Quantum Technology Innovation Strategy

(Final Report)

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Integrated Innovation Strategy Promotion Council

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I. Circumstances Surrounding Quantum Technology

(1) Changes in domestic and international situations

• Currently, the world is in the midst of a historic paradigm shift in economic and social structures. The economy and society are making a discontinuous transition to a knowledge-intensive type that differs from the conventional labor- and capital-intensive type. Appropriately capturing this transition is the key to Japan's international competitiveness. In addition, Japan's geopolitical position and the international environment surrounding high-tech hegemony are undergoing drastic changes.

• Japan is the first country in the world to advocate “Society 5.0” and “data-driven society” as visions of society that it should aim for in the future. It has become an important technological infrastructure that is the source of power. Quantum technology is the key fundamental technology for further dramatic and discontinuous development of such important technological infrastructure. • From this point of view, in recent years, the international attention on quantum technology has been rapidly increasing. We are accelerating our efforts.

• In a world where major changes can occur in all aspects, as international competition to acquire advanced technologies and realize innovation intensifies, the strengths and Strategic efforts that carefully analyze and evaluate competitiveness and use international collaboration/cooperation and international competition properly are essential.

(2) Trends in other countries regarding quantum technology •

In other countries, mainly in the United States, Europe, and China, quantum technology is clearly positioned as a strategic core technology, and in recent years, significant investments in research and development have been made. In addition to expansion, it is developing strategic initiatives such as establishing research and development bases and developing human resources.

• In the United States, through the formulation of the “National Strategy for Quantum Information Science” and enactment of laws related to quantum information science, support for the formation of international research bases through the Department of Energy (DOE) and the National Science Foundation (NSF) It strategically invests more than $200 million in research and development every year, including support for the formation of an industry-academia consortium on international standardization by the National Institute of Standards and Technology (NIST). • In addition, the EU has compiled the “Final Report on Quantum Technology Flagship” and has started projects on a scale of 1 billion euros from 2018. In addition, in the United Kingdom, Germany, etc., after positioning a wide range of quantum technologies as important technologies, the government is promoting research and development projects and forming research and development bases, thereby significantly expanding investment. . • In China, quantum computers are positioned as a major science and technology project, and quantum information Approximately 7 billion yuan is being invested in the development of the national research laboratory. • Outside the government, large IT companies (Google, IBM, Intel, Alibaba, etc.) and venture companies (D-Wave, Rigetti, IonQ, etc.), mainly in Europe, the United States, and China, are developing quantum technologies such as quantum computers. are actively investing in In October 2019, Google announced in the English scientific journal Nature that it had achieved “quantum supremacy” for the first time using a quantum computer that it independently developed. The competition is intensifying, such as announcing that it has demonstrated that it surpasses in computing power.

(3) Trends in Japan concerning quantum technology

• In the "Fifth Science and Technology Basic Plan" (decided by the Cabinet in January 2016), Japan positioned "optical and quantum technology" as a priority technology area for the future. In addition, in the "Integrated Innovation Strategy" (approved by the Cabinet in June 2018), as an innovative technology that will bring about changes in society, "maintaining and improving the international competitiveness of the optical and quantum technology infrastructure in which Japan has strengths". We are considering and promoting initiatives based on these. • The Ministry of Education, Culture, Sports, Science and Technology (MEXT) formulated the "New Promotion Policy for Quantum Science and Technology (Optical/Quantum Technology)" (August 2017), and positioned quantum information processing, quantum measurement/sensing, and next-generation lasers as priority areas. rice field. Based on this, from FY 2018, we have started providing intensive support for quantum technology, including the launch of a new research and development program, the Photonics and Quantum Leap Flagship Program (Q-LEAP).

• On the other hand, until now, the entire country has not formulated a medium- to long-term strategy for quantum technology. In response, the government as a whole has not always taken consistent efforts, such as conducting R&D efforts individually.

(4) Necessity to work on quantum technology as a nation

•In the United States, Europe, China, and other countries, quantum technology will bring changes to the economy and society of the future. In addition to formulating strategies, the country and industry are working together to significantly expand investment.

• On the other hand, due to the accumulation of basic research on quantum technology over many years, Japan has strengths, superiority, and competitiveness in terms of basic theory, knowledge, and basic technology. It must be said that Japan is in an extremely serious situation, with some fields and domains lagging behind other countries in its efforts to promote globalization, etc.

• Although the government positioned photonics and quantum technologies as important technologies for the first time in the 5th "Science and Technology Basic Plan" (FY2016) and "Integrated Innovation Strategy" (FY2018), at present, relevant government agencies Ministries and companies are at the stage of individually starting research and development, etc., and are not necessarily coherent and sufficient. If this situation continues, Japan will fall far behind other countries in the development of quantum technology, and it is necessary to strongly recognize that the future growth and development of the country and the foundations of the safety and security of the people may be threatened. . • For this reason, the government will look ahead to future changes in the industrial and business structure, and after clearly setting a vision of society that it should aim for, will not stop at short-term technological development, but will also pursue industry and innovation to achieve that vision. With this in mind, we formulate this "Quantum Technology Innovation Strategy" as a new national strategy from a medium- to long-term perspective of 10 to 20 years.

• In the future, based on this strategy, Japan's industry, academia, and government will gather together to drive innovation in quantum technology. continue.

II. Basic policy

• Quantum technology is an innovative technology (core technology) that is the key to the rapid and discontinuous development of Japan's economy and society (Quantum Leap). It is essential to ensure that this leads to the resolution of the various issues facing Japan and to the sustainable growth and development of the future.

For this reason, in this strategy, we refer to these ideas and concepts as “quantum technology innovation.” We will clearly position it as a priority, and develop comprehensive and strategic efforts on a nationwide basis.

• In doing so, instead of restricting the concept of “quantum technology” in a narrow sense, from the perspective of “quantum technology innovation,” we will broadly include technologies related to quantum technology and technologies that are indispensable as peripheral technologies. It is necessary. Furthermore, it is extremely important to combine these “quantum technologies” and existing (classical) technologies in a complementary and synergistic manner and to promote them in an integrated and comprehensive manner.

• In addition, under the “Integrated Innovation Strategy” formulated by the Integrated Innovation Strategy Promotion Council, toward the realization of “Society 5.0”, it is defined as “the most advanced basic technology that affects all science and technology innovation”. The three strategic technologies of AI, biotechnology, and quantum technology will ensure the acquisition and strengthening of essential basic technologies for Japan in the future, and the direction of driving industry and innovation in the future will be important.

• From this perspective, the “AI Strategy,” “Bio Strategy,” and “Quantum Technology Innovation Strategy,” which will be discussed and formulated at the conference, will be positioned as three important technology strategies of the country. The government as a whole will strongly promote and develop consistent efforts while closely integrating and cooperating with each other in a form that covers the major areas of the government.

• Furthermore, in promoting the “Quantum Technology Innovation Strategy,” we will clarify the areas of quantum technology that should be strengthened as a nation, amid budget and resource constraints, to ensure Japan’s strengths and competitiveness, It is essential to implement strategic initiatives that combine effective cooperation and coordination. At the same time, with regard to quantum technology, considering that the time axis (time span) for industrialization and commercialization differs greatly for each individual technology, we have projected a medium- to long-term period of about 10 to 20 years and a period of about 5 to 10 years. It is important to take a bird's-eye view of the whole from both the short- and medium-term perspectives, and to promote systematic and strategic efforts, bearing in mind the spread of related and peripheral technologies and social implementation.

• At this point, the following three basic policies are set forth in this strategy.

<Three basic policies> ÿ

Strategic development of “quantum technology innovation” ÿ Integrated

and comprehensive promotion of quantum technology and existing (classical) technology ÿ

Integration and strengthening of collaboration among quantum technology innovation strategy, AI strategy, and biotechnology strategy

<Scope of quantum technology innovation> • Based on

quantum science and applied technology (quantum technology), a wide range of related technologies (including technologies that are essential as peripheral technologies) will be included, and the results will be applied. Refers to innovation that leads to industrialization and commercialization.

III. Vision of Society Created by Quantum Technological Innovation

• While the paradigm shift to a knowledge-intensive society is progressing rapidly, Japan is aiming to realize the next-generation social image of "Society 5.0" and "data-driven society" through "quantum technology innovation". It is important to clearly set the image of the future society to be achieved.

• In this strategy, the following three social images are presented as the future image that Japan should aim for. In order to realize this, in the following chapters, we will analyze and evaluate Japan's strengths and competitiveness from both the medium- to long-term and short- to medium-term perspectives, and identify key technological areas and specific promotion measures. shall be specified.

<Three visions of society to aim for> (1) Realization of a productivity revolution In the near

future, with the rapid aging of the population and declining working population expected, Through the "quantum revolution" following IT (digital) and AI, we will strengthen Japan's industrial competitiveness and achieve a dramatic improvement in productivity.

``Quantum computer technology'' and ``quantum simulation technology'' that process ultra-high-speed, massively parallel information to solve problems that require unrealistic time with current supercomputers can be used in a wide range of fields such as information communication, manufacturing, finance, transportation, pharmaceuticals, and chemistry. Create new value in the industrial and social fields. In addition, through "quantum measurement and sensing technology," which has accuracy and sensitivity surpassing existing technologies, and "quantum physical properties and material technology (quantum material technology)," which utilizes the quantum properties that appear in the microscopic world, , semiconductors, device manufacturing, power storage, energy saving, energy creation, etc.

ÿ Realization of a healthy and long-lived society

As Japan faces a super-aging society ahead of other countries, we will realize a world-class health and longevity society through innovative medical care and health management using quantum technology. Quantum measurement and sensing technology, such

as quantum sensors and imaging that have ultra-high sensitivity and high resolution compared to conventional technologies, will enable therapeutic methods and drug discovery based on the essential understanding of life phenomena, as well as high-precision early diagnosis and monitoring. It has brought about dramatic developments in life sciences and medical care, and has brought about innovations in related medical care, pharmaceuticals, and medical device industries.

ÿ Ensuring the safety and security of the country and citizens

With the rapid increase in highly confidential digital information, including personal information, we will realize a highly secure society and ensure the safety and security of the country and its citizens through communication and encryption technologies that apply quantum effects.

Due to the rapid development of quantum computer technology in recent years, there is a possibility that public key cryptography and other technologies may be broken. Quantum communication and cryptography technologies possessed by Japan will contribute to building and upgrading a security environment with confidentiality and integrity, as well as strengthening industrial competitiveness. In addition, through highly sensitive and highly accurate "quantum measurement/sensing technology" that surpasses existing technology, we will establish our own technological base that does not depend on other countries, and utilize "quantum computer technology" in a wide range of fields. and contribute to ensuring the safety and security of the country and its citizens.

IV. Five Strategies for Achieving Quantum Technology Innovation 1. Technology development strategy

• Based on the fact that individual technologies included in quantum technology have different time frames for social implementation, domestic and overseas R&D trends and national strengths and competitiveness will be analyzed and competitive from both medium- to long-term and short- to medium-term perspectives. After evaluation, it is necessary to specify the technical areas that should be prioritized. • At that time, in addition to the quantum technology itself, we will complementarily combine these with existing (classical) technologies, and after taking a bird's eye view of the entire technology system including related and peripheral technologies, It is extremely important to prioritize research and development and strategically develop initiatives for the realization of gradual commercialization.

(1) Main technology areas

• In order to achieve the future social vision set forth in III through quantum technology innovation, the following four technology areas will be established as the “main technology areas” as the foundation of quantum technology. • After analyzing and evaluating domestic and overseas R&D trends, Japan's strengths and competitiveness, and contributions to Japan's future industries and innovations, we will establish medium- to long-term and short- to medium-term plans for each major technology area. Set overall and individual policies foreseen. On that basis, the national government will specify technical issues that should be promoted promptly (priority technical issues) and research issues that should be steadily promoted from a medium- to long-term perspective (basic technology issues). , set. • International competition is intensifying in the four major technological areas listed here, and the technology is advancing extremely rapidly. For this reason, it is essential to accurately grasp the latest trends and flexibly review priority technical issues based on this.

Goal: Create a "technology roadmap" for each priority technology issue, and conduct research based on these
Promote and develop strategic initiatives such as development assistance

<Main technical areas>

Quantum computer/quantum simulation Quantum measurement/
sensing Quantum communication/
cryptography Quantum
materials (quantum physical properties/materials)

<Overall policy>

Each major technological area and each individual Since the time spans for social implementation are different, depending on the characteristics of each technology, research and development will be prioritized, and efforts toward practical application will be considered and promoted.

Quantum computers/quantum simulations require strategic efforts with a mid- to long-term outlook for hardware development, while some technologies for software, quantum measurement/sensing, and quantum communication/cryptography are complementary to existing (classical) technologies.•Because it is expected that practical application, etc., will be possible in the short to medium term through collaboration, strategic initiatives will be developed for prioritization and practical application, etc. for each technical area based on the following individual policies.

At the same time, both quantum technologies and related existing (classical) technologies Promote efforts to connect related/peripheral technologies to practical applications through software development.

<Specific measures> Under

the cooperation and cooperation of related ministries and agencies, the national government will take a bird's-eye view of the overall technology system, including related and peripheral technologies, targeting priority technical issues, and implement measures for the next 20 years or so. In the meantime, we will create a "technology roadmap" that shows specific initiatives that should be promoted by the public and private sectors, and formulate it integrally with this strategy.

Based on this roadmap, the national government will implement projects under the direct control of the government and R&D funding (e.g., Cabinet Office "Strategic Innovation Promotion Program (SIP)", Ministry of Education, Culture, Sports, Science and Technology "Q-LEAP", Japan Science and Technology Agency (JST) "Future Society Creation Project", Ministry of Economy, Trade and Industry/New Energy and Industrial Technology Development Organization (NEDO) Promote research and development support.

Based on this roadmap and based on the support mentioned above, the national government will invite investment from the private sector according to the progress of research and development. Promotion and development of a wide range of initiatives, etc.

From a medium- to long-term perspective, the national government should conduct basic and foundational research through R&D funding (e.g. Grants-in-Aid for Scientific Research, JST Strategic Basic Research Promotion Project) targeting basic and fundamental technology issues. Promote support, etc.

ÿ) Quantum computers and quantum simulations • Quantum computers make it possible to solve some problems that require unrealistic time scales even with current supercomputers (classical computers) in a short period of time and with ultra-low power consumption. It is an innovative technology that can bring about dramatic innovation in all fields of industry and society. Development competition among governments and companies is intensifying, especially in Europe, the United States, and China, and as research and development investment expands significantly, strategic efforts are essential for Japan as well.

• Among the basic technologies for realizing gate-type quantum computers, superconducting qubits are a technology originating in Japan and are one of the leading candidates. Japan possesses world-class technological capabilities in the fabrication and control of high-quality superconducting qubits, and there are well-known internationally acclaimed researchers.

On the other hand, in other countries, for example, IBM is promoting the commercialization and service of quantum computers using superconducting qubits, and Google is also using its own quantum computer of the same type. In the past few years, we have seen rapid progress in technology, such as the publication of a paper in October 2009 stating that "quantum supremacy" was achieved. Furthermore, the competitive environment is becoming more intense with the entry of venture companies such as Rigetti and Chinese companies (Alibaba, etc.). However, issues such as controllability and scalability (large-scale integration) have been pointed out for superconducting qubits. • With regard to silicon qubits, the international R&D competition is intensifying, such as the application of existing semiconductor integration technology and attention toward multi-qubits. In Japan, RIKEN has succeeded in developing silicon qubits with the world's highest fidelity. Compared to superconducting qubits, there are delays in the scale and progress of research and development, and scaling (large-scale integration) is also an issue.

• Regardless of which base technology is used, it is expected that it will take 20 to 30 years to put an error-tolerant general-purpose gate-type quantum computer into practical use. The “quantum supremacy” paper published by Google is evaluated as one of the important milestones, but there are many problems to be overcome for the practical application of versatile quantum computers. Therefore, for the development of actual quantum computers (hardware), it is necessary to promote research and development from a medium- to long-term perspective based on Japan's strengths and competitive technologies. In parallel with this, it is important to promote multifaceted research and industrial development, such as the realization of quantum computers without error correction (NISQ) and the development of related and peripheral technologies. .

• Software for quantum computers (quantum software (architectures, algorithms, compilers, applications, etc.)) has recently seen accelerated competition in the development of both gate-type and annealing-type software, mainly by venture companies in addition to universities and research institutes. are doing. Development of gate-type quantum computer software is progressing rapidly in the United States and other countries. Japan does not have a large number of researchers, but there are young researchers who are internationally recognized in both the gate-type and annealing-type fields. In the future, in parallel with the development of quantum computers (hardware), this is an area where dramatic progress and acceleration in research and development and social implementation are expected.

• Quantum simulation is expected to contribute to the elucidation of the functions of materials and the search for new materials through the simulation of many-body electron systems, and the R&D competition between Europe, the United States and China is expanding. In Japan, too, there are researchers who are internationally acclaimed. In addition to prospects for technological development for the practical use of simulators and annealing-type quantum computers that make use of them, technological areas that are expected to spread and expand to related industries, such as the development of optical technology and refrigerators, are: Its importance is increasing.

• As a quantum computer specializing in combinatorial optimization problems, annealing-type quantum computers are ahead of gate-type computers in terms of their practical use. Based on the annealing method theoretically proposed by Japanese researchers, D-Wave of Canada has developed and released the world's first commercial device using superconducting qubit technology. Although other countries have taken the lead in the development of actual machines, Japan still has world-class researchers in terms of theory. In 2018, the National Institute of Advanced Industrial Science and Technology (AIST) succeeded in manufacturing Japan's first superconducting quantum annealing machine (50 qubits). Furthermore, RIKEN and NEC Corporation (NEC) are also conducting research and development for the development of ac

• An ion trap is a technology that confines ions in space using an electromagnetic field such as a laser, and is attracting attention as a promising physical system for realizing a quantum computer. In the United States, companies have already commercialized NISQ devices. On the other hand, regarding cooling ions, issues such as the length of the qubit gate time and the decrease in fidelity related to gate operation, as well as the individual control of qubits and the miniaturization of optical elements for scaling. there is

• Optical quantum computers use technology that expresses quantum bits using photons produced by lasers, and in recent years there has been great progress in research and development. Since it can operate at room temperature and in the atmosphere, it does not require refrigerators or vacuum equipment, and it is promising because it can be networked using optical communication, and the gate can be operated at high speed and miniaturized. technology. On the other hand, problems have been pointed out, such as the difficulty of gate operation and the improvement of gate accuracy.

