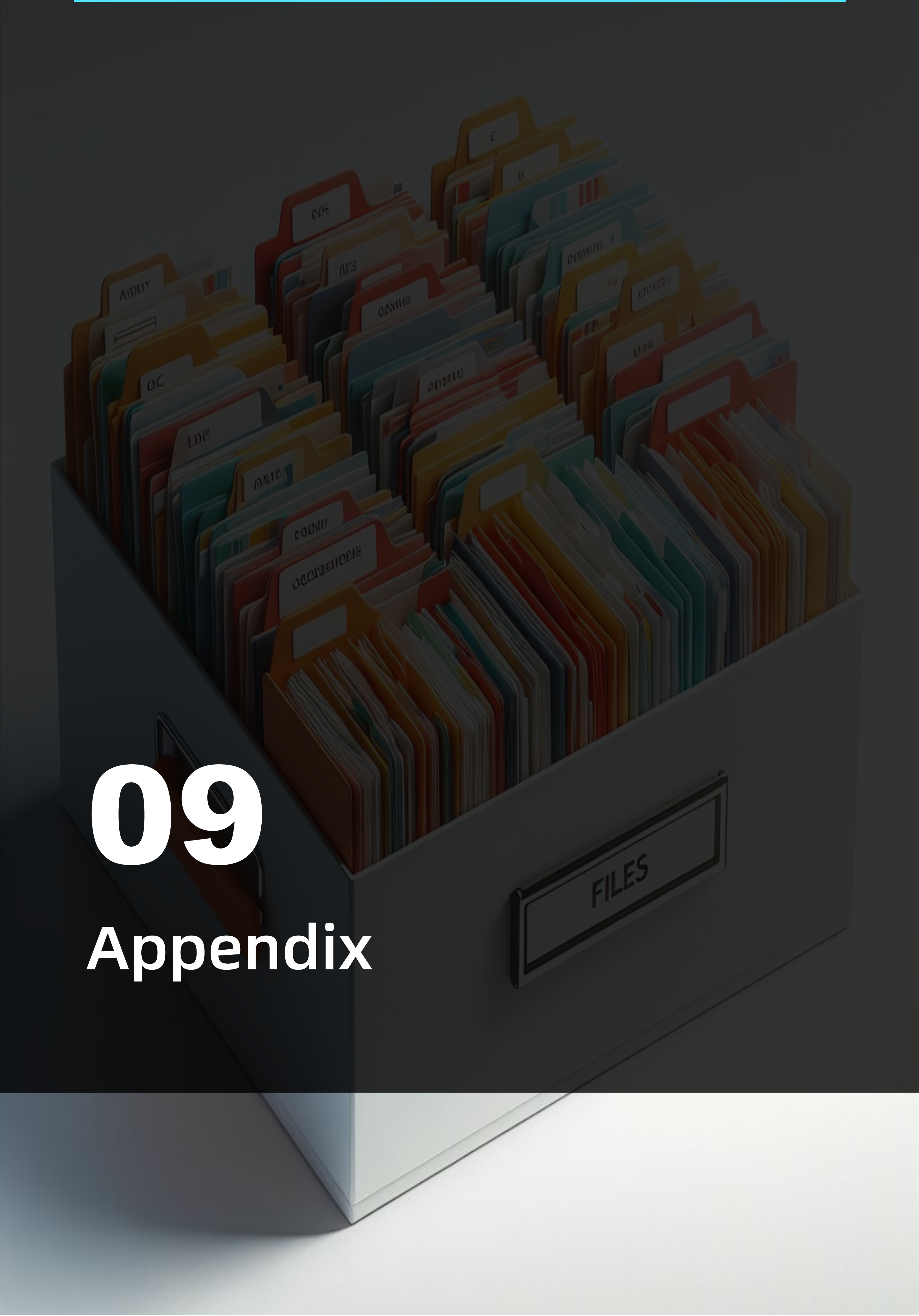
The quantum random walk algorithm proposed by the Beijing Computational Science Research Center provides a universal, efficient, and simple method for positive operator measurement and has been successfully demonstrated in physical applications. This method utilizes the characteristics of quantum random walks, providing new ideas for the development of algorithms in quantum precision measurement.