<Priority technical

issues> Gate-type quantum computer (superconducting qubit)

Quantum software (gate-type/annealing quantum computer) Quantum simulation (cold

atoms) Annealing-type quantum computer

(superconducting qubit)

<Fundamental technology issues>

silicon qubit ion trap

Optical quantum computer, etc.

<Individual policy>

Gate-type general-purpose quantum computers are expected to take 20 to 30 years to be put into practical use, and are expected to require a large amount of money to develop actual machines. However, the development and possession of actual hardware and the establishment of basic technology for this are extremely important not only for maintaining and strengthening the nation's research and development capabilities, but also from the perspective of industrial policy. while promoting national R&D efforts.

At that time, based on the fact that the favorite technology to realize the computer has not yet been decided, while promoting a wide range of research and development from the viewpoint of ensuring diversity, we will focus on superconducting qubits, where Japan has strengths and competitiveness. Promote strategic initiatives in two areas that will be prioritized.

In addition, as a step-by-step approach toward the development of actual equipment, NISQ, quantum bit fabrication technology (structural analysis technology, microfabrication technology, three-dimensional packaging technology), dilution refrigeration technology, microwave control technology, low-temperature electronics technology, and hardware Research and development of related and peripheral technologies such as architecture will be promoted in parallel, and efforts will be made to put them to practical use in the short to medium term.

In parallel with hardware development, quantum software (both gate-type and annealing-type quantum computers) will promote research and development, etc., with a particular focus, while gaining the participation of companies. By developing "quantum-classical hybrid type" software that complements and cooperates with "technologies and quasi-quantum technologies (see (3) below)", we will promote efforts toward practical application in the short to medium term.

Quantum simulation (cold atoms) is a technological area that is expected to be utilized and applied in the materials and chemical industries in which Japan has competitiveness. etc.

Regarding annealing-type quantum computers, in addition to foreign companies, Japanese companies are also making progress in research and development efforts in collaboration and cooperation with national research institutes. Expand.

ii) Quantum measurement/sensing

• The domestic and international markets for sensors are expanding further, and expectations for quantum measurement/ sensing as a next-generation core technology are extremely high. Europe and the United States are significantly expanding R&D investment in this area, and international competition with Japan is intensifying.

In addition, the targets of quantum measurement and sensing are wide-ranging, including magnetic fields, electric fields, temperature, and acceleration, and the measurement methods are becoming more diverse and complex.

• Also, as a ripple effect (spin-out) toward the practical application of quantum computers, these quantum measurement and sensing technologies are expected to be put into practical use and implemented in society at a relatively early stage. Also, it is extremely important to work on internationally competitive research and development with a view to commercialization and marketization.

• Solid-state quantum sensors (diamond NV centers, etc.) have the advantage of being able to measure magnetic fields, electric fields, and temperature at room temperature and in the atmosphere with ultra-high sensitivity, and are particularly competitive among sensor materials. Japan has high technological capabilities in the development of materials for solid-state quantum sensors (Tokyo Institute of Technology, National Institutes for Quantum and Radiological Science and Technology (QST), National Institute for Materials Science (NIMS), National Institute of Advanced Industrial Science and Technology (AIST), etc.). We are providing materials to overseas research groups. It also has internationally advanced technical capabilities in measurement technology. It is also an area that is expected to be utilized in a wide range of industries, and the participation of Japanese companies in research and development is expanding. • Quantum inertial sensors are technologies that detect acceleration and angular velocity using quantum effects, and are expected to have a large ripple effect in a wide range of industries, such as high-precision self-positioning devices. It is also an important core technology from the viewpoint of safety. In addition, optical lattice clocks are clocks that achieve several orders of magnitude higher accuracy than conventional atomic clocks, and Japan is overwhelmingly leading the world in terms of accuracy and continuous operation time. This area is expected to contribute to the redefinition of the second in the International System of Units and to have ripple effects as an infrastructure for ultra-high-precision spatio-temporal measurement. In both cases, there are researchers who lead the world in this field, and Japan possesses the world's top level technology, and it is essential to maintain and strengthen these. • With regard to quantum entanglement optical sensors, research and development is progressing on “quantum entanglement microscopes,” which surpass the measurement accuracy of conventional optical microscopes, and “quantum OCT,” which dramatically improves the resolution of optical coherence tomography (OCT). . Japan is leading the world in the development of quantum entanglement light sources and application use, etc., in collaboration and cooperation with companies, mainly universities. So far, we have succeeded in demonstrating resolution exceeding that of existing technologies using quantum entangled light. This is very important.

• A quantum spintronics sensor is a technology that detects changes in spins in matter caused by external stimuli by means of quantum mechanical effects. Companies are entering the field of magnetic sensors that use tunnel magnetoresistive (TMR) elements based on technology related to product development such as MRAM. In Europe and the United States as well, venture companies are actively entering the market, and they are beginning to search for future practical application and industrialization. In addition, the spin heat flow sensor is a new sensor that can utilize heat flow information, and is expected to be used in heat-related industries and social infrastructure. Japan is leading the world in basic principles, etc., and it is necessary to steadily promote research and development. • Ultrashort pulse lasers are progressing from femtosecond to attosecond science, and are expected to lead to expanded applications in a wide range of industrial fields, such as the elucidation of material properties and the development of magnetic devices. Japan has strengths and competitiveness in laser light source technology, etc. for both high-repetition and high-intensity types. As competition with Europe, the United States, China, and other countries intensifies, it is important for Japan to steadily advance research and development with future industrial applications and uses in mind.

<Priority technical issues>

Solid-state quantum sensors (diamond NV centers, etc.) Quantum
inertial sensors/optical lattice clocks Quantum
entanglement optical sensors

<Fundamental technology issues>

Quantum spintronics sensors Gravity sensors
Attosecond
lasers, etc.

<Individual policy>

Solid-state quantum sensors are expected to be applied in a wide range of fields including medical and health fields in the future because Japan has strengths in manufacturing technology. Focus on promoting a wide range of research and development. On the other hand, since early utilization and application in device development, etc. are expected, we will promote the active participation of companies, etc., and develop initiatives for practical application and commercialization in the short to medium term.

Quantum inertial sensors and optical lattice clocks are technologies that have prospects for technical establishment and are expected to be used and applied in various fields. , the government is also involved in developing strategic initiatives for early commercialization.

For quantum entanglement optical sensors, we are conducting research and development of a hybrid type that combines "quantum OCT" and existing (classical) OCT. As for absorption spectroscopy, by promoting research and development aimed at demonstrating the principle, while promoting the participation of companies, etc., efforts are being made toward practical application in the short to medium term.

iii) Quantum communication

and cryptography • In recent years, due to the development of computing technology, AI, medical technology, etc., highly confidential and important digital information is being generated one after another. If such important information is leaked, the social and economic impact will be enormous, so ensuring confidentiality and integrity over a very long period of time is an extremely important issue.

• With the rapid progress of gate-type quantum computers, there is a possibility that the public-key cryptography technology that supports modern Internet security can be deciphered. On the other hand, there is a risk of compromise even in quantum-safe computer cryptography. We are rapidly advancing research and development related to • In Japan, Toshiba Corporation and NEC manufacture the world's fastest BB84 quantum cryptography device, while the National Institute of Information and Communications Technology (NICT), the University of Tokyo, Nippon Telegraph and Telephone Corporation (NTT), Mitsubishi Electric Corporation, etc. , leading the world in theoretical research and demonstration. NICT is leading the world in the development of quantum communication/cryptographic transmitter/receiver equipment, and has the world's longest operational track record in the metropolitan area testbed "Tokyo QKD Network." The University of Tokyo is a quantum computer

However, we are promoting research on cryptographic algorithms that cannot be deciphered. As for satellite quantum communication, China surprised the world by announcing that it had succeeded in quantum communication with the ground using its independently developed satellite, Mozi. In Japan, NICT has successfully conducted a demonstration experiment between a low earth orbit satellite and a ground station.

• Japanese companies are working toward early commercialization and commercialization of cryptographic transmitters and receivers. Along with NICT, the European Telecommunications Standards Institute (ETSI) and the International Telecommunications Union (ITU) are working on standardization. We are promoting activities and leading the world.

• In quantum repeater technology (quantum memory, quantum entanglement, etc.), Osaka University, NTT, NICT, etc. are leading the world in quantum entanglement between cooled atomic quantum memory and photons, and proof of principle of all-optical quantum repeater systems. . Challenges include verification of long-distance transmission, multiplexing, integration, and scale-up. International competition is intensifying, with numerous research and development projects being launched in Europe, the United States, China, and other countries. • With regard to networking technology (construction, operation, maintenance, etc.), quantum memory and quantum repeaters are at the proof-of-principle stage. For this reason, a trusted node architecture related to quantum communication is being studied, and ITU-T is discussing standardization based on this architecture.

• From the perspective of ensuring the safety and security of the country and its citizens and strengthening industrial competitiveness, Japan will: Research and development, commercialization, and standardization of quantum communication and cryptography, which have confidentiality and integrity as a means of safely storing important digital information, and are highly competitive internationally in anticipation of marketization. It is extremely important to work together as a nation.

<Key technical issues>

Quantum communication/cryptographic link technology

<Fundamental technology issues>

Quantum repeater technology (quantum memory, quantum entanglement, etc.) Networking technology (construction, operation, maintenance, etc.), etc.

<Individual policy>

Among the quantum communication and cryptographic link technologies, the basic technology of the transmission/reception equipment for quantum communication using optical fiber has been established, and Japanese companies are at the stage of practical application and commercialization. , the government will also be involved in promoting strategic initiatives to realize business development in Japan and overseas in the short to medium term. Regarding satellite quantum communications, in light of the importance of national and public safety and security as well as industrial policy, we will focus on research and development from both the short-, medium-, and long-term perspectives, and improve the communications environment. , develop strategic initiatives for practical application, etc.

iv) Quantum materials (quantum physical properties/materials) •

Quantum materials, whose physical properties/materials exhibit functions by precisely controlling the quantum state, are theories, experiments, and materials developed through many years of basic and applied research in Japan. In terms of development, etc., it is an area that has strengths and competitiveness globally. On the other hand, in recent years, condensed matter physics

The concept of topology, etc., was actively introduced in the field of science, and based on that, the search for substances that express new functions and the research on understanding their functions rapidly expanded. Competition is intensifying.

• In this technological field, high-quality research and development is being carried out at Japanese universities and research institutes, and in addition to having a deep pool of human resources, Japanese industries and companies have a broad base and are highly competitive internationally. keeping. The development of next-generation devices and the creation of materials with new physical properties are positioned as a promising technological area that will lead to the enhancement of Japan's industrial competitiveness, which has been lagging behind the rest of the world in the field of international growth industries. .

• Topological quantum materials such as graphene are materials that are expected to be applied to energy-saving devices and materials with new physical properties through the realization of highly efficient spin-charge conversion, etc., and have a high industrial ripple effect in the future. regarded as a technical area. While research and development is becoming more active in the United States, Europe, and China, Japan has core researchers who are conducting research and development that is highly regarded internationally.

• Materials that can use spin current (spin current materials) are expected to be innovative materials that can be used in spintronics devices that acquire energy from heat, vibration, light, etc. in a single device. Spintronics technology is a technological area in which Japanese universities and research institutes have accumulated basic research over many years. Sensing using such materials is expected to be a new sensing technology for measuring heat flow and rotation flow, and it is important to steadily promote it from the basic research stage.

<Fundamental technology issues>

Topological quantum materials (graphene, etc.) Topological magnets Spin current materials, etc.

(2) Quantum Fusion Innovation Area

• For each major technological area related to quantum technology, it is necessary to promote strategic efforts based on the measures listed in (1). On the other hand, based on these technological fields in which Japan has strengths, quantum technology and related technologies (including existing technologies) will be combined with quantum technology and related technologies (including existing technologies) in order to increase the speed and reliability of innovation toward the realization of the future social vision set forth in this strategy. It is extremely important to build and develop a new technology system unique to Japan that integrates and links these technologies.

• Quantum computers are expected to have computational performance that far surpasses that of classical computers for specific problems, and AI technologies such as machine learning and clustering are highly complementary and are expected to be one of the important killer applications. Expectations are rising. Although it is attracting international attention, research and development is still in progress, while Japan maintains strengths in quantum software development. For this reason, "quantum AI technology," which replaces part of AI technology with quantum computers (including Japan's own quantum-inspired technology) and fuses and utilizes it as an accelerator, is positioned as an extremely promising technological area.

• “Quantum biotechnology,” which fuses quantum technology with life and medical care, such as the clarification of the functions of life phenomena at the cellular level and the use of solid-state quantum sensors in the medical and health fields, is a field unique to Japan.

We are at the stage where the development of new technologies has begun. On the other hand, it is a promising technological area that is expected to have an extremely large ripple effect in solving the problems facing Japan such as the aging of the population, extension of healthy life expectancy, and soaring medical costs, and in realizing a healthy and long-lived society. .

• With the progress of quantum computer technology, there is a possibility that the current public key cryptography technology can be deciphered. "Quantum security technology," which aims to make the world a better place, is an extremely important technological area. While Europe, the United States and China are promoting large-scale research and development, Japan is also promoting pioneering efforts, and it is an urgent task to develop this as a solid base technology. • These new technological areas that integrate and link quantum technology and related technologies are clearly positioned as "quantum fusion innovation areas." As such, we will strongly promote and develop strategic initiatives.

Goal: Set the "quantum fusion innovation area" as the most important area for the future development of Japanese industry and innovation. Strengthen and promote strategic initiatives <Quantum fusion innovation area> Quantum AI technology (e.g., quantum-classical hybrid computation (supervised/unsupervised learning),

algorithm/system architecture development

(including

utilization of quantum-inspired technology), etc.) Quantum life technology (Quantum biotechnology) (Example: Bio-nano quantum sensor, quantum entanglement optical imaging,

hyperpolarized nuclear magnetic

resonance technology (hyperpolarization/ultra-miniature MRI), etc.) Quantum security technology (Example: quantum secure cloud, optical/quantum

network cryptography etc.)

<Overall policy>

In the field of quantum fusion innovation, Japan should maintain its particular strength and competitiveness, and achieve practical application and commercialization as soon as possible with a high degree of certainty. Targeting technical areas that are expected to make a large contribution.

For each quantum fusion innovation area, from a medium- to long-term perspective, the nation will promote research and development with the highest priority. Strategic efforts to realize practical commercialization, including the spread and development (spin-out) to

<Specific measures>

Under the coordination and cooperation of relevant ministries and agencies, etc., the national government, targeting the quantum fusion innovation area, takes a bird's-eye view of the overall technology system, including related and peripheral technologies, and from a medium- to long-term perspective, develops a plan for the next 20 years or so. Create a "roadmap for interdisciplinary fields" that indicates strategic and specific measures to be taken in the interim, and formulate it integrally with this strategy.

Based on the “Roadmap for Interdisciplinary Areas,” the government will provide intensive R&D support, etc. through large-scale projects under the direct control of the government and large-scale R&D funding for each quantum fusion innovation area. At the same time, based on these, we will actively invite investment from the private sector, and promote and develop a wide range of initiatives for research and development and practical application through industry-academia collaboration and public-private collaboration.

(3) Quantum-inspired technology and quasi-quantum technology

• In Japan, companies, in particular, are promoting ideas and methods of quantum technology, such as annealing technology and technology that uses laser pulses equivalent to quantum bits (utilizing the quantum nature of light). Original innovative technology development and products incorporating existing (classical) technology (classical computers, etc.) and service development are progressing.

• For example, Hitachi Ltd.'s CMOS annealing machine, Fujitsu Ltd.'s digital annealer, Toshiba's simulated branching machine, NTT's LASOLV (QNN at the time of the Cabinet Office's Disruptive Research and Development Promotion Program (ImPACT) project), etc. Technological development and commercialization of actual machines for Ising computers, which can process specific combinatorial optimization problems much faster than classical computers, are progressing ahead of the rest of the world. This is a unique movement, and there is no other example in the world.In addition, from a global perspective, for example, efforts are being made to speed up classical algorithms inspired by quantum algorithms.

• In particular, scaling and commercialization of gate-type general-purpose quantum computers requires efforts from a medium- to long-term perspective. In addition to the evaluation and verification of quantum computers in the future, these unique Japanese technologies are expected to be applied and developed in various industrial fields such as finance, insurance, manufacturing, and transportation. It should be highly evaluated as a technical area. • For this reason, we will clearly position such a system of technologies as “quantum-inspired technologies, quasi-quantum technologies,” and develop initiatives such as research and development and social implementation.

Goal: Evaluate and identify promising “quantum-inspired technologies and quasi-quantum technologies” originating in Japan, and promptly enhance and promote strategic research and development and practical application support.

<Overall policy>

“Quantum-inspired technologies and quasi-quantum technologies” are original technologies mainly developed by Japanese companies. At the same time, develop strategic initiatives to link to industrialization and commercialization in the short to medium term.

<Specific measures>

Through support for research and development funding, etc., the national government will promote industry-university collaboration and collaboration utilizing “quantum-inspired technologies, quasi-quantum technologies” owned by Japanese companies, such as CMOS annealing machines, digital annealers, simulated bifurcation machines, and LASOLV. Promote innovative research and development (application development, etc.) and social implementation through public-private collaboration.

With the cooperation of Japanese academia, companies, etc., the government will develop promising “quantum-inspired technologies.” Identify and evaluate quasi-quantum technology.