The platform will evolve towards greater intelligence, high integration, and comprehensive services

In terms of intelligence, the platform will leverage artificial intelligence and machine learning to automate data analysis and processing, improving efficiency and accuracy in data processing, and enabling users to obtain precise measurement results more quickly. High integration refers to the platform's ability to integrate various types of quantum sensors and measurement devices to provide diverse precision measurement functions, significantly reducing users' procurement and management costs and increasing equipment utilization. Comprehensive services include remote monitoring and maintenance of equipment, data storage and management, and analysis and interpretation of measurement results. The platform will emphasize cloud-based service analysis and management functions, enabling users to monitor, analyze, and manage their quantum measurement systems in real-time, accelerating research and application progress.

In 2023, Infleqtion launched the Oqtant platform, a rare global product platform that provides innovative quantum applications for researchers, innovators, and students. Oqtant also offers powerful data management and analysis tools, enabling users to efficiently process and analyze experimental data, accelerating research progress and innovation. These analysis services may involve data visualization, pattern recognition, machine learning, and other technologies to help users uncover valuable information and patterns hidden in the data.

Additionally, QLM Technology's quantum gas laser radar and QLM Cloud offer high performance and accuracy, providing users with better services and experiences through cloud-based data analysis and management. The China Electric Power Research Institute's quantum power measurement platform utilizes quantum technology to establish a highly stable electrical quantum metrology standard system, providing the power industry with more reliable and accurate measurement methods.



09

Appendix

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01 Supplier Evaluation System (CTF Model)

The CTF model is an evaluation and analysis model for future industry participants. ICV TA&K's CTF model helps the public understand the development of cutting-edge technology fields and corresponding companies. Cutting-edge technologies exhibit characteristics such as unconverged technical pathways, high uncertainty in technical development, and early-stage commercialization. As technologies continue to evolve, a rational model is needed to evaluate companies and form a "consensus" on specific periods of cutting-edge technology suppliers.

The CTF model is presented in four layers of different-sized fan-shaped regions, along with three-dimensional coordinates. The horizontal axis represents the Maturity of Technology (technical aspects such as supplier's technology, research and development, team, etc.), the lateral axis represents the Commercialization of Technology (business aspects such as supplier's revenue, customers, use cases, etc.), and the implicit variable represents the Implicit Variable (fundamental aspects such as elements accumulated by suppliers' long-term operations to promote business development). The CTF model divides suppliers into four fan sectors—Pilot, Overtaker, Explorer, and Chance-seeker—based on their comprehensive performance in different dimensions.

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

Fan1—Pilot: Companies in this sector have large-scale operations and have accumulated considerable experience in the previous technology development cycle, laying a solid foundation for entering new cutting-edge technology fields. These companies have the ability and resources to become leaders in new rounds of cutting-edge technologies and may have a profound impact on the future direction of the industry.

Fan2—Overtaker: Companies in this sector have developed to a certain scale after a period of time, with a major advantage being strong capabilities in new technology research and development. Based on their accumulated expertise in specific technology fields, these companies are expected to "overtake" and become industry leaders in the future.

Fan3—Explorer: Companies in this sector are relatively small in size but have embarked on the development track of emerging technologies early on. The development of specific technologies is still in the early stages, and compared to Pilots and Overtakers, they typically have a gap in overall technological capabilities.

Fan4—Chance-seeker: Companies in this sector have keen business instincts and are newly entering the industry. Although they are not large in scale, the founding team members have certain resources, enabling the company to seize development opportunities in new fields. These companies currently have few engineering prototypes of products, with limited market exposure opportunities.

Using the CTF model can help clients in the cutting-edge technology field evaluate the procurement and investment in a particular technology supplier. It is essential to note that suppliers in the Pilot sector are not always the best choice. Depending on the actual needs of the enterprise, companies in the Overtaker or Explorer sectors may be better choices.

02 Global Advances in Quantum Precision Measurement Research

Jan

- The research team from Colorado State University and Colorado School of Mines published a study in Physical Review Letters that combines classical and quantum optics to achieve super-resolution imaging. They utilized single-photon interferometry and single-pixel imaging techniques to enhance image resolution and noise resistance, providing a new method for high-precision observation of biological samples.

Feb

- The United States Air Force Research Laboratory is developing next-generation quantum atomic clocks, quantum sensors, and component technologies to enhance positioning, navigation, and timing capabilities in space. By utilizing cold atom sensors and models of ultralight dark matter, they have achieved improvements in dynamic range and accuracy, laying the groundwork for quantum computing and networking.

- A research team from Nanjing University published a model-free quantum imaging protocol in NPJ Quantum Information. They used undetected photons for non-interacting single-pixel quantum imaging of structural objects, reducing detection requirements and sample damage, paving the way for applications in characterizing fine samples at silicon-detectable wavelengths using single-pixel imaging.

- A research team from Peking University and Tsinghua University published a study in Nature Communications on observing different quasi-particle behaviors between different quantum phases in a cold atomic optical lattice system. By employing an improved band mapping method and non-adiabatic linear response theory, they have provided new insights and methods for detecting equilibrium correlations in quantum many-body systems.

- A team from the University of Rome La Sapienza and the Institute of Photonics and Nanotechnologies (IFN-CNR) developed a model-free reinforcement learning algorithm for optimizing the estimation of multiple parameters. They combined it with deep neural networks to achieve rapid non-scanning quantum state tomography, improving the performance of quantum sensors.

Feb

- A team from the Hefei Institutes of Physical Science, Chinese Academy of Sciences, University of Science and Technology of China, and Sichuan University published a study in Nano Letters on coherent manipulation and high-pressure magnetic detection of silicon carbide double vacancy spin quantum states in high-pressure environments. Using silicon carbide double vacancy color centers as a novel type of quantum sensor, they have achieved precise measurement of magnetic fields under high pressure, providing new tools for high-pressure physics and materials science.

- A team from the USTC published a study in Nature Communications on quantum-enhanced microwave ranging using silicon vacancy centers in SiC. They utilized subwavelength localization of micro/nano quantum sensors with electromagnetic fields to achieve positioning accuracy of 10^-4 wavelengths, providing new technology for quantum communication and quantum imaging.

- This study demonstrates the capability to manipulate and identify a small number of interacting photons (photon ensembles) with high correlation, marking an important milestone in the development of quantum technology.

- Furthermore, a team from Shanghai Jiao Tong University addressed the problem of quantum incompatible limits in quantum multiparameter estimation. They proposed a theoretical criterion for measuring the degree of incompatibility between precision limits of parameters and designed quantum probes that can simultaneously approach the theoretical limits of quantum measurement precision for two incompatible physical parameters. This achievement enables simultaneous measurement of nanoscale lateral displacement and nanoradian-level angular deflection of the same light beam.

- In addition, a team from Boston College used quantum sensors to convert light in Weyl semimetals into electrical energy. They employed quantum magnetic field sensors in nitrogen vacancy centers in diamond to image the local magnetic field generated by photocurrents and reconstruct the complete flow lines of photocurrents, opening up new directions for finding other highly photosensitive materials.

- Lastly, a team from the University of Sydney and the University of Basel showcased the ability to manipulate and identify a small number of interacting photons (photon ensembles) with high correlation, marking an important milestone in the development of quantum technology.

Mar

May

- The team at the University of Illinois at Urbana-Champaign chemically introduced nitrogen-vacancy (NV) impurities into diamonds, endowing them with exceptional sensitivity to electric fields. This enables NV centers to measure strong electric fields and paves the way for the development of reliable and robust sensors.

- The Weizmann Institute of Science team has published a groundbreaking scanning probe microscope, the Quantum Distortion Microscope, in Nature. It allows the study of interference phenomena between two-dimensional materials at the atomic scale, delving into their fascinating physics, laying a solid foundation for scientists to further explore quantum materials.

- Teams from the China Manned Space Agency and the University of Science and Technology of China have completed the rendezvous and docking of the Shenzhou 16 spacecraft with the Tiangong space station, conducting a series of in-orbit tests and experiments across various fields including quantum phenomena, high-precision space-clock systems, verification of general relativity, and the origin of life.