(4) Fundamental research •

Quantum technology is expected to develop dramatically in the future, but many technological areas are still at the basic research stage. It is extremely important to steadily promote science-based (basic research stage) research and development from a medium- to long-term perspective. • Also, in order to develop the technological areas listed in (1) to (3), in addition to quantum technology

itself, after analyzing and evaluating Japan's strengths and competitiveness, it is necessary to develop fundamental technologies and related Fundamental research with a wide range of technologies and peripheral technologies (e.g. microstructural analysis, microfabrication technology, light wave control/optical device technology, semiconductor technology, cooling technology such as dilution refrigerators, cryogenic electronics, analysis/evaluation technology) is required. In addition, we will promote commercialization and practical application with a view to strengthening the international competitiveness of these basic technologies and domestic production, develop and share infrastructure facilities and equipment such as advanced equipment to realize them, and further promote infrastructure facilities.•It is essential to ensure and actively promote the securing of strategic substances that

are indispensable for the operation of facilities. • For this reason, we will further enhance and strengthen such basic research, development and sharing of infrastructure facilities and equipment, etc., including the technical areas listed in (1) to (3) and related areas. while promoting steadily.

2. international strategy

(1) Strategic development of international cooperation

• In the United States and Europe, science-based (basic research stage) research and development of quantum technology is being promoted through various forms of funding, and expectations are rising for expanded cooperation with Japan in this field. In particular, the Japanese and U.S. governments discussed the acceleration of Japan-U.S. cooperation on quantum technology at the ministerial-level Joint High-Level Committee on Science and Technology Cooperation held in May 2019. Since last year, the governments of Japan and the EU have agreed on the importance of expanding cooperation in the field of quantum technology, and held a joint symposium. The United Kingdom, Germany, and other countries also have high hopes for cooperation agreements with Japan at the government level.

• Under these circumstances, from the perspective of ensuring the safety and security of the country and its citizens and from the viewpoint of industrial policy, Japan will establish partnerships with countries and regions that share common values and have high levels of research and technology related to quantum technology. In the future, it will be extremely beneficial and important for Japan's strategy to develop and build a framework for multilateral cooperation at the government level.

• In addition, with countries such as the United States, the United Kingdom, and Germany, which have high levels of research technology related to quantum technology, consideration will be given to Japan's strengths and competitiveness, as well as the merits and demerits of research cooperation, for each specific technological area. After that, it is important to build a multilayered and strategic bilateral cooperation framework among governments, universities, research institutes, etc., and promote concrete cooperation.

Goal: Within five years, develop and build a government-level multilateral and bilateral cooperation framework for quantum technology, mainly in Europe and the United States <Specific

measures> Quantum

technology (In addition to discussing and agreeing on a multilateral framework for cooperation on quantum information science, etc., we will also consider and promote the expansion of research cooperation through the holding of joint symposiums and workshops.

Actively utilize existing frameworks such as the Joint Committee for Science and Technology Cooperation with the United States, the United Kingdom, Germany, etc., and consider and promote specific bilateral cooperation frameworks (MOUs, etc.) on quantum

technology. . International joint research with specific countries/regions while taking into consideration the strengths and merits of Japan Promote the establishment of a joint funding mechanism and the holding of joint symposiums.

(2) Thorough security trade control • Quantum

technology is an important basic technology from the perspective of future industry and security. . Furthermore, based on the National Defense Authorization Act, etc., in recent years, the United States has been considering tightening regulations on advanced technologies, including quantum technology, in terms of both export and investment. The EU and other countries are also tightening investment regulations on quantum technology.

• Based on the agreement of the international export control regime, Japan promotes strict security trade control based on the “Foreign Exchange and Foreign Trade Law”. Based on this law, etc., we are also encouraging universities and research institutes to develop management systems for advanced technologies. is in a situation where

• For this reason, the government as a whole will promote security trade control targeting advanced technologies including quantum technology, and further promote the development of systems for legal compliance and proper control within organizations. It is essential to strengthen and promote the development of management systems at universities and research institutes.

Goal: Strengthen and promote the development of management systems, etc., including compliance with foreign exchange and foreign trade laws, etc., at universities and research institutes that conduct research, etc. on advanced technologies such as

quantum technology

<Specific measures> Government promotes and thoroughly enforces security trade control based on the Foreign Exchange and Foreign Trade Law, based on international discussions on strengthening control over

sensitive technologies. Based on the “Guidance for Controlling Sensitive Technology Related to Security Trade (for Universities and Research Institutions),” the government will further strengthen and promote efforts to strengthen security trade control systems at universities and research

institutions. Universities and research institutes, etc., are required to establish security export control regulations, etc. within their universities and institutions based o

In addition to accelerating preparations, the operational system will be further strengthened by thoroughly informing researchers.

3. Industry and Innovation Strategy

(1) Formation of “quantum technology innovation hubs (international hubs)”
• In Europe and the United States, the formation of quantum technology hubs is progressing rapidly (e.g. Delft University of Technology (QuTech) in the Netherlands,•University of California, Lawrence Berkeley National Laboratory, University of Oxford, UK, etc.), and these bases function as stage settings to attract excellent researchers from Japan and abroad. In Japan, a relatively small number of researchers are dispersed among universities, research institutes, companies, etc., and the lack of top-class research centers that are internationally recognized and evaluated is a major issue.

• With regard to quantum technology, from the perspective of further increasing the depth of research and human resources that have been accumulated over many years at Japanese universities and research institutes, and ensuring the diversity of basic and foundational research, such universities should be established.•It is important for the government to enhance and strengthen continuous support for a wide range of research at research institutes.

• On top of that, from the viewpoint of securing and strengthening international competitiveness, focusing on technological areas where Japan maintains its strengths and competitiveness, we will gather human resources and technologies according to the characteristics of the technology, and conduct basic research and technology demonstration. , open innovation, intellectual property management, and human resource development, etc. A new “quantum technology innovation base (international hub)” will be formed as such an international research and development base. • Centering on national research institutes and universities, the center will bring together excellent researchers and engineers from Japan and overseas, actively attract investment from companies, and promote organic collaboration between universities and companies.•Build a cooperative system. At the same time, we will collaborate and connect with multiple universities and graduate schools, etc., and develop and build a role as a core base for developing human resources in the field of quantum technology that will lead the future.

Goal: Develop and form at least 5 “quantum technology innovation hubs (international hubs)” in Japan

in the 5 years

from FY2020 Internationally competitive core technology

etc.

It is a technological area in which Japanese universities, research institutes, companies, etc. have high potential and where dramatic development of industry and innovation is expected in the future. Large

investments are expected from domestic and foreign companies, and excellent human resources from overseas are concentrated.

and is expected to be a technical area.

Integrating human resources, technology, budget, etc. is a beneficial and efficient technological area.

<Example of type of center> Open platform type that deepens and strengthens collaboration between universities/research institutes and companies (Example: IMEC, Tohoku University International Center for Electronics Integration (cies)).

Although it is under the umbrella of a university/research institute, it is a base that ensures independent management with a high degree of freedom. Molding (e.g. Ministry of Education, Culture, Sports, Science and Technology "World Premier International Research Center Initiative (WPI)").

Under the umbrella of a research institute, a center type that has developed and strengthened as an organization of a research department (e.g. strategic centers such as the National Institute of Advanced Industrial Science and Technology (AIST)).

<Candidate sites>

Superconducting quantum computer research center

Quantum device development

center Quantum software (quantum AI, etc.) research center

Quantum life (bio) research center (solid-state quantum sensor utilization, etc.)

Quantum materials research center

Quantum inertial sensor and optical lattice clock research

center Quantum Security Research Center

<Specific measures>

Based on the above requirements, the national government promotes the formation of international research and development bases, "quantum technology innovation bases (international hubs)" mainly composed of universities and research institutes. Regarding this base, in addition to medium- to long-term support such as financial, tax, and institutional aspects (including utilization of the special zone system, etc.) by relevant ministries and agencies, we will seek appropriate investment from domestic and foreign companies. Developed and promoted as a research and development base that brings together the public and private sectors.

(2) Establishment of the "Quantum Technology Innovation Council (provisional name)"

Quantum technology is highly recognized and expected to be an important technology that will lead to future industry and innovation. . On the other hand, in the United States, for example, there is a movement to form a new consortium led by NIST, in which academia and industry consider the research and development and utilization of quantum technology based on bills related to quantum information science.

Under these circumstances, in Japan as well, various stakeholders, including industry, academia, and government, have gathered to analyze the current state of quantum technology, advance research and development, and examine and discuss the utilization of quantum technology in industry and society (consortium). It is extremely useful to have Related initiatives such as the creation of the "(one company) Quantum ICT Forum" have already started, and with these in mind, we will establish the "Quantum Technology Innovation Council (provisional name)" targeting specific technological areas.

Industry-academia-government will collaborate and cooperate in this council to lead the study of specific initiatives and roadmaps for individual technical issues, etc., and promote open innovation in cooperative areas based on these (build an ecosystem). Furthermore, based on the latest research and technology trends, etc., we will consider and promote strategic promotion measures and support measures for Japanese industry, including cooperation with overseas companies and research institutes.

Goal: Composed of universities, research institutes, companies, etc. for each specific technology area within 5 years Quantum Technology Innovation Council (provisional name) established

<Positioning and Roles of the Council> It should

be a proactive effort by academia and industry. Multiple companies, etc. participate,

and universities, research institutes, related ministries and agencies, etc.

It should be an initiative in which a variety of organizations, institutions, etc., with an interest in specific areas of interest participate.

Analysis of the current state of technology, direction of research and development, and utilization in industry and society for the specific area It should be an initiative that considers and discusses from a wide range of perspectives, such as use.

<Council Candidates>

Quantum Computer and Software Council Quantum Sensor Utilization Council, Quantum Materials Utilization Council Quantum Information Communication and Network Technology Council (Quantum ICT Council)

<Specific measures>

The government will support the creation of independent "Quantum Technology Innovation Council (provisional name)" by academia and industry and efforts related to activities for each specific technology area (e.g., academia and industry bridging with the world, participation of relevant ministries and agencies, support such as subsidies).

(3) Improving the startup and investment environment • In Europe and the United States, giant IT companies such as Google, IBM, Microsoft, and Intel are While investing a huge amount in research and development for cutting-edge quantum technology such as computers, Expectations are rising for the creation of new industries, such as venture companies with advanced technology and high international recognition, such as Rigetti, D-Wave, and IonQ.

• In Japan, quantum technology is still at an immature stage and the future is uncertain. On the other hand, although the number of venture companies based on university technology is smaller than in other countries, active movements such as the establishment of MDR and QunaSys are emerging. From the perspective of linking quantum technology to industry and innovation, it is extremely important to develop an environment that further promotes the creation of university-or corporate-launched venture companies based on such advanced quantum technology. • Furthermore, in order to commercialize and industrialize quantum technology, from the perspective of inducing investment from both the developing company side and the user side, the government should take the lead in promoting the introduction and utilization of the technology while referring to the examples of Europe and the United States. It is extremely important to improve the environment to promote investment by companies, etc.

Goal: Within 10 years, universities/research institutes or companies based on quantum technology 10 or more new venture companies, including those related to elemental technology <Specific measures>

We actively support the creation of venture companies based on the excellent technology seeds of our company.

The government, through the "Quantum Technology Innovation Council (provisional name)", etc., We support the development and expansion of an environment that nurtures corporate ventures.

In order to expand the creation of venture companies based on quantum technology, the government is considering support through government-affiliated financial institutions and the Innovation Investment Corporation, as well as expansion of support for fostering entrepreneurs and startups. The national government promotes advanced introduction and utilization of advanced technologies and products related to quantum technology, including quantum cryptography devices.

4. Intellectual Property and International Standardization Strategy

(1) Intellectual Property Strategy • With regard to quantum technology, not only the government but also giant IT companies are actively investing and working closely with universities and research institutes. At the same time, we are developing state-of-the-art research and development. These companies skillfully use both open and closed systems, and are promoting strategic intellectual property management with a view to future enclosure of particularly important core technologies. • Strategic management of quantum technology-related intellectual property is essential amid intensifying competition that transcends national and corporate boundaries. In addition, as industry-academia collaboration and open innovation efforts in this field are rapidly expanding both in Japan and overseas, it is extremely important to strengthen open and closed strategies, mainly at universities and research institutes, prior to projects. is.

Goal: Intellectual property strategy based on open/closed strategy for quantum technology

<Specific measures> The government will

flexibly acquire rights for research and development results related to quantum technology at universities and research institutes, including related technologies based on an open/closed strategy.•Promoting utilization, etc.

The government will promote the matching of promising quantum technology seeds owned by universities, etc., with the needs of companies and ventures, as well as promote commercialization and bridging between universities and such companies.

(2) International standardization strategy • In areas close to social implementation, such as quantum computers and quantum cryptography, it is important to promote efforts toward international standardization of quantum technology and related technologies. In the field of quantum information science, the United States has built an industry-university consortium centered on NIST, and has begun deliberations toward obtaining standardization. In addition, ISO/IEC JTC1 has set up a research group on quantum computing and is extracting work items for standardization, mainly in China and Japan. • In order to strengthen international competitiveness and gain market share, Japan will develop strategic initiatives related to international standardization that make the most of its technological superiority, especially in the area of quantum technology, where it has particular strengths. is essential. In doing so, it is particularly important to cooperate with the United States and European countries, which share common values, and to promote speedy and accurate international standardization strategies.

Goal: Quantum technology areas in which Japan has strengths and which are expected to have a large economic ripple effect

<Specific Measures>

Support the acquisition of integrated international standards from the research and development stage.

The national government, in collaboration and cooperation with relevant organizations such as organizations related to international standardization and certification bodies, We have established a support system for identifying technologies that require standardization, formulating standards, and obtaining certification.

Regarding quantum technology, the government promotes the development and securing of human resources capable of proposing projects and participating in deliberations at international standardization organizations such as the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), and the ITU.

5. Talent strategy

(1) Fostering and securing excellent human

resources • As international competition over quantum technology intensifies, the number of researchers engaged in research and development of quantum technology in Japan is thin compared to other countries. be. In particular, as companies in the United States and China are making huge investments in quantum computers and quantum software, etc., and attracting excellent human resources from Japan and overseas at high remuneration, there is a risk that they will fall far behind the international competition to acquire human resources. . • For this reason, in order to dramatically improve the quality and depth of human resources in the field of quantum technology, Japan will also enhance and strengthen the education and research environment in quantum technology-related fields at the higher education level, including universities. It is extremely important and essential to strategically nurture and secure excellent young researchers and engineers, etc., who will be responsible for research and development in the relevant fields through • Furthermore, in anticipation of post-AI, it is important to appropriately coordinate human resource development based on the "AI strategy." For students studying AI at universities and young researchers involved in research and development, we will enhance and secure opportunities to acquire knowledge about cutting-edge quantum technology in addition to AI technology, and become familiar with quantum technology-related fields. It is necessary to increase the depth of the human resource base.

Goal: At an early stage within five years, promote human resource development through the establishment of courses and majors related to quantum technology at universities, etc., and the development of systematic educational programs. Collaborate

and cooperate with

companies, etc. to strategically develop and develop researchers and engineers.

Consider a roadmap for securing human resources, and support the development and securing of human resources at universities, etc.

The national government will coordinate and cooperate with universities and inter-university research institutes, and link them with human resource development measures in the AI strategy. Considering and promoting the development of an environment and opportunities to provide comprehensive education.

Universities, etc. should develop systematic and common educational programs (teaching materials, curricula, etc.) related to quantum technology, and utilize and implement them in undergraduate and graduate education at each university. Consider and promote. The national government collaborates and cooperates with universities, research institutes,

and companies, etc., and enables outstanding researchers and engineers to develop quantum technology-related fields through personnel exchanges, transfers, cross-appointments, etc., transcending organizational and field boundaries. Secure opportunities to acquire new knowledge and skills.

(2) Promotion of brain circulation • As competition between nations and companies over

quantum technology intensifies, securing excellent human resources is a common issue. The competition to acquire human resources is rapidly progressing around the world. Japan still maintains the world's top-level research capabilities in fundamental technologies, basic theories, material development, etc. related to quantum technology. It has also been pointed out that the poaching of excellent researchers belonging to them has begun.

• Considering that quantum technology is at the forefront of international competition in the field of advanced technology, it is necessary to maintain and strengthen Japan's research capabilities and human resources, as well as to secure future industrial competitiveness. Therefore, in addition to securing domestic researchers, it is extremely important to strategically promote efforts to invite and secure excellent researchers from overseas.

• Furthermore, in order to improve the knowledge and skills of outstanding young researchers and engineers in Japan, it is necessary to secure opportunities for them to study at overseas universities.

Goal: Realize brain circulation by holding an international symposium on quantum technology innovation every year with the participation of top-level domestic and foreign researchers and engineers based on multilateral and bilateral cooperation frameworks. <Specific measures>

The national government will cooperate with universities and research institutes, including the "Quantum Technology Innovation Hub (International Hub)," to invite and secure excellent researchers and engineers involved in quantum technology innovation from overseas. Support and strengthen.

Universities, research institutes, etc., are required to secure and train excellent researchers and engineers from Japan and overseas. In addition to improving the environment, we promote active promotion by securing posts.

In cooperation with universities, research institutes, etc., the national government should secure opportunities for young researchers and promising students belonging to universities, etc. to belong to overseas research institutes and engage in cutting-edge research and development related to quantum technology. At the same time, we will promote active promotion to universities, etc. afterwards.

(3) Fostering Quantum Natives • Quantum technology is a field that requires medium-to long-term strategic research and development, and it can be said that fostering and securing researchers who will lead the future is an extremely important policy issue. The United States, Europe, and other countries have already taken steps to provide opportunities to learn about quantum technology and related fields from a relatively early stage, with the aim of fostering and securing future researchers and engineers. We are working on it.

• In Japan as well, high schools and colleges of technology are particularly interested in fostering and securing "quantum natives" who have advanced knowledge and skills to master quantum technology from an early stage. It is extremely important to actively provide students with opportunities to learn about quantum mechanics and other related fields.

• Furthermore, through school education and social education, etc., efforts will be made to arouse children's and students' interest in the content of state-of-the-art quantum technology and the current state and future of its utilization in society and industry. It is also important to promote

Goal: To develop and secure "quantum natives" who will be responsible for the future, provide learning opportunities especially for high school and technical college students, and develop a wide range of scientific communication activities. Measures> The government will improve science and mathematics education such as mathematics and

physics in senior high

schools and colleges of technology. Promoting the provision of opportunities to learn related academics and cutting-edge research, such as processing, physical properties and materials science. The national government collaborates and cooperates with universities, research institutes, companies, science museums, etc., and enhances and secures opportunities to come into contact with quantum computers and other cutting-edge quantum

technologies through science communication activities.

V. Promotion system for this strategy

• It is necessary to develop and build a system to steadily promote initiatives based on this strategy, with the "Integrated Innovation Strategy Promotion Council" playing a central role. In particular, under this strategy, targeting "quantum fusion innovation areas" and "priority technical issues", etc., based on a roadmap that incorporates specific measures to be taken over the next 20 years or so from a medium- to long-term perspective. It is extremely important to establish a system to strategically promote research and development. • In addition, from the perspective of ensuring the effectiveness of initiatives based on this strategy, relevant ministries and agencies will collaborate and cooperate under the "Integrated Innovation Strategy Promotion Council" to consider all kinds of measures, including tax, fiscal and institutional aspects. , it is necessary to put it into practice.

• From this point of view, the expert panel "Quantum Technology Innovation" was reorganized in a developmental manner, and under the "Integrated Innovation Strategy Promotion Council," a Consider setting up a Technology Innovation Council (provisional name). • In light of the current state of rapid changes in trends surrounding quantum technology, this conference will seek to grasp the latest domestic and international trends in a timely and appropriate manner, and steadily implement this strategy (including technology roadmaps and interdisciplinary field roadmaps). Conduct follow-up. In implementing the follow-up, considering that the strategy is to invest in research and development over the medium to long term amid severe financial conditions, from the perspective of promoting an appropriate division of roles between the public and private sectors and the proactive participation of the private sector, individual In addition to conducting cross-sectional evaluation and verification of the status of efforts in projects, etc., we will flexibly review priority technical issues and roadmaps.

(Attachment 1)

Holding of the Advisory Council "Quantum Technology Innovation" to Promote the Strengthening of Innovation Policy

February 12, 2019 Partial
revision on November 26, 2019 Chairman
decision of the Integrated Innovation Strategy Promotion Council

1. Establishment of the “Expert Council for Strengthening and Promoting Innovation Policy” (July 27, 2018 Decision by the Integrated Innovation Strategy Promotion Council) ” (hereinafter referred to as “meeting”).

2. Based on the provisions of paragraphs 2 and 3 of the same, the chairperson and members of the meeting shall be as shown in the attached sheet.

3. The operation of the meeting shall be as described in paragraphs 4 through 7 of the same.

(another paper)

"Quantum Technology Innovation," an expert panel for strengthening and promoting innovation policies

<Chairman and members>

Yasuhiko Arakawa Specially Appointed Professor, Institute for Nano-Quantum Information Electronics, University of Tokyo

Kohei Ito Professor, Faculty of Science and Technology, Keio University

Makoto Gonokami President of the University of Tokyo

Chair Yoshimitsu Kobayashi Chairman of the Board, Mitsubishi Chemical Holdings Corporation

Masahide Sasaki Senior Researcher, Advanced ICT Research Institute, National Institute of Information and Communications Technology

Tetsuomi Samukawa, Director of NTT Advanced Technology R&D Center

Yoshinori Tokura Distinguished Professor, Tokyo College, The University of Tokyo

Yuichi Nakamura Senior Chief Engineer, NEC Central Research Laboratories

(Chairman Kobayashi until November 26, 2019, and President Gonokami as chairman of the Advisory Council after the same day)

(Attachment 2)

History of considerations for formulating a quantum technology innovation strategy

March 29,
2019 1st Advisory Panel

April 18: 2nd Expert Meeting

May 16, 2019
3rd Expert Meeting

June 11 5th Integrated Innovation Strategy Promotion Conference

June 19th 45th Conference on Science, Technology and Innovation

July 5th 4th Expert Meeting

July 30 Compilation of interim report on “Quantum Technology Innovation Strategy”

September 24: 5th Expert Meeting (Rotating around the establishment of WG)

September 30, 1st Quantum Computer Simulation WG (closed)

October 2, 1st Quantum Communication/Cryptography WG (closed)

October 4 1st Quantum Metrology and Sensing WG (closed)

October 29, 2nd Quantum Computer Simulation WG (closed)

November 5, 2nd Quantum Communication/Cryptography WG (closed)

November 6 2nd Quantum Metrology and Sensing WG (closed)

November 27 6th Expert Meeting

January 21,
2020 Compilation of the final report of the 6th Integrated Innovation
Strategy Promotion Council “Quantum Technology Innovation Strategy”

technology roadmap

• This roadmap summarizes the outlook for the development of each technology over the next 20 years or so, based on domestic and international research trends, etc., targeting priority technical issues. • In each roadmap, describe (1) technological goals, (2) core technology systems, (3) peripheral and related technologies, and (4) social and economic impacts brought about by these.
One of the purposes is to share the future vision between the public and private sectors.

• Based on this roadmap, the government plans to strengthen research and development support for priority technical issues. Based on these supports, etc., new investment from the private sector will be encouraged.
It is strongly hoped that this project will be developed into a national industry-academia collaboration and public-private collaboration project.

(1) Gate-type quantum computer (superconducting qubit)

• Realization of a general-purpose digital quantum computer that can perform large-scale and complex calculations with high speed, high precision, and low power consumption • Implementation of about 1,000 physical qubits after 10 years. In addition, about 50 qubits with quantum error correction will be implemented.

Economic and social impact

- Random Number Generation Using Quantum Computing
- Development of Distributed Quantum Computer
- Realization of Secure Distributed Quantum Computing Blind Quantum Computing
- Development of quantum secure network technology
- Expansion of science and technology frontiers (development into elementary particle and condensed matter physics research, application to quantum life phenomena)
- Application to drug discovery, fluid, structural analysis, etc.
- Advances in computer science triggered by the realization of quantum supremacy
- Development of high-temperature superconductors, artificial photosynthetic materials, innovative devices, highly efficient catalysts, etc.
- Demonstration of quantum supremacy
- Realization of quantum supremacy with NISQ
- General purpose digital quantum computing beyond NISQ
- Development of ultra-low power consumption devices and advanced system control HW/SW technology
- Pioneering unexplored areas of IoT by realizing innovative systems in computing, communication, measurement and sensing
- Realization of high-performance quantum sensing

technological progress

Qubit integration

- Arbitrary control of physical qubits (about 50 qubits) becomes possible
- Arbitrary quantum control of physical qubits (approximately 100 qubits) becomes possible
- Quantum computer with 500-1,000 physical qubits emerges
- Appearance of a quantum computer equipped with quantum error-corrected logic bits (10 to 50)
- Demonstration of quantum supremacy (by about 50 qubits)
- Demonstration of algorithms for NISQ (with 100-1000 qubits)

cloud service

- Development of quantum cloud service for NISQ
- Development of cloud services for large-scale quantum computing
- Implementation of cloud services for large-scale quantum computing
- Development of an error-correcting quantum computer
- Utilization of Quantum Computer Network Construction of Quantum Internet

Systemization technology

- Development of scalable qubit integrated circuit architecture
- Developing a scalable routing architecture
- Miniaturization and integration of control electronics
- Construction of a large-scale quantum computer

Manufacturing technology

- Development of quantum bit manufacturing technology
- Ultra high density mounting
- Development of scalable chip package
- Development of Integrated Qubit Signal Processing Circuit
- Development of low-temperature front-end signal processing circuit

Control and measurement technology

- Ultra High Bandwidth Arbitrary Waveform Generator, Analog to Digital Converter
- On-chip control integrated circuit by cryo CMOS, RFSQ, etc.
- Autonomous AI type quantum gate calibration device

Development of peripheral technologies that support this technolog

Refrigeration and cryogenic technology

- Cable connector Miniature integration of microwave components
- Larger dilution refrigerator system

Design support technology

- Quantum circuit layout design development environment development
- Development of automation technology for all design and inspection processes

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039)

(2) Quantum software (gate type)

• Physical and chemical calculations of large atomic and molecular systems enable a wide range of applications such as materials, medicine, drug discovery, machine learning, finance, and security. Implementation on quantum computers that implement architecture • Creation of algorithms suitable for quantum computing based on basic theories of physics, chemistry, and computational science, and pioneering fusion areas

Economic and social impact

- Verifiable random number generation using quantum computing
- Development of quantum secure network technology
- Realization of Secure Distributed Quantum Computing Blind Quantum Computing
- Direct data input from quantum sensors to quantum computers
- Advantages and added value created by combining quantum infrastructure (quantum communication networks, quantum sensors, quantum computing devices, and quantum software)
- Direct machine learning from quantum IoT (quantum sensors, etc.)
- Demonstration of quantum supremacy
- Contribution of quantum ICT to ICT
- Expansion of science and technology frontier • Development to elementary particle and condensed matter physics research • Application to quantum life phenomena
- New functional materials (academic understanding) , high-temperature superconducting materials, artificial photosynthesis, interfacial functions, high-efficiency catalysts, photo-functional materials, transport phenomena
- Advanced scientific calculation / Thermo-fluid analysis •Inverse matrix calculation •Structural mechanics analysis •Linear system solver

technological progress

soft implementation

- Demonstrate the usefulness of quantum-classical hybrid algorithms
- Miniaturization of quantum error correction architecture
- Emergence of architectures that enable programmable error correction
- Quantum open source software is created, enabling an architecture that fuses quantum technologies

soft

- Software development to bring out the performance of quantum-classical hybrid algorithms
- Demonstration of quantum supremacy with miniature applications
- Enables automatic optimization of high-speed quantum circuits
- Software that enables efficient use of hardware resources
- Diversification of applications by developing algorithms that can be implemented
- Establishment of quantum algorithms with quantum advantage running on fault-tolerant quantum computers
- Establishing the foundations of quantum programming languages and compilers
- Accelerating compilers for large-scale automation Advances in automation

architecture

- Quantum software design evaluation Noise compensation Performance evaluation linked with hardware Development of quantum classical interface Development of quantum software using HPC and reduction of development cycle
- Design of quantum error correction architecture and proof-of-principle using actual machine Design of architecture reflecting error characteristics of implementation Optimization of arithmetic processing depending on architecture
- Design of quantum error correction architecture to enable quantum IoT Eliminate incompatibility between quantum information systems
- Development of architecture design according to application

basic theory

- Development of computational physics and chemistry using quantum computers, implementation of computational physics and chemistry theory
- Creation of interdisciplinary fields, implementation on quantum computers
- Theoretical research applied to multiscale/multiphysics Theoretical research applied to quantum chemistry/biomedical chemistry
- Deepening the basic theory of quantum computing (fusion with computational theory) / Quantum complexity theory research
- Quantum Distributed Computing/Quantum Algorithm Theory Research
- Design and evaluation of quantum device systems Development of optimization theory
- Development of quantum system verification theory

Development of peripheral technologies that support this technolog

hardware

- Arbitrary quantum control of physical qubits (about 50 qubits) becomes possible
- Arbitrary quantum control of physical qubits (approximately 100 qubits) becomes possible
- Quantum computer with 500-1,000 physical qubits emerges
- Emergence of quantum computers with quantum error-corrected logic bits (10-50)

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039)

(3) Quantum software (annealing type)

• Supports various optimization problems, from optimization of traffic, factory processes and manufacturing schedules to application to autonomous driving technology for automobiles • 5 to 10 years later, modeling of issues to be incorporated into combinatorial optimization problems and Ising models application to machine learning, traffic and factory processes, automobile technology, etc. • Promote large-scale social implementation by developing tools for users and advancing middleware and software technology that can be applied to various fields.

Economic and social impact

Learning speed of machine learning is accelerated, learning only necessary items while selecting necessary learning (clustering)

Significant improvement in performance and processing speed of inference and information processing in AI

Application of actual problems such as control of small unmanned guided vehicles and process schedules to combinatorial optimization problems Real-time

traffic optimization such as automatic driving support and evacuation route planning in the event of a disaster

Weekly small group job scheduling

Start of application to real-world problems such as large-scale transportation logistics, marketing, manufacturing process efficiency improvement, network optimization, and autonomous driving

Emergence of a user environment that can be used without being aware of the hardware model

Expansion to physical physics research

Solving social issues such as searching for optimal evacuation routes in the event of large-scale traffic congestion or disasters

Utilization to save energy by optimizing manufacturing processes and networks

Work style reform support by optimal job scheduling, easy recovery from accidents by real-time optimization of train diagrams, on-demand transportation

Facilitating social implementation by reducing the cost of quantum annealing systems

Contributing to the development of devices with new functions

technological progress

optimization problem

Some combinatorial optimization problems can now be solved by annealing computers

Annealing type computer started to be applied to solve some real-world problems

Combined with solvers and algorithms for solving linear programming problems and quadratic programming problems, annealing has become an accelerator for all optimization problems.

Software/ middleware

Developing Middleware to Use Annealing

Development of SDK environment that utilizes annealing and diversification of application fields

Research and development of drivers and middleware that adopt annealing type computers as part of general-purpose operating systems

Develop APIs to appropriately convert Ising models to suit various hardware architectures

Development of software for hybrid use of quantum annealing machine and classical annealing machine

Construction of basic theory on Ising model and graph theory

Research and development of middleware that uses a combination of annealing-type and gate-type hardware

Ising model conversion middleware

Ising model conversion middleware

Typology of theoretical development and sophistication of applicable combinatorial optimization problems

Development of integrated software for combining other types of computers available at the time, such as classical computers and gate-type quantum computers, with annealing-type computers

Development of peripheral technologies that support this technolog

Quantum annealing hardware

Fabrication of 100-qubit annealing system with high coherence performance and excellent scalability

Fabrication of 2000 qubits with high coherence performance and excellent scalability (good solution for medium-scale combinatorial optimization)

Realization of a large-scale quantum annealing machine (from 10,000 qubits) with high scalability and high coherence performance (good solution for medium- and large-scale combinatorial optimization)

Other methods of annealing hardware

Realization of hardware (LASOLV) implementing about 10k spins in full coupling

Realization of hardware (LASOLV) implementing about 100k spins in full coupling

Miniaturization of LASOLV

Realization of hardware (LASOLV) that implements 1M or more spins, and further scale-up

Utilization and development of annealing hardware (CMOS annealing, digital annealing, etc.) using circuits

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039)

ÿ Quantum simulation (cold atoms)

• Development of two types of quantum simulators: a physical property quantum simulator that promotes the elucidation of new material phases, and an optimization quantum simulator that accelerates the solution of social and industrial problems. Realization of a quantum simulator with more than 106 qubits in 10 years • Application to gate-type general-purpose quantum computers; development of high-precision optical control technology to medical and life sciences and optical microfabrication

Economic and social impact

- Enables scientific understanding of new material phases (high-temperature superconductivity, quantum magnetism, topological properties, high-energy physics, non-equilibrium dynamics)
- Development of new devices based on the understanding of material phases using quantum simulators (high-temperature superconductors capable of low-loss power transport, high-performance memory utilizing quantum magnetism, etc.)
- Social Perception of Quantum Superiority over Classical
- It is now possible to solve industrially meaningful problems
- Solving social issues such as truck delivery, traffic congestion relief, and predictive health management. Quantum chemical calculations of complex molecules. Acceleration of industrial problem-solving such as materials and drug discovery design
- Application to gate-type general-purpose quantum computers
  Development of high-precision optical control technology to medical life sciences and optical microfabrication

technological progress

simulation

- Realization of many-body ground states and many-body excited states, and exploration of the mechanism of appearance of new material phases
- Feeding back knowledge obtained from quantum simulations to materials science and demonstrating the emergence of new material phases in solid materials
- Quantum simulation of 10 to 100 qubits Solving optimization problems
  Demonstrating quantum superiority
- Realization of 1,000 qubit quantum simulation Solving small-scale quantum chemical problems Solving small-scale social problems
- Implementation of a quantum simulator with more than 106 qubits
- Reduction of simulation time and high efficiency of quantum simulation by automatic optimization of parameters

simulation

- Cooling to many-body ground states, generation of many-body excited states, and observation of nonequilibrium quantum many-body dynamics
- Development of quantum gas microscope
- Development of observation methods for new material phases (methods for measuring correlations in time, space, momentum, spin, etc.)
- Development of implementation methods for physical and chemical models
- Hybridization technology with classical computers
- Scaling full connectivity of physical qubits
- Implementation of quantum error detection and correction mechanism
- Development of high-fidelity qubits
- Exploring challenges that exhibit quantum supremacy
- Development of Algorithms with Quantum Superiority to Solve Industrial Problems

common

- Development of single-atom optical tweezers
- Development of theoretical methods to verify the results of quantum simulations

Development of peripheral technologies that support this technolo

Fundamentals of Cold Atomic Systems

- Exploring atomic properties in cold atomic systems
- Control of new atomic species and mixed systems in cold atomic systems

Light source and optical system technology

- Development of spatial shape control of light (arrangement technology for arbitrary multiple sites, trap shape control technology)
- Development of an integrated light source system capable of fully automatic, computer-controlled, high-speed operation, and phase intensity modulation
- Implementation of an on-premises quantum simulator

Mounting technology

- Build a user interface that implements the problem in hardware
- Development of a fully integrated cooled atomic quantum simulator

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039)

Five

ÿ Annealing quantum computer (superconducting qubit)

• After 10 years, practical use of annealing quantum computers with high coherence performance of about 10,000 qubits will lead to optimization of logistics and transportation, acceleration of machine learning, Improving real-time performance of searches, etc. • Promote the expansion of the scale of annealing-type quantum computers by developing a development environment that supports low-temperature electronics and 3D wiring design. We will pursue development

Economic and social impact

Learning speed of machine learning is accelerated, learning only necessary items while selecting necessary learning (clustering)

Significant improvement in performance and processing speed of inference and information processing in AI

Application of actual problems such as control of small-scale automated guided vehicles and process scheduling to combinatorial optimization problems

Start of application to real-world problems such as large-scale transportation logistics, marketing, manufacturing process efficiency, network optimization, and autonomous driving

Solving social issues such as searching for optimal evacuation routes in the event of large-scale traffic congestion or disasters

Utilization to save energy by optimizing manufacturing processes and networks

Work style reform support by optimal job scheduling, easy recovery from accidents by real-time optimization of train diagrams, on-demand transportation

Real-time traffic optimization such as automatic driving support and evacuation route planning in the event of a disaster

Emergence of a user environment that can be used without being aware of the hardware model

Facilitating social implementation by reducing the cost of quantum annealing systems

Weekly small group job scheduling

Expansion to physical physics research

Contributing to the development of devices with new functions

technological progress

Hardware systemization

Fabrication of 100-qubit annealing system with high coherence performance and excellent scalability

2,000 qubits manufactured (improved coherence performance essential)

Fabrication of 2000 qubits with high coherence performance and excellent scalability (good solution for medium-scale combinatorial optimization)

Realization of a large-scale quantum annealing machine (from 10,000 qubits) with high scalability and high coherence performance (good solution for medium- and large-scale combinatorial optimization)

Qubit integration

Development for significant improvement of qubit coherence performance

Evolution to general-purpose quantum computers

Development for large-scale integration of qubits

Hybridization technology with classical computers

Manufacturing technology

Development of 3D packaging technology for quantum circuits

Development of bit integration technology using large-scale circuit manufacturing equipment

Development of process manufacturing technology for large-scale quantum circuits

Yield improvement, evolution of mass production technology

Non-defective product rate improvement technology and stabilization technology

Control and measurement technology

Control technology using superconducting digital circuits and microwave devices

Development of on-chip quantum-classical interface integrated circuits using cryo-CMOS, superconducting digital circuits, etc.