Jun

- Teams from Ohio University, Argonne National Laboratory, University of Illinois at Chicago, and others have captured the world's first X-ray signal from just one atom, linking synchrotron X-rays with the quantum tunneling process, potentially revolutionizing how scientists detect materials.

- Teams from the Royal Navy, Imperial College London, and others have successfully tested a quantum navigation system that can pinpoint a ship's precise location globally without relying on GPS, offering new innovative methods for maritime navigation and warfare.

- Researchers from the Chinese Academy of Sciences have fully measured the recoil ion momentum vector two-dimensional spectrum produced by charge exchange between Ar^8+ and He, confirming the significance of electron-electron interactions in low-energy, high-charge-state ion charge exchange collisions.

- Teams from the University of Naples Federico II, University of Wrocław, University of Bergen, and others have investigated a quantum gravity model for particle propagation, discovering preliminary evidence supporting predictions of this effect, marking a significant milestone in quantum gravity research.

- Researchers from the University of California, Berkeley, and the Lawrence Berkeley National Laboratory have demonstrated the first silicon-based quantum light source, achieving over 30 times enhancement in light emission intensity, close to unity atomic-cavity coupling efficiency, and an eightfold acceleration in single-photon emission rate, paving the way for large-scale integration of all-silicon quantum optical devices and systems.

- Teams from the City University of Hong Kong and others have proposed a new quantum theory explaining the "light-induced phase" of matter and predicting its novel functionalities, offering new insights for research in room-temperature quantum photonics and quantum control.

Aug

- A research team at the Massachusetts Institute of Technology (MIT) has achieved a twofold change in spin density by manipulating the spin density of diamonds using laser or microwave beams, opening up new possibilities for advanced quantum devices.

Sep

- The Stanford Linear Accelerator Center has achieved the world's most powerful X-ray laser, capable of producing molecular-level "movies" of atoms and electrons, expected to advance the fields of chemistry, biology, quantum materials, and optical technology.
- The Shanghai Institute of Microsystem and Information Technology of the Chinese Academy of Sciences, in collaboration with Fudan Quantum Technology, has successfully developed a portable superconducting single-photon detection system, paving the way for high-performance single-photon detection applications on future mobile platforms.
- Beijing Institute of Technology has proposed a high-resolution large-scale single-photon imaging technology driven by physics. By modeling multiple physical noises, they achieved high-resolution, high-fidelity large-scale single-photon imaging.
- Scientists at the University of St Andrews have made breakthroughs in compact laser technology, producing OLEDs with world-record optical output. By combining polymer laser structures, they have developed a new type of laser that emits green laser beams.

Oct

- Professor Xue Peng's team at the Beijing Computational Science Research Center has proposed a universal and efficient method for implementing positive operator-valued measurements in quantum walks applications, and demonstrated the application of positive operators in quantum state tomography.
- A team from the University of Science and Technology of China (USTC) has utilized nitrogen-vacancy (NV) centers in diamonds as solid-state spin quantum sensors to detect the dynamic connections of neuronal synapses under external stimulation, showcasing the multi-channel signal transmission and processing processes in neuromorphic nervous systems.

Nov

- A team from the City University of New York and the California Institute of Technology demonstrated the world's first electrically pumped mode-locked laser with high pulse peak power, generating ultra-short optical pulses, setting the highest level for mode-locked lasers under the platform of nanophotonics.
- A research group from the Swiss Federal Institute of Technology in Zurich detected a new type of ferromagnetism in artificially produced materials, with different alignments of magnetic moments, bringing new discoveries to the field of materials science.
- Researchers demonstrated non-line-of-sight imaging for the first time using superconducting nanowire single-photon detectors, expanding the spectral range of imaging technology and potentially finding applications in fields such as unmanned vehicles and robot vision.
- QDM.IO launched a quantum diamond microscope, utilizing nitrogen vacancy diamond quantum technology to measure the sensitivity of Natstrum to magnetic fields. With excellent image resolution, it provides experimental devices for research institutions.

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