Development of peripheral technologies that support this technology

Refrigeration/ low temperature technology

Cable connector Integration of microwave components

Larger dilution refrigerator system

Design support technology

Quantum circuit layout design, development of operation simulation technology

Automatic low-temperature test inspection technology for efficient selection of non-defective products

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039)

ÿ Solid-state quantum sensor (diamond NV center, etc.)

• Realization of a compact, robust, ultra-sensitive solid-state sensor is expected to be used in magnetoencephalography (medical/healthcare), extreme environments, life sciences, etc. • 10-12T (Tesla) in 5 years, 10 years from now Accomplished observation of weak magnetic field under room temperature of 10-14T. Furthermore, we will establish simultaneous measurement technology for temperature and current.

Economic and social impact

Contribution to energy saving, security and safety, etc. • Energy saving by high-precision control of power electronics and batteries, safety improvement by temperature monitor • Detecting small amount of foreign matter in food, chemicals, battery materials, etc.

Contribution to healthcare, medical care, and BMI through compact, wearable magnetoencephalography and nerve measurement Clarification of brain structure and function, nervous system immune mechanism, dementia, depression, etc. Psychiatric medicine and health applications through the spread of magnetoencephalography measurement systems , use in drug discovery • Realization of electrode-free brain machine interface

Infrastructure, space, resource exploration, exploration in extreme environments using robust ultra-sensitive sensors Failure prediction by monitoring infrastructure such as electric power Exploration of resources such as oil, space situation monitoring/exploration

Quantum Cryptographic Communication, Quantum Computing, and Quantum Networks: Realization of Distributed and Secure Quantum Computers with Quantum Entanglement Connections

Development in the field of quantum life science: Contribution to medicine by developing cell screening and hyperpolarized MRI using biological nano-quantum sensors

technological progress

Solid-state quantum sensor (magnetic)

• Establishment of simultaneous temperature/current measurement technology • Environment-resistant (under high temperature, under radiation) sensor • Biocompatible (uncooled, non-toxic) sensor • Realization of cell measurement sensor

• Single-molecule-level biodynamic measurement • Realization of room-temperature, high-spatial-resolved NMR • Realization of quantum memory

• Realization of compact and wearable biomagnetic measurement system • Realization of room-temperature, high-spatial-resolution, small-sized MRI • Realization of robust ultra-high-sensitivity magnetic sensor under extreme environment • Standard measurement by biological nano-quantum sensor and nano-quantum probe • Cell/biological measurement Contribution to efficient screening of cells by

Achieving magnetic field sensitivity sub

Achieved 10 fT wide-

Achieving ultra-high sensitivity in the aT region

Quantum metrology device

pT Realization of environmental spin noise decoupling

field high-precision synchronous quantum phase detection, realization of ensemble nuclear spin transfer Development

Deepening fusion with quantum optical measurement exceeding the shot noise limit

Development of electrical detection

of current/spin injection technology Realization of quantum manipulation by spin waves, etc. Realization of large area and high-speed growth

material

technology Realization of high-speed growth, research on luminescence centers other

than NV centers Deepening of the theory and technology of quantum measurement by

quantum hybrid systems Advanced quantum state control such as

Quantum repeater Quantum network Development to quantum computing

quantum entanglement, nuclear spin hyperpolarization technology, phonon manipulation realization of

Quantum Physics/ Theory

Development of high-sensitivity technology using quantum memory

Quantum repeater using quantum memory Quantum network Integration with quantum computing

Elucidation of noise mechanism, demonstration of low-noise signal detection method, high-efficiency spin control method

Development of peripheral technologies that support this technolog

system

Development of three-dimensional measurement inverse problem analysis technology (cells-nervous tissue-brain function, etc.)

Application of AI deep learning, etc. (low noise processing, image recognition, anomaly sign detection, internal estimation, etc.) Microwave

Implementation/ inte

antenna technology Development of integrated circuit technology Development of active shield technology Realization of on-chip implementation

Development of shieldless technology

Realization of chip array

Development of nanophotonics integration technology

Sophistication of optical technology (green VCSEL, high-performance high-sensitivity image sensor, etc.)

Present (FY2019) | 5 years later (FY2024) | 10 years later (FY2029) | 20 years later (FY2039)

ÿ Quantum inertial sensor

• Realization of navigation equipment that surpasses the accuracy of current equipment. Multiple safety assurance for self-driving cars and ships, utilization for earthquake disaster prevention combined with optical lattice clocks • Realization of high-sensitivity gyro operation in a ship environment in 5 years, demonstration of quantum inertial navigation system in 10 years Prototype • Prove the principle of a cooled ion gyro, and proceed with the establishment of a technology to precisely measure the angular velocity of a cooled atom gyro under ship-level acceleration and rocking.

Economic and social impact

- Improving the efficiency of marine resource exploration using an autonomous unmanned underwater vehicle (AUV) (making it possible to precisely link resources with latitude/longitude information)
- Establishment of technology for safely navigating self-driving ships (advanced logistics) (countermeasures against piracy using GPS deception)
- Establishment of technology to ensure multiple safety in highly automated passenger transportation (countermeasures against terrorism using GPS deception)
- Establishment of technology for real-time measurement of geoid height changes in the waters around Japan using ships, making it possible to assess the risk of plate-type earthquakes (collaboration with optical lattice clocks and star trackers)
- Establishment of technology to ensure multiple safety for self-driving cars (anti-aging measures) (countermeasures against GPS interruption/GPS deception), cyber-attack countermeasures against connected cars
- Establishment of technology to acquire Japan's geoid continuously in real time and space using probe cars, self-driving cars, etc., enabling risk assessment including direct earthquakes

*RLG: Ring laser gyro

technological progress

Cooled atomic gyro
- Verification of 1-2 orders of magnitude higher sensitivity than RLG
- Vessel-level acceleration Achieves high-sensitivity operation under rocking conditions
- Automobile-level acceleration Realizes high-sensitivity operation under rocking motion
- Realization of quantum inertial navigation system compatible with platforms with high mobility Position accuracy: 2 to 3 orders of magnitude higher (compared to conventional models) Size: 100 L or less
- Realization of a quantum inertial navigation system compatible with a platform that is compact, lightweight, and has high mobility Position accuracy: 2 to 3 digits (compared to conventional models) Size: 10 L or less

Cooling ion type gyro
- Achieves 1 to 2 orders of magnitude higher sensitivity than RLG
- Demonstration prototype of quantum inertial navigation system with double-digit positional accuracy

full ten Sol Gravity Gradiometer
- Sensitivity (10n /m/ $\sqrt{}$Hz) prototype
- Operates under ship-level acceleration and rocking (10n/m/Hz) $\sqrt{}$
- Achieves high sensitivity operation (1n/m/Hz) under ship-level acceleration and rocking $\sqrt{}$
- High-sensitivity operation (100p/m/Hz) under ship-level acceleration and rocking $\sqrt{}$

Higher accuracy High exercise tolerance
- Vessel-level acceleration Establishment of technology to separate acceleration and angular velocity from the output of a cooled atom/ion interferometer under rocking conditions
- Automobile-level acceleration Establishment of technology to separate acceleration and angular velocity from the output of a cold atom/ion interferometer under rocking conditions
- Demonstration of compact and portable atomic wave waveguide technology that guarantees high coherence
- Realization of a highly sensitive gyro using a cooled atomic wave waveguide
- Proof-of-principle cooling ion gyro
- Establishment of basic technology to improve gyroscopic sensitivity in a practical manner using quantum entanglement (spin squeezing)
- Establishment of quantum entanglement technology compatible with atomic wave waveguide technology
- Realization of compact portable coherent continuous atomic wave source

Gravity gradient correction
- Introduction of Gimbal Structure to Gravity Gradiometer
- Miniaturization of gravity gradiometer considering application of quantum technology

Development of peripheral technologies that support this technolog

soft
- Establishment of a hybrid quantum navigation algorithm
- Exploring quantum navigation based on new concepts

High performance
- Development of highly sensitive classical accelerometer
- Examination of Hybridization with Quantum Technology

Downsizing and portability
- Atomic source Downsizing and weight saving of vacuum device
- Maturity of atomic wave waveguide fabrication technology
- Downsizing and weight saving of light
- Minimization of light source by introduction of PLC technology, etc.
- source Downsizing and weight saving of control circuit

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039)

ÿ Optical lattice clock

• Capturing new time business markets such as next-generation communications and relativistic positioning by widely supplying ultra-high-precision time to society • Efforts to further downsize and popularize optical lattice clocks, Demonstration of standardization and relativistic geodesy • In addition to developing elemental technologies for improving the precision of optical lattice clocks, advance elemental technologies that lead to miniaturization, portability, and geodesy

Economic and social impact

- Large-scale earthquake risk assessment (coordinated with quantum inertial sensors)
- Asynchronous high-speed, large-capacity communication •High-speed, high-accuracy advanced location information services (VLBI, radar, etc.) •High-speed optimization of power network smart grid (stable operation in the event of a potential large-scale disaster)

technological progress

light lattice clock

- Demonstration of an optical lattice clock with 19 digits of precision, which is 4 digits more accurate than conventional atomic clocks.
- Volumetric Optical Lattice Clock Device Downsized to 400L
- Compact optical lattice clock device with a volume of 200L
- Portability of the optical lattice clock device Price reduction (popularization)
- Field demonstration of relativistic geodesy (displacement observation in mm order)
- Redefinition of second by high-precision optical atomic clock (18-digit precision)
- GNSS-independent spatio-temporal network, high-precision distributed system (18-digit precision) Real-time mapping of gravitational potential (cm order)

High precision (high reliability)

- Atom capture, miniaturization of cooling technology, high reliability
- Uniform, zero magnetic field high-precision control technology
- Highly stable and robust optical frequency control technology
- Reliability of optical lattice clock devices
- Mass production technology for optical lattice clock devices

Geodetic mapping

- 19-digit optical lattice clock long-term stable operation, high reliability, unmanned operation
- Geodetic mapping system using optical lattice clock

Development of peripheral technologies that support this technolog

Downsizing and portability

- Higher performance, higher reliability, and stable supply of semiconductor lasers
- Narrow line width, highly integrated compact optical circuit Optical module technology, high reliability
- Compact and highly reliable optical-electrical circuit technology
- Uniform magnetic field high-precision control technology
- Optical lattice clock device technology including in-vehicle use

networking

- Long distance optical link (1000km class)
- Optical lattice clock optical link repeater technology, high reliability, low cost
- Lower cost of optical fiber networks

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039)

(9) Quantum entanglement optical sensor

• Contribute to a safe and secure society through advances in medical technology such as non-invasive observation of cells, precise measurement of retinal thickness, and high-sensitivity detection of chemical substances . In addition, quantum infrared absorption spectroscopy up to the far infrared region is realized with a visible light detector. Advance treatment development

Economic and social impact

- Innovative evaluation and inspection technology for transparent electronic devices (image elements and optical ICs) using high-resolution quantum OCT
- 3D high-resolution quantum OCT enables in situ observation of cells, contributing to the development of regenerative medicine, etc.
- Ultra-high-resolution observation by quantum OCT enables early detection of diseases and contributes to healthy longevity.
- A compact device for identifying hazardous substances using mid-infrared quantum absorption spectroscopy for a safer and more secure society.
- Far-infrared quantum absorption spectroscopy enables the detection, identification, and analysis of chemical substances and drugs anywhere, and has a major ripple effect on environmental monitoring, drug manufacturing, and medical care.
- Quantum Life Science Research, Ripple to Solid State Quantum Sensors

technological progress

Quantum Optical Coherence Tomography (Quantum OCT)

- Quantum OCT with vertical resolution (1 ÿm or less) improved by 3 to 5 times or more compared to current classical technology (OCT)
- Realization of 3D quantum OCT with volume resolution (1 ÿm3 or less) that is two orders of magnitude better than current technology (cell shape recognition is possible)
- Realization of three-dimensional quantum OCT with a volume resolution (0.1 ÿm3) that is three orders of magnitude higher than the current technology . Realization of multi-functional quantum OCT such as 3D measurement of concentration of specific substances

infrared quantum absorption spectroscopy

- Realization of quantum absorption spectroscopy in the mid-infrared region (2 to 5 ÿm) that eliminates the need for conventional infrared detectors (quantitation of specific molecules)
- Realization of quantum absorption spectroscopy in the far-infrared region (5 to 20 ÿm) (enables discrimination and identification of complex molecules)
- Miniaturization (A4 size) by modularizing the quantum entanglement light source
- Further miniaturization (palm size) by making the entangled light source into a chip, etc.
- High functionality for infrared quantum absorption spectroscopy imaging

light source

- Increasing the intensity of quantum entangled light sources using waveguide-type quasi-phase-matching devices
- Development of modularized quantum entanglement light source Development of far-infrared quantum entanglement light source
- Development of quantum entanglement light source integrated with excitation light source Development of semiconductor on-chip quantum entanglement light source

photon detection

- Longer wavelength and faster superconducting photon detector
- Realization of ultra-high-speed signal processing by fusion of superconducting photon detector and superconducting circuit
- Miniaturization of superconducting photon detectors
- Longer wavelength detection of up-converted photons (mid-far infrared)
- Miniaturization of up-converted photon detection and systemization as evaluation equipment (cooperation with quantum networks)
- Array of semiconductor photon detectors Higher sensitivity Higher speed

Image processing/ theory

- Creation of quantum entangled optical adaptive optics technology and fusion with AI technology
- Further enhancement of resolution Enhancement of photon sensing data processing to support multi-functionality
- Quantum optics Nonlinear optics Development and deepening of photon measurement theory
- Creation of new measurement and imaging methods Expansion of quantum entanglement light wavelength range (X-ray terahertz)

Development of peripheral technologies that support this technolog

signal processing

- Advances in high-speed electrical processing technology for photon detection signals (up to 50 GHz) Development of new technologies such as superconducting circuits High-speed parallel signal processing of a large number (up to 1 million) of detection signals

Light source/light

- Miniaturization and sophistication of excitation laser light sources On-chip optical circuit technology Progress in integration technology with laser light sources, etc.

Cryogenic technology

- Miniaturization and price reduction of compact cryogenic devices for photon detectors (table top)

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039) Ten

(10) Quantum spintronics sensor (tunnel magnetoresistive sensor/spin heat flow sensor)

• Tunnel magnetoresistive (TMR) sensor: Application to social infrastructure, buildings, agricultural land, and biological monitors by realizing a safe, high-performance, and inexpensive magnetic field sensor with low cost and mass productivity Spin heat flow sensor: Information on heat flow It can be used, and is expected to be used in heat-related industries such as plants and social infrastructure.

• In 10 years time, power-saving and self-oscillating TMR sensor, compact, portable, matrix type spin heat flow sensor will be realized • Improvement of ferromagnetic tunnel junction fabrication technology, quantum rectification mechanism by spin and topological electronic structure Promote the development of thermoelectric conversion technology using

TMR sensor

Economic and social impact

- Industrial applications such as inspection of infrastructure such as tunnels, bridges, and pipes, detection of flaws on high-precision metal surfaces, and management of factory production line equipment.
- Sensors are placed everywhere, such as autonomous driving support and power monitoring of smart grids. Can be used as big data by connecting to the cloud
- Application to healthcare such as simple measurement of human body functions, wearable sensing such as pulse wave, fetal movement, etc.
- Achieving magnetocardiography and applying it to medical and healthcare applications
- Achieving the measurement of magnetoencephalography and spinal cord magnetism, and realizing advanced medical care

technological progress

TMR sensor (magnetic)

- Achieved low-cost, high-performance implantable magnetic sensor with high sensitivity and low noise Achieved electrical detection of low-frequency magnetic field of 100fT
- Achieved a magnetic sensor that can transmit data in any environment by saving power Achieved electrical detection of a low-frequency magnetic field of 10fT
- Realization of sensors that combine multiple functions such as light and magnetism, vibration and magnetism, and heat and magnetism Enables NMR measurement, realizing a system that can simultaneously measure the magnetic field shape Achieved electrical detection of a low-frequency magnetic field of 1 fT

Higher sensitivity and higher functionality

- Development of high-performance tunnel magnetoresistive materials
- Improving magnetic tunnel junction fabrication technology
- Development of noise reduction technology
- Functional enhancement of ferromagnetic tunnel junctions (development of elements with power generation function and elements with self-oscillation function)
- Establishment of mutual information transfer technology between ferromagnetic tunnel junctions and other physical quantities Establishment of NMR measurement technology using ferromagnetic tunnel junctions
- Realization of coherent magnetoresistive sensor by realization of tunnel magnetoresistive element with NV center

Advances in peripheral technologies that support this technology

Design, control technology, etc.

- Design of magnetoresistive characteristics Development of control technology
- Development of peripheral circuit technology for noise reduction Development of uniform element processing technology
- Fusion of single spin quantum sensor and magnetoresistive device Fusion of power supply and measurement circuit Packaging/system cost optimization

Spin heat flow sensor

Economic and social impact

- Realization of abnormal heat flow detection Realization of smart air conditioning
- Development of continuous monitoring and operation optimization services for large-scale plants using heat flow sensor information (domestic scale of 1 trillion yen/year) Use for infrastructure maintenance/management and crime prevention/disaster prevention
- Achieving disease prevention and detection Wide-ranging IoT infrastructure construction Data utilization services deployed (several trillion yen/year in Japan)

technological progress

Spin heat flow sensor

- Parasitic thermal resistance is dramatically reduced, realizing a flexible thin-film sensor (film)
- Achieved heat flux sensitivity of 10mV/(W/m2)
- Realization of high-performance heat flow sensors such as small size, portability, and matrix type
- Realized a key component of an autonomous sensing node that collects various sensing data including heat flux data Realized large area/mass production Achieved heat flux sensitivity of 100mV/(W/m2)
- Realization of small size and high integration by three-dimensional stacking

Development and advancement of thermoelectric conversion ele

- Search for Weyl structure of matter Development of thermoelectric conversion technology using quantum rectification mechanism by spin and topological electronic structure (spin Seebeck anomalous Nernst effect, etc.)
- Development of material development technology using AI
- Advances in topological electronic structure control technology
- Advances in manufacturing and mounting technology for thermoelectric conversion elements that surpass the conventional Seebeck effect and are inexpensive
- Advances in AI-based technology for obtaining high-order environmental information from thermoelectric noise
- Development of self-supporting environment sensor element with thermoelectric conversion function and heat flow sensor function at the same time
- Advances in environment-friendly sensor embedding technology

Advances in peripheral technologies that support this technology

Fusion technology, etc.

- Progress of Dramatic Cost Reduction of Cloud Computing
- Fusion development with simulation technology such as real-time visualization technology for heat flow distribution Development of security infrastructure monitoring technology by fusion of heat flow magnetic field information and AI
- Development of medical diagnostic methods using weak heat flow and weak magnetic field

Present (FY2019)	5 years later (FY2024)	10 years later (FY2029)	20 years later (FY2039)

(11) Quantum communication/cryptographic link technology

• Strengthening the security of various security applications through the commercialization of quantum cryptography equipment • Quantum cryptography communication at 10 Mbps in metropolitan areas by 5 years, and expansion to inter-city scale (longer distance) by 10 years Demonstration • Research and development of high-performance single-photon detectors, quantum entanglement light sources, random number sources, etc. In addition, research and development of new methods of QKD

Economic and social impact

- Enhancing security applications using cryptographic keys that cannot be deciphered by any computer
- Commercialization of one-to-one quantum cryptography equipment
- Popularization of commercially available quantum cryptography devices

technological progress

- Quantum cryptography communication at 10 Mbps in metropolitan areas
- Demonstration of extension to inter-city scale (longer distance)
- Quantum cryptography communication of several hundred kilometers at 1 Gbps by multiplexing

Terrestrial link

- Speeding up current protocols and improving implementation safety
- Improved performance with new protocol
- Longer distance by link connection (1-link demonstration test)
- Longer distance by link connection (5-link demonstration test)
- Trial operation of link connection equipment
- Fusion with quantum repeaters
- Optical communication and line sharing possible Completion of CV-QKD technology
- Compact modularization of CV-QKD equipment
- Realization of high-speed, long-distance transmission over commercial lines using CV-QKD
- Sophistication of safety assurance technology
- Field demonstration of QKD method independent of equipment implementation
- Practical application of QKD method independent of equipment implementation

satellite link

- Sophistication of satellite-mounted quantum cryptography technology
- Demonstration of satellite quantum cryptography
- Trial operation of satellite quantum cryptography
- Practical application of satellite quantum
- Demonstration of basic technology for quantum communication with high transmission efficiency
- cryptography Demonstration of quantum communication in deep space

Quantum communication device

- High-speed quantum entanglement light source Miniaturization
- Practical application of quantum entangled light sources
- High-performance photon detector Miniaturization High-
- New detection device
- performance superconducting photon detector
- High-speed, low-noise coherent photodetector for CV-QKD Development and commercialization of coherent photodetector for CV-QKD Stabilization technology for long-distance optical phase-difference detection
- Development and practical application of quantum communication multiplexing technology
- Advancement of tracking technology, ultra-high-sensitivity low-loss optical transmission/reception antenna (satellite system)
- Low-loss optical cable (~150km)
- Low-loss optical cable (~200km)
- 200km~

Development of peripheral technologies that support this technology

- thermal noise random number source
- Acceleration and miniaturization of quantum noise random number sources
- Realization of a long-lived and highly stable random number source
- Stable supply of high-performance single-photon detectors Extension of device-
- Practical application of variable delay interferometer
- independent QKD theory Advancement of theory proof
- Quantum Communication Based on Continuous Quantities Advances in Cryptographic Theory
- considering imperfections of actual devices

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039)

(12) Quantum repeater technology (quantum memory, quantum entanglement, etc.)

• Accelerate data processing by realizing secure quantum computation and distributed quantum computation through quantum internet connection
Realization of key generation that exceeds the limit • Research and development of quantum memory implementation, quantum entanglement generation, and connection technology with light to realize a quantum repeater

Economic and social impact

Quantum cryptography communication that connects users via the quantum internet is possible Quantum computers and

users are connected via the quantum internet, enabling secure quantum computation Quantum computers are connected via the quantum internet, enabling

distributed quantum computation Quantum sensors are quantum Quantum sensor network enabled by internet connection

technological progress

quantum entanglement delivery

Demonstration experiment of quantum repeater function in field environment

Improved operability, reduced cost, and ensured stability of quantum repeaters using quantum memory Enables long-distance (>500km)

Quantum entanglement distribution between three points becomes possible via quantum repeaters

quantum entanglement distribution via quantum repeaters Many-body quantum entanglement at multiple locations

Quantum entanglement distribution enables key generation at rates exceeding 1 kbps New applications emerge using

quantum entanglement

Quantum entanglement generation between photons and quantum memory by light emission realized

Realization of quantum entanglement generation between quantum memories by light emission and light reception

Realization of quantum entanglement generation between quantum memories via photons for communication

via quantum memory generation is realized

global multipoint quantum entanglement

quantum memory

Realization of quantum memory that realizes operability equivalent to quantum media conversion and semiconductor memory

Operational fidelity of 99.9% or higher for quantum entangled gates

Quantum memory with 100 to 1000 qubits capable of individual quantum manipulation is realized Fault-tolerant logical

Realization of scalable and reconfigurable quantum repeater system by fusion of quantum memory method and all-optical quantum repeater method

Quantum memory of about 10 bits with a memory time of 1 minute or more is realized

Complete bell measurement between different media

quantum memory is realized by quantum coding

quantum interface

Realization of quantum media conversion between photons and quantum memory

Realization of quantum media conversion between quantum bits and quantum memory

Realization of quantum entanglement distribution and connection with quantum computers and quantum sensors

Advancement of quantum wavelength conversion

technology Advancement of single-photon fiber coupling technology

Realization of Fiber Modularization of Quantum Wavelength Converter

Realization of wavelength multiplexing quantum communication using quantum wavelength converters

light source

Realization of single photon source, quantum entanglement light source

Advances in single-photon sources and quantum entanglement sources

Demonstration of all-photonic quantum repeater

Development of peripheral technologies that support this technolog

optical circuit

Advancement of quantum circuits based on optical integrated circuits

Enables non-destructive measurement of photon number and gate operation between photons

Quantum communication experiment using new light source

System development

Automated system calibration

Advances in quantum authentication technology

Improving the performance of control microwave lasers

Modularization of quantum repeaters

Long-term maintenance-free operation including refrigerators for quantum repeater systems

material development

Purification and functionalization of diamond, semiconductors, dielectrics, etc.

Advances in microfabrication technology

array integration

Mass production of quantum repeater module

Present (FY2019) | 5 years later (FY2024) | 10 years later (FY2029) | 20 years later (FY2039)

(13) Network technology (construction, operation, maintenance, etc.)

• Building a quantum cryptography network that integrates terrestrial and satellite systems, a deep space quantum communication network, and the quantum internet, and realizing a secure and highly efficient network

• Urban mesh within 10 years, global quantum cryptography within 20 years Realization of networks, demonstration of deep space quantum communication and quantum internet • Research and development on quantum communication and cryptographic networking technology and quantum internet infrastructure technology using link technology and quantum repeater technology

Economic and social impact

- Quantum technology service platform that integrates functions such as quantum computing, quantum measurement sensing, quantum communication cryptography, etc.
- Realization of a secure communication network that covers all of Japan
- Global quantum cryptography network as a service

technological progress

quantum medium Successor quantum internet

- Demonstration of basic functions of the quantum internet
- Standardization of connection specifications, routing, address management, etc. of the quantum internet
- Quantum Internet Testbed Trials
- Establishment of elemental technologies for quantum repeaters
- Development of quantum internet architecture
- Long-distance quantum repeaters and multi-point

Quantum Cryptography Network, Quantum Communication

- Practical application of global quantum cryptography network
- Trial operation of a global quantum cryptography network that integrates satellite and terrestrial networks Construction and trial operation of a
- Stable operation and practical use of metropolitan quantum cryptography networks
- metropolitan area mesh Inter-city backbone quantum cryptography network
- Interconnection of deep space quantum communication, satellite-to-ground quantum communication
- Key management technology, quantum cryptography network control Sophistication of management technology
- Relaxation of node security requirements by next-generation quantum cryptography technology, improvement of resistance to service denial attacks by link redundancy
- Introduction of CV-QKD technology to access networks
- Installation of quantum communication devices on satellites, architecture development of satellite quantum communication networks

Development of peripheral technologies that support this technolog

Network control and management technology, protocol

- Development of Software-Defined Network Control Technology and its Introduction to the Field of Quantum Communications and Cryptography
- Advances in photonic network technology, low-loss optical routing
- Advances in quantum multi-party protocol theory and development of implementation methods

Satellite communication technology

- Improving the performance of satellite optical communication technology and accumulating space demonstration results
- High performance, miniaturization, and portability of optical ground stations
- Miniaturization of satellite buses, advancement of satellite constellation technology

Present (FY2019) | 5 years later (FY2024) | 10 years later (FY2029) | 20 years later (FY2039)

Interdisciplinary Roadmap

• This roadmap summarizes the prospects for the development of each area over the next 20 years or so, based on domestic and international research trends, etc., targeting the quantum fusion innovation area. • Each roadmap describes (1) progress in interdisciplinary fields, (2) technological systems that support interdisciplinary fields, and (3) social and economic impacts resulting from these, with the aim of sharing future visions between the public and private sectors. is one of • Based on this roadmap, the government plans to strengthen research and development support for the

quantum fusion innovation area. Based on these support, etc., from the private sector

It is strongly hoped that new investment and active participation in the field will be promoted, and that the project will develop into a national industry-academia collaboration and public-private collaboration project.

(1) Quantum AI technology

• Maximize the potential of AI, such as elucidating and demonstrating quantum mechanical elements in future neural networks and human learning mechanisms • Quantum AI systems that combine quantum infrastructure (quantum communication/Internet, quantum sensors, quantum computers) • Integrate machine learning (AI) and quantum information processing to build the basic theory of quantum machine learning, apply quantum AI methodologies to chemistry/materials/property calculations such as materials informatics, quantum simulation, and control of quantum systems. application

Economic and social impact

- Learning speed of machine learning is accelerated, learning only necessary items while selecting necessary learning (clustering)
- Significant improvement in performance and processing speed of inference and information processing in AI
- Expansion of science and technology frontiers • Expansion to elementary particle and condensed matter physics research • Application to quantum life phenomena
- New functional materials (Academic understanding) •High-temperature superconducting materials •Artificial photosynthesis •Interfacial functions •High-efficiency catalysts •Photofunctional materials •Transport phenomena
- Advanced scientific calculation •Thermal fluid analysis •Inverse matrix calculation •Structural mechanics analysis •Linear system solver

Area progress

Annealer type hardware/ software

- Application of the Ising model to quantum machine learning
- Development of quantum AI functions from machine learning
- Elucidation of Computability of Quantum Neural Networks
- Applications of Quantum Boltzmann Machine Learning Theory
- Establishment of calculation methods for accelerating AI
- Actual computational performance when facing NP-hard problems
- Application of classical pseudo-impossible dynamics
- Academic exploration of the mathematics of quantum AI
- Challenging complex phenomena such as the elucidation of glass mechanisms in the natural world
- Elucidation of quantum mechanical factors in human learning mechanisms

Gate type hardware/ software

- Development of quantum machine learning frameworks such as quantum circuit learning, quantum kernel methods, and quantum generative models
- Building Advanced Quantum Machine Learning Algorithms with Exponential Acceleration
- Application of quantum machine learning to real data and real problems
- Application of quantum AI approach to quantum control
- Building Quantum Machine Learning by Combining Quantum Sensing and NISQ Machines
- Application of Quantum Machine Learning Combining Quantum Sensing and NISQ to Quantum Life Science
- Application of Quantum AI Approach to Quantum Many-Body Systems (Materials Chemistry)
- Implementation of quantum machine learning using NISQ machines
- Quantum materials informatics and quantum cheminformatics using quantum machine learning and quantum chemical calculation
- Performance evaluation of quantum machine learning algorithms
- Construction of an interface data structure between classical and quantum data
- Dequantization, construction of quantum-inspired algorithms
- Academic exploration of quantum AI mathematics (construction of quantum models, information geometry of parameter space, development of parameter adjustment methods, analysis of expressive and separable capabilities of quantum feature space)

Technological progress supporting this area

Annealer type hardware/ software

- Fabrication of 100 qubits with high coherence performance and excellent scalability
- Fabrication of 2000 qubits with high coherence performance and excellent scalability
- Realization of a large-scale quantum annealing machine with high scalability and high coherence performance
- Some combinatorial optimization problems can now be solved by annealing computers
- Annealing type computer started to be applied to solve some real-world problems
- Combining it with solvers and algorithms that solve linear programming problems and quadratic programming problems, Annealing has become an accelerator that spreads over all optimization problems.

Annealer/ gate common

- Establishing the foundations of quantum programming languages and compilers
- Accelerating compilers for large-scale automation Advances in automation

Gate type hardware/ software

- Arbitrary control of physical qubits (about 50 qubits) becomes possible
- Arbitrary quantum control of physical qubits (about 100 qubits) becomes possible
- Emergence of quantum computers with 500-1,000 physical qubits
- Appearance of a quantum computer equipped with quantum error-corrected logic bits (10 to 50)
- Demonstration of Superiority of Quantum-Classical Hybrid Algorithms
- Design of quantum error correction architecture and demonstration of quantum superiority using actual equipment
- Emergence of architectures that enable programmable error correction
- Quantum open source software will be created, enabling an architecture that fuses quantum technologies

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039)

(2) Quantum Life Science (Biological Nano Quantum Sensors)

• It will be possible to screen cells with specific properties and abilities, and it is expected to improve the efficiency of biopharmaceutical production and regenerative medicine. and build a method for predicting and reconstructing life phenomena.

Economic and social impact

- Efficient production of biopharmaceuticals and regenerative medicine through cell screening and cell quality control using bio-nanoquantum sensors
- AI diagnostics, wearable devices, and "quantum smart vesicles/quantum smart cells" enable early detection of various diseases, self-care before illness, and prevention of aggravation and recurrence.
- Measurement by biological nano-quantum sensors will become the standard measurement technology for cell measurement analysis in all bio-related industries, regardless of basic applications.
- By understanding "how matter becomes life" based on biodata infrastructure, it becomes possible to construct life from atoms and molecules, predict the behavior of life, and understand the evolution of life.

Area progress

Biological nano-quantum sensor

- Wide variety of cell types Physiological conditions Converting information obtained from measurement items into big data and unifying data interpretation International standards Clarifying molecular processes occurring in living cells through comprehensive research Establishment of AI diagnostic technology Basic biology Construction of an open database for development (fusion of biotechnology and digital technology) Complete physical clarification Whole body Commercialization of a sensor reading system for the deep part
- Commercialized as a general research sensor kit suitable for measurement applications such as temperature and pH.
- of the body. Promoting research on proliferation and metastasis of cancer cells Realizing efficient screening technology for cells with specific properties and abilities

Technological progress supporting this area

Measurement item

- Expansion of measurement items such as temperature, hardness, magnetic field, pH, and the amount of specific physiologically important substances
- Construction of a system that reads a large number of measurement item data from a wide range of three or more simultaneous measurement items at once and tracks changes over time
- Development of a biological nano-quantum sensor that autonomously learns the items to be quantified and returns appropriate measurement information according to the purpose (biological phenomena and pathology)

delivery technology

- Development of technology to deliver to specific sites in cells (nucleus, mitochondrial membrane, etc.) Elucidation of noise mechanism, demonstration of low-noise signal detection method, high-efficiency spin control method Number of cells: about 5,000-10,000
- Development of specific delivery technology for sensors at the whole body level, such as tumors and specific organs

High sensitivity •Measuring range

- Developed an ultra-wide-field optical detection magnetic resonance microscope capable of batch measurement of a large number of cells Achieved magnetic field sensitivity of sub-nano Tesla at the nanometer level
- Development of single-cell level whole-brain imaging technology and whole-body measurement technology
- Achieving nanotesla-order magnetic field sensitivity at the nanometer level
- Advancement of optical system and high-frequency irradiation technology and realization of environmental spin noise decoupling
- Development of multi-functional technology for biological nano-quantum sensors by 13C concentration and surface functionalization
- Development and global deployment of integrated diagnostic and therapeutic technology by combining hyperpolarized MRI/NMR
- Development of high-efficiency and high-control electron/ion beam irradiation technology
- Realization of observation of deep parts of the body with a depth of about 2 mm Development of sensor materials that emit light in the infrared region
- Achieving whole-body measurement at a depth of about 10 mm
- Establishing a reading method that does not rely on fluorescence such as magnetic fields and sound waves Developing basic technology for "quantum smart vesicles/quantum smart cells" that enable artificial control of cell functions
- Quantum manipulation technology for realization of deep observation of 10 mm or more, deepening the theory and technology of quantum measurement Self-care medical application of "quantum smart vesicle / quantum smart cell"

cell function artificial manipulation

- Development of cell introduction technology for nanosystems/quantum nanosensors for on-off control of gene expression

Present (FY2019)	5 years later (FY2024)	10 years later (FY2029)	20 years later (FY2039)

(3) Quantum life science (ultra-high sensitivity MRI/NMR using quantum technology)

• Drug screening is expected to contribute to new drug development, and metabolic imaging can be used to determine the effectiveness of deep cancer treatments, diagnose intractable diseases, and early detection. 10 years from now, medical diagnosis will be realized and clinical trials will start. Also developed hyperpolarization technology for multiple molecules

Economic and social impact

- High-speed drug screening based on molecular structure information has spread to biochemistry and pharmaceutical laboratories and drug discovery manufacturers, greatly contributing to new drug development.
- Metabolic Imaging Spreads in Biomedical Science Laboratories, Significantly Contributes to Elucidation of Life Phenomena and Pathology
- Immediate determination of the therapeutic effects of cancer deep in the human body, such as the pancreas, prostate, and kidney. Diagnosis of intractable diseases such as cardiovascular and brain diseases is also possible
- Safe and eco-friendly nano-imaging technology put into practical use as a contrast medium
- Realization of a seamless social system for early detection and prevention of aggravation and recurrence, etc.

Area progress

Room temperature hyperpolarization technology

- Room-temperature hyperpolarized biomolecular structure
- analysis Room-temperature hyperpolarized drug screening
- Realization of long-term visualization of metabolic processes by quantum coding
- Room temperature hyperpolarized pharmacokinetic study
- Realization of room temperature hyperpolarized metabolic imaging in large animals
- Practical application of biometabolic imaging by development of polarization technology that contributes to cost reduction
- Realization of biomolecular analysis and in vivo analysis using large-scale quantum entanglement in various molecules
- Conducting a clinical trial to determine the effect of anticancer drug treatment using a room temperature hyperpolarized probe
- Implementation of clinical trials for high-speed disease diagnosis technology using multi-molecular hyperpolarized probes/sensors
- Clinical application of multi-molecular hyperpolarized probes/sensors

Low temperature hyperpolarization technology

- Metabolic Imaging of Long-Life Probes with High Polarization Cryogenic Hyperpolarization

Composite technology

- Nanosensor contrast media and hyperpolarization technology enable clear observation of early stage cancers of 1 mm or less and pancreatic cancer deep within the body, which are difficult to observe with conventional methods.
- Establishment of in-situ pathological diagnosis and onset prediction technology that does not require cancer biopsy through multivariate measurement using hyperpolarized nanosensor contrast media and AI analysis

Technological progress supporting this area

hyperpolarized probe

- 10,000-fold increase in sensitivity for small-volume samples 1,000-fold increase in sensitivity for large-volume
- 10,000 times higher sensitivity for large volume samples
- 10,000 times higher sensitivity
- samples Hyper- polarization of pyruvic acid for anticancer drug effect determination at room temperature
- Development of hyperpolarization technology for multiple
- molecules Development of highly polarized long-lived molecular probes Practical application of longer-lived probes
- Development of quantum coding sensor technology
- Development of quantum-encoded entanglement sensor technology
- Development of more advanced quantum-encoded sensors by utilizing large-scale quantum chemical calculations and quantum AI through quantum computing
- Development of high-sensitivity magnetic resonance

Hyperpolarizer

- Development of a small-capacity room-temperature
- equipment that combines hyperpolarization and small magnets Large-scale equipment for social
- hyperpolarization device Development of a high-polarization rate, low-cost
- implementation Improvements such as capacity increase, polarization efficiency improvement, price reduction, GMP compliance, etc.

Nanosensor Imaging technology

- low-temperature hyperpolarization device Advancement of nanoparticle-based delivery to lesions and imaging technology, and development of
- Clinical application development of nano-imaging technology

Algorithm and database

- multiple nanosensor contrast agents Pathology estimation algorithm based on
- multivariate measurement Constructing a database for the purpose of automating pathological estimation of cancer, brain disease, etc.
- Realization of pathological estimation technology using multivariate measurement, nanoimaging technology, and AI
- Establishment of information technology that enables "MRI pathological diagnosis" by large-capacity multivariate image analysis

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039)

ÿ Quantum life science (Elucidation and imitation of quantum life phenomena)

• Realization of technology that mimics biological functions such as photosynthesis is expected to contribute to energy conservation, production of useful substances, sustainable primary production, and improvement of the global environment. Expand to the cellular level in

2020 • Quantum state measurement in organisms such as quantum coherence in photosynthesis, dynamic structure analysis of biomolecules, and integrated analysis by information science

Economic and social impact

- Realization of ultra-efficient and low-cost drug discovery by simulating biological reactions to candidate substances Ultra-early detection of disease using improved ultra-sensitive substance sensors that mimic the sense of smell
- Imitating and improving the functions of fermentation microorganisms and enzymes of medicinal plants to add value to food products
  Creating useful crops through smart breeding that controls mutations at the quantum level and contributing to sustainable primary production
- Sustainable energy production and useful substances (biofuels, biomaterials, biopharmaceuticals, etc.) that are both economical and environmentally friendly through artificial photosynthesis, artificial enzymes, ultra-energy-saving fertilizer production, etc. that imitate living organisms and use common elements.) production and agricultural production Disseminate and improve the global environment Elucidation of the most fundamental academic question, "How do
- substances gather and become life?" Reconstruction of life from atoms and molecules and the behavior of life (such as human consciousness) can be predicted

Area progress

Elucidation of biological phenomena in the nano-scale world that can only be explained by quantum physical laws and the mechanisms that affect the macro-scale world

Development and commercialization of technology that mimics biological functions

Elucidation and imitation of quantum biological phenomena

- Elucidation of mechanisms of photosynthesis, respiratory chain system, biological nitrogen fixation, etc. from quantum to cellular level
- Elucidation of the mechanism of environmental reception such as olfaction and magnetism at the quantum to cellular level
- Elucidation of the mechanisms of mutation, evolution, and gene expression at the quantum and cellular levels
- Precise elucidation of molecular interactions such as enzymatic reactions and signal transduction by receptors
- Mechanism elucidation based on quantum-to-individual level measurement of brain functions arising from various neural circuits
- Elucidation of mechanisms that affect organ and individual levels
  Realization of artificial photosynthesis systems, solar cells, and ultra-energy-saving nitrogen fixation technology that mimics the mechanisms of biological functions and the elements used Development of olfactory sensors, etc., and their application to detection of pathogenic substances, etc.
  Quantum effects Development of substance production technology using controlled artificial enzymes
- Prediction of brain function

Technological progress supporting this area

Quantum state measurement

- High-precision observation of quantum coherence in photosynthesis and respiration, and quantum measurement of biological nitrogen fixation reactions using ultrashort pulse lasers Spectroscopic analysis of quantum effects in
- biological magnetism and olfactory perception mechanisms
- Molecular design based on biological functions using quantum effects
- Measurement and theoretical analysis of quantum superposition states in DNA mutations, enzymatic reactions, etc.
- Quantum measurement of biomolecules by pump-probe method using high-brightness synchrotron X-rays Theoretical calculation of wave
- functions of biomolecules

Dynamic structural analysis of biomolecules

- Neutron structure analysis system capable of high-resolution molecular structure analysis of 1 or less
- Quantum-level structural analysis combining X-ray complementary data, expanding the analysis target to high molecular weights of 100,000 or more
- Seamless high-precision dynamic structural analysis that integrates quantum-level structural analysis and experimental dynamics analysis with quantum simulation analysis
- Structural analysis of a wide variety of biological species with sub-resolution in supramolecules and time division in sub-picoseconds Quantum chemical
- calculation of over 100,000 electron orbitals in 1-2 hours

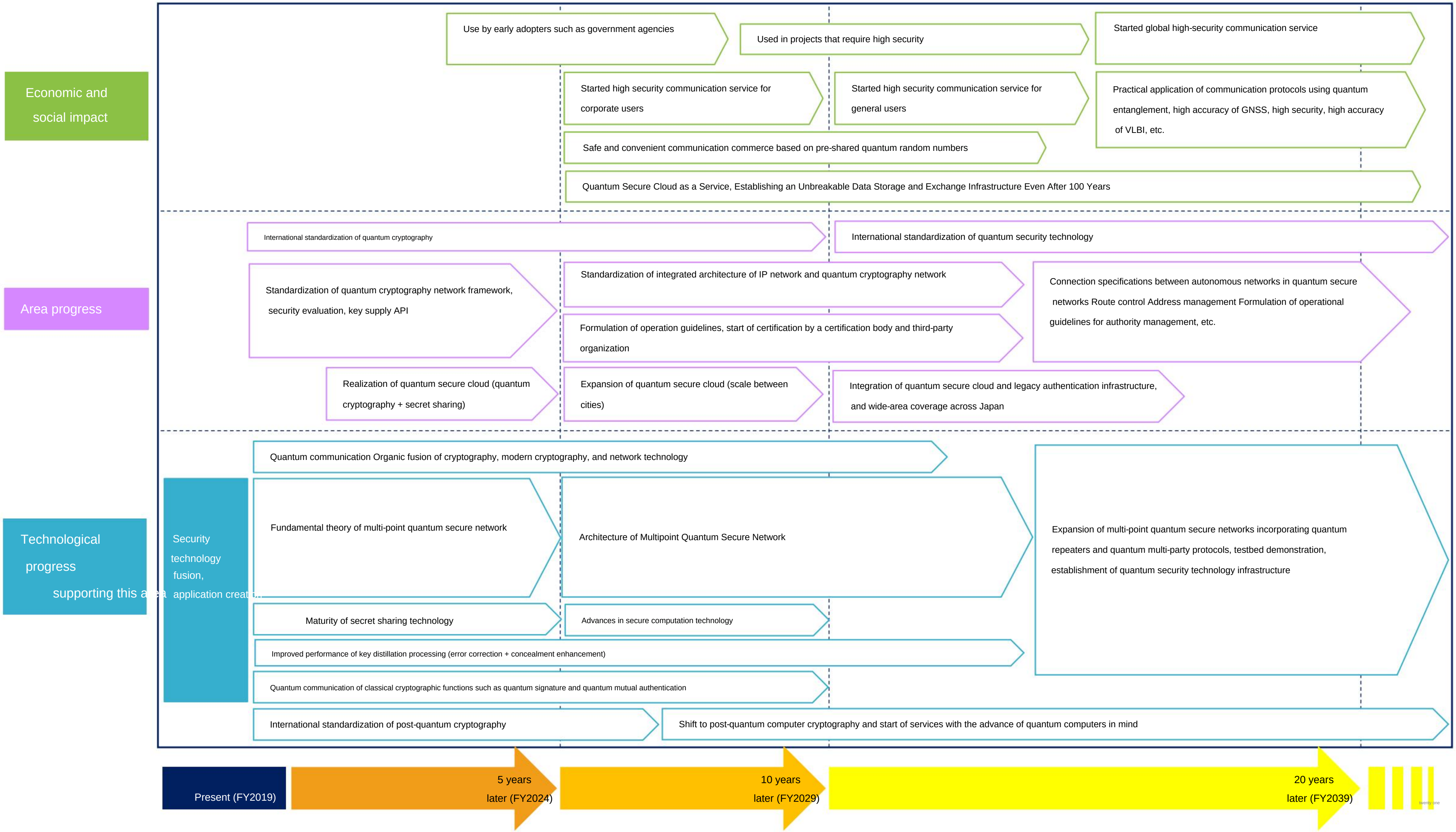
Information science

- Construction of an open database for integrated analysis of biodata of each layer of organisms obtained by new measurement technology Application of quantum probabilistic framework to life science
- •Comprehensive analysis of biodata by information science •Chemical understanding of life functions based on the understanding of material functions and chemical reactions deepened by quantum computers •Life science application of quantum machine learning by quantum sensing and NISQ ÿ Systems to understanding life phenomena as

Present (FY2019) → 5 years later (FY2024) → 10 years later (FY2029) → 20 years later (FY2039)

ÿ Quantum security technology

• Realization of use by early adopters such as government agencies and high security communication services for corporate users and general users • Realization of quantum secure cloud in 5 years, integration of quantum secure cloud and legacy authentication infrastructure in 15 years and wide-area expansion • Organic integration of quantum cryptography technology and security technology that does not depend on computational complexity (secret sharing technology, etc.), and promotion of collaboration between these and authentication infrastructure



Reference material

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Foreign trends surrounding quantum technology

• **Overseas, mainly in the United States, Europe, and China, "quantum technology" is positioned as an important technology that will bring about major changes in the economy and society, and government-led research and development strategies are formulated .** In recent years, we have significantly expanded R&D investment and strategically developed R&D bases and human resource

•Major IT companies in each country are also actively investing, and the establishment and funding of venture companies are also progressing.

• Government initiatives

ü **In September 2018, the National Science and** Technology Council **formulated a National Strategy Outline for Quantum Information Science** ü In December 2018, a law was enacted concerning investment of **up to $1.3 billion (approximately 140 billion yen) over five years from 2019** (Excluding DOD and CIA) ü Centered on DOE and NSF, **about** 10 bases for R&D and human resource development are formed.

ü **In June 2017, the European Commission** 's panel of experts **formulated an R&D strategy** ü **1 billion** **In addition, each country started research and development with its own budget. Especially** , the **Netherlands and the United Kingdom formed international research** bases. Attracting Private Investment

ü **In** the 13th Five-Year Plan for Science and Technology Innovation (2016) , quantum communication and quantum computers are positioned as major science and technology projects and are actively invested ü Establishment of the National Laboratory for Quantum Information Science **in Hefei City, Anhui Province** Under construction at a cost of **7 billion yuan (approximately 120 billion yen)** (**scheduled** for completion in 2020) .

• Efforts of representative companies

<Major IT company>

Established **Google Quantum Artificial Intelligence Laboratory (2013-)**

IBM

$3 billion research investment over 5 years (2014-)

Microsoft

Established Station Q (since 2005)

阿里巴巴 Alibaba **(Alibaba)**

Established a quantum computing laboratory at the Chinese Academy of Sciences (2015-, 30 million yuan/year)

<Venture>

D-Wave The Quantum Computing Company

Sold **the world's first commercial quantum annealing machine .** Raised $200 million.

rigetti

Developed a superconducting quantum computer. Raised **approximately $120** million.

Note) The exchange rate is calculated based on the standard foreign exchange rate and the arbitrage foreign exchange rate announced by the Minister of Finance of Japan for the month at the time of the announcement.

How to advance quantum technology is at a crossroads as global competition intensifies

Current Status of Quantum Technology Efforts in Japan

- **Quantum technology was positioned as an important basic technology for the first time in the 5th Science and Technology Basic Plan, but the amount**

  Sub-technology strategy has not yet been formulated. Each ministry independently conducts research and development

- **Japan has superiority in basic theory and basic technology, but there are issues in efforts toward practical application and industrialization (systemization) of technology.**

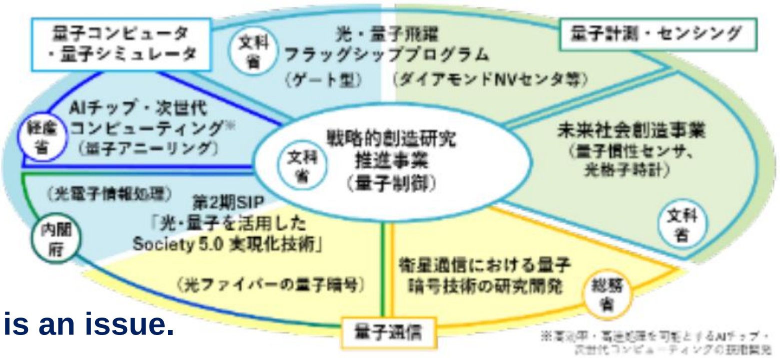
- **In the 5th Science and Technology Basic Plan (decided by the Cabinet in January 2016), the Integrated Innovation Strategy (Cabinet decision in June 2018) is** positioned **as the first light/**

  quantum technology. Research and development is being actively promoted in

  Europe, the United States, and China because it is an **innovative technological field that makes possible what was previously impossible and brings about social change . For** the realization of Society 5.0, Japan will work to maintain and improve the international competitiveness of its core photonics and quantum technology, which is one of Japan's strengths.

• Each ministry conducts R&D individually

ü Cabinet Office Quantum cryptography (optical fiber), optoelectronic information processing ü Ministry of Internal Affairs and Communications Quantum cryptography (satellite communications) ü Ministry of Education Quantum information processing (gate type), quantum measurement and sensing ü Ministry of Economy, Trade and Industry Quantum information processing (quantum annealing)



• Japan has an advantage in basic theory, etc., but the systemization of technology is an issue.

1998Professor Hidetoshi Nishimori (Tokyo Institute of Technology) published a paper on the quantum annealing method as a quantum computing method.

2010Canadian venture D-Wave announces the world's first commercial machine

(Source: D-Wave)

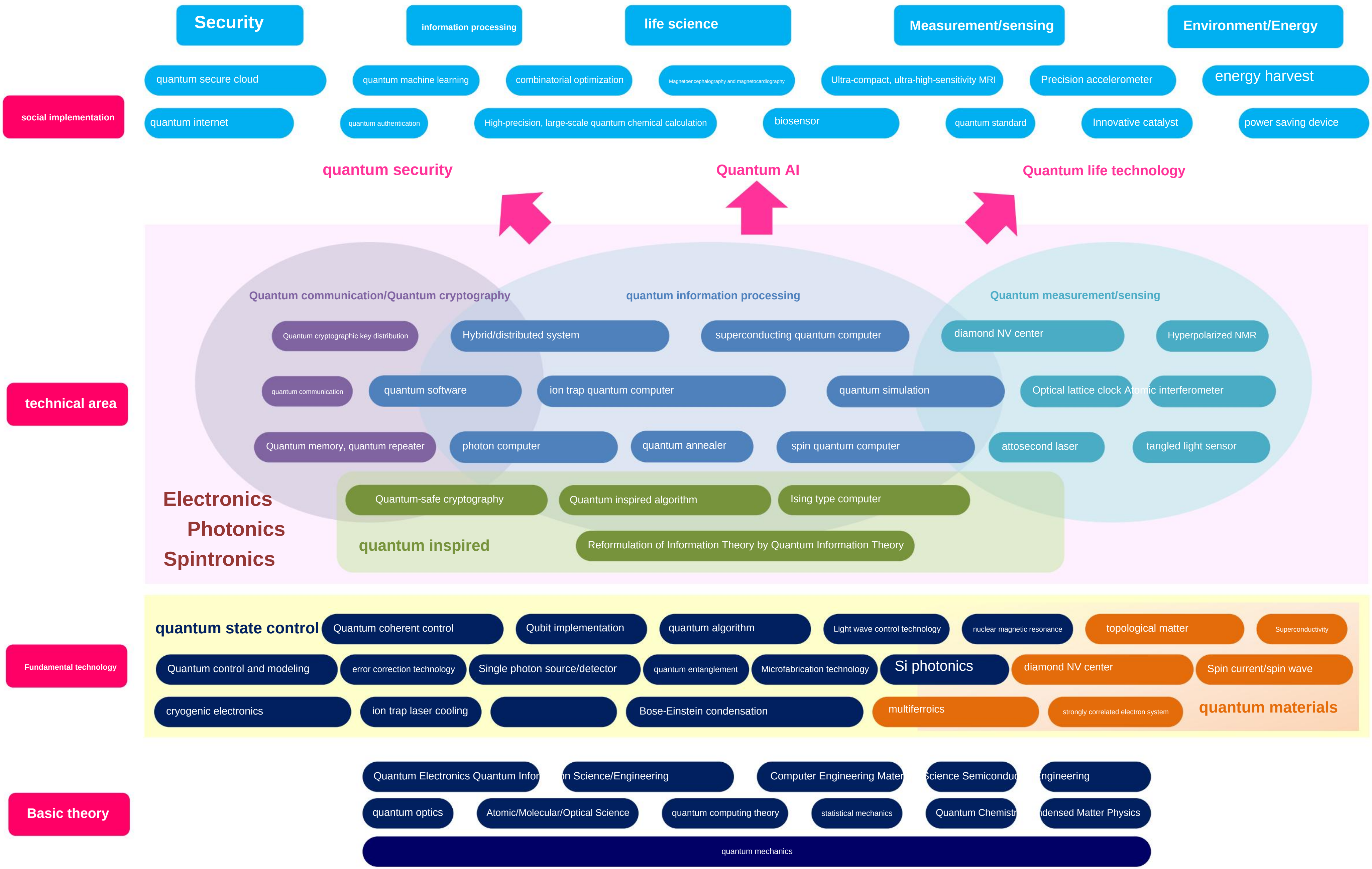
1999 Yasunobu Nakamura and Zhao Shen Tsai (at that time NEC) published a paper on a quantum bit using a superconducting circuit

2016 IBM released the world's first gate-type quantum computer to the cloud

(Source: IBM)

If this situation continues, Japan will fall far behind other countries, and the foundation for future growth of the country will not be threatened.

Scope of technologies covered by the Quantum Technology Innovation Strategy (draft)



Main technical area (1) Quantum computer/quantum simulation

•Although there are technical issues in the realization of gate-type quantum computers and quantum simulations, they contribute to streamlining the development of novel materials and pharmaceuticals, improving security technology, and making dramatic innovations in all fields of industry and society. • Quantum **annealing is actively moving toward solving real problems, including companies. By solving combinatorial optimization problem** **Contribute to improving productivity by resolving traffic congestion and optimizing factory production processes**

Gate-type quantum computer (superconducting qub...)

ü **Computers that use quantum mechanical states as information processing units (qubits) ü Japan was the first in the world to succeed in producing superconducting qubits . Maintaining high technological capabilities in** the production and control of high-quality superconducting qubits

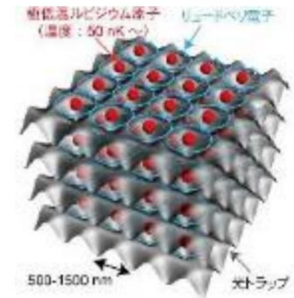
ü Scaling with high-quality superconducting qubits Theme

ü Large-scale massively parallel computing **is expected to enable computation of problems such as factorization, search, and quantum deep learning in a short time with** ultra-low qubit cooling and control device power consumption (Professor Nakamura, University of Tokyo)

Quantum simulation (cold atoms)

ü**Technology** for conducting simulation experiments by controlling the quantum state of many artificial particles for **problems specific** to the behavior and interaction of quantum many-body **systems Leading the world**

ü There are issues related to **the implementation of long-distance interactions between multiple atoms .** Expectations for the ripple effect of peripheral technologies such as light and cooling equipment **on ind**



Concept of Ultrafast Quantum Simulator
(Prof. Omori, Institute for Molecular Science)

quantum software

ü**Research and** development of OS, system architecture, algorithms, and applications required to perform calculations on quantum **computers Intensification**

ü **Expectations for innovation in industry and society due to the increase in speed and scale of** quantum computation such as machine learning and quantum chemical calculation

Quantum computer hardware/ software hierarchy

quantum annealing

ü Using quantum mechanical "superposition" to derive the optimal combination A **computer** specialized **in** _

Quantum annealing machine developed by D-Wave (Canada) (Source: D-Wave)

Inspired hardware development is active

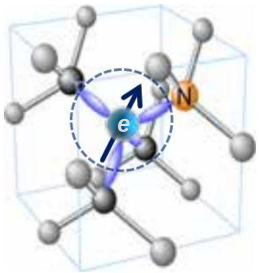
ü **Efforts to solve real-world problems such as traffic problems take precedence**

Main technical area (2) Quantum measurement/sensing

• **Quantum measurement and sensing are technologies that take advantage of the fragility of quantum states to achieve sensitivity and accuracy that surpass conventional technologies.** Contribute to the construction of a healthy and long-lived society through the improvement of **life and medical** technology, and a safe and secure society with disaster prevention, etc.

solid-state quantum sensor

ü **A highly sensitive magnetic field sensor using electron spin states.** Higher sensitivity (100,000 times) and higher spatial resolution (about 100 times) than the conventional magnetic field measurement method (Hall element) **are realized at room temperature ü Japan has strengths in material fabrication technology .** Consistent R&D from basics to device development is required



ü Expectations for **health care, safe driving, preventive treatment of brain diseases,** etc. through advanced measurement of **magnetoencephalography**

quantum inertial sensor

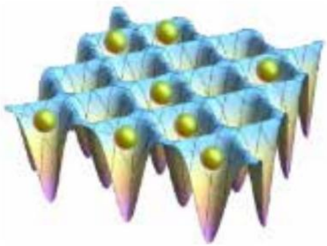
ü A sensor that measures acceleration and rotation speed using the wave properties of atoms . **A two-digit improvement in accuracy is expected compared to the** currently widely used ring laser gyro. **ü While the level of optical technology in Japan is high, it remains at the proof** of principle . It is possible to realize fully self-driving vehicles and autonomous underwater vehicles (AUV) that can confirm their own position and reach their destination **even** without signals.

(Source: JAMSTEC)

optical lattice clock

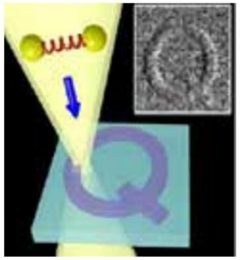
ü **A clock that uses laser light to measure time with several orders of magnitude higher accuracy than conventional atomic clocks ü A Japanese researcher proposed the principle. Accuracy of Japanese optical lattice clock** Continuous operation time leads the world. **Further miniaturization Portability Improving environmental resistance is important**

ü **Candidates for a new definition of the second ü** Expected to be useful for disaster prevention related to **earthquakes** and volcanoes by measuring weak gravitational changes and verification of constancy of physical constants.



tangled light sensor

ü **High-sensitivity** sensor using quantum entanglement that **affects** two photons even if they are separated It is done. **üA high-sensitivity, compact infrared spectrometer required for** non-invasive observation of cells, **precision measurement of tissue thickness such as the retina, and** drug manufacturing management at chemical plants can be realized.



Main Technology Area (3) Quantum Communications/Cryptography

• Quantum cryptography realizes a cryptographic service that is absolutely unbreakable, so highly confidential information can be imported without fear of security compromise.

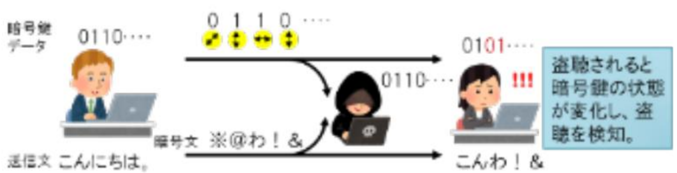
A society in which people can interact on the Internet will be realized.

Quantum Cryptography|Optical Fiber

ü **The cryptographic key data is carried on photons, and the quantum key is delivered by optical fiber .** The only encryption method **that detects all eavesdropping attacks and has proven information-theoretical security**

ü **Japan's strength is its high-performance quantum cryptography equipment. On the other hand, cost reduction and integration with applications are issues**

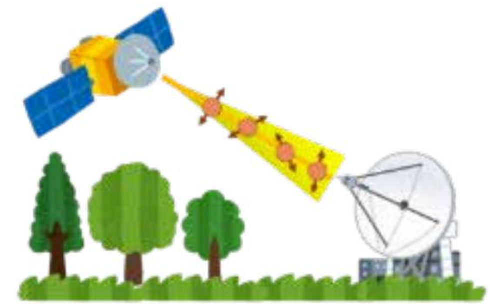
ü It is important to develop **a system** unique to Japan that combines data storage and secure calculation , and connect it to social implementation.



Quantum cryptography|Satellite communications

ü **Implement quantum key distribution between satellites and between satellites and ground station technology that enables highly confidential communication in**

ü Japan has also developed **the world's smallest microsatellite in the field of optical communication ,** and is conducting preliminary **experiments .** Important

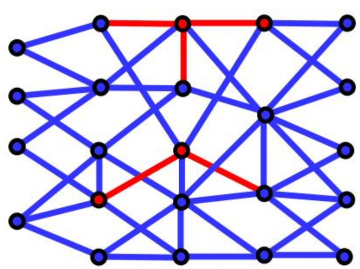


quantum communication

ü **For transmission and control of photon superposition and quantum entanglement Technology that realizes ultra-high-efficiency communication**

ü **Development for network architecture and integration, and research and development of quantum receivers for ultra-high-efficiency communication**

ü**In** addition to ultra-high-efficiency communication, it is expected to be applied to a means of transmitting quantum **information** to a quantum computer.



quantum repeater

ü **Quantum cryptography is limited to a communication distance of about 100km due to loss of light.** Currently, relaying is done using a classical method that physically prevents eavesdroppers from intruding , **and no theoretically secure relaying technology has been established .**

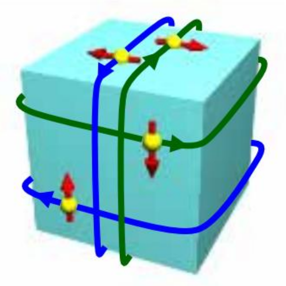
There is a technology that can be an advantage in the integration of quantum repeater devices. ü**On** the other hand, there are issues such as transmission speed and error correction, **which need to be addressed from a** long-term perspective.

Main technical area (4) Quantum materials

• With the development of nanotechnology, it is becoming possible to control single-nano-order and one-atom-layer levels, making it possible to access quantum phenomena that were previously unobservable. **• By controlling these phenomena, not only innovations such as quantum information processing but also current technologies such as energy conversion and electronics innovations It is expected to realize a level of function that cannot be reached at the technical level**

topological quantum matter

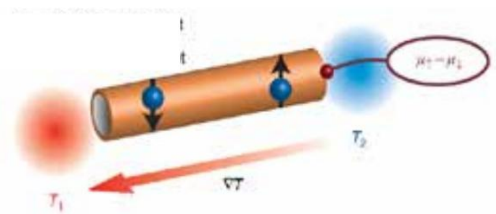
ü **Utilizing a new material, topological insulator, which is an insulator in the bulk but a metal on the surface , enables highly efficient spin-to-charge conversion.** ü**In addition, Majorana particles, which are topological superconductors,** are expected to be robust qubits, and research is being conducted all over the world. **ü Contribute to the realization of ultra-low power consumption devices and new methods of quantum computers**



topological insulator

energy conversion materials

ü Utilization of the spin **- Seebeck effect, which is a thermoelectric effect due to spin-charge conversion . Contributing to the realization of unpowered IoT sensors using harvesting technology**

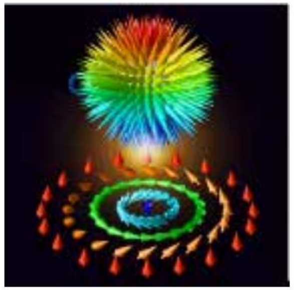


Spin Seebeck effect

spintronic materials

ü **Skyrmions, which are nanoparticles consisting of many spins ,** are being researched **as potential information carriers that can be driven with** a small amount of current. Enables **ultra-low power consumption and large-capacity memory**

contribution

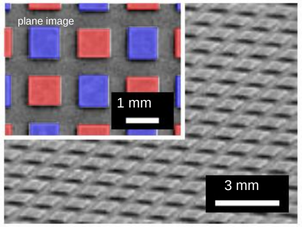


Skyrmion

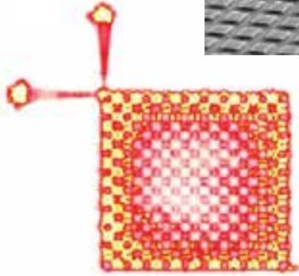
photonics materials

ü **Development of high-efficiency lasers using new concepts such as single-photon emission from quantum dots and topological photonic crystals is** progressing **ü In addition, by using metamaterials , devices and** Realization **of electromagnetic wave shielding ü**

Contribution to the realization of energy-saving light sources and next-generation quantum communication



metamaterial



topological photonic crystal

Quantum fusion innovation area (1) Image of quantum AI technology

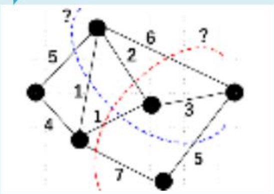
• Sophistication of artificial intelligence is an important key to realizing Society 5.0. AI is being deployed in the real world one after another. The development of next-generation computing technology will also be an important factor in the future.

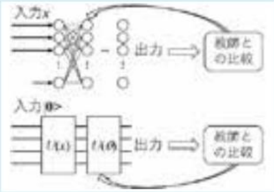
•Machine learning is attracting attention as a candidate for a killer application for quantum computers. It has been pointed out that in the future, when the sophistication of quantum computers is realized, the possibility of superiority will emerge. Lead the world by conducting intensive research and development

Unsupervised Learning/Supervised Learning

ü **Aiming** to develop unsupervised learning, supervised learning, and reinforcement learning based on QAOA and quantum circuit learning, developing **initiatives that contribute to practical applications** **Contributing to the realization of**

artificial intelligence based on large-scale and complex data


Example of MAXCUT problem
(unsupervised machine learning)


Contrasting Neural Networks and
Quantum Machine Learning

Quantum

Technology Quantum Algorithm, Quantum Computer etc…

×

Information

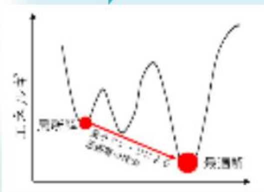
science machine learning, system architecture, etc…

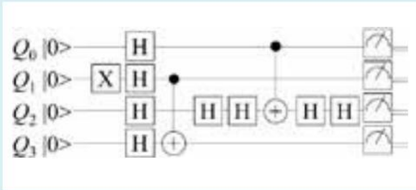
New algorithm development

ü Develop new algorithms that lead to higher sophistication and precision of artificial intelligence ü Evaluate and verify the performance of developed algorithms, such as quantum superiority

Realization of

expansion of usage


Principles leading to Ising
machine solutions


Quantum computer gate
operation image

system architecture

ü Identify areas where quantum **computers** excel in AI information processing ü Optimize computational resources of quantum computers and modern computers

Contribute to the sophistication and precision of artificial intelligence

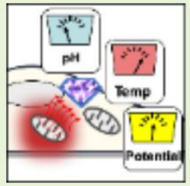
Cooperation image

With quantum AI technology, we will realize faster and more accurate artificial intelligence, which is the key to economic and social development, and contribute to the creation of highly competitive industries and the resolution of various issues facing Japan!

Quantum fusion innovation area (2) Image of quantum biotechnology

- **Along with the recent development of quantum technology, the knowledge obtained by applying quantum technology to life science and elucidating life phenomena by quantum theory Research aimed at linking observations to innovations in medical technology and environmental technology is being initiated.**
- Important innovations will be brought about, such as the realization of a healthy and long-lived society such as ultra-early diagnosis/treatment and anti-aging, and the creation of highly functional materials that **mimic** the quantum effects of organisms such as "quantum entanglement" and "superposition". **There is a possibility, and we need to work on it ahead of the rest of the world.**

Biological nano-quantum sensor



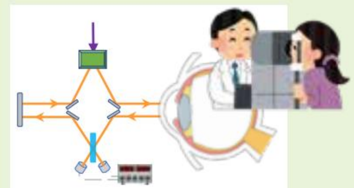
Diagnosis with 1-cell accuracy (image)

ü **Application of nano-quantum sensors to living cells**

ü **Enables the acquisition of parameters inside cells and tissue that could not be measured before, such as** local pH, temperature, current, etc. such as nuclei and mitochondria

Realization of new diagnoses such as prediction of aging status and cancer before onset

Quantum entanglement optical imaging


Fundus examination (image)

ü **Entangled light for imaging**

Utilization ü High sensitivity exceeding the S/N ratio of conventional l

High-definition measurement enables detailed observation of capillaries, etc.

Achieving ultra-early diagnosis of ophthalmic diseases and arteriosclerosis

Quantum

technology Quantum entanglement, superposition, tunnel effect, etc...

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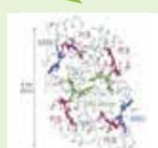
Life Science

Structural Biology, Cell Biology, Developmental Biology, etc...

quantum biomimetics

ü **Elucidation of the mechanism of** the “quantum effect” that realizes the high olfaction and highly efficient photosynthetic respiration **of** organisms

High-sensitivity detection of narcotics and explosives and realization of artificial photosynthesis


A light-harvesting protein that achieves 100% energy transfer through the “superposition effect”

Hyperpolarized nuclear magnetic resonance technology

ü**Utilization** of spin- **polarized compounds that** align the directions of nuclear spins in MRI examinations

üThe **sensitivity is more than 1,000 times higher than conventiona**

Enables **shortening of MRI examination time and real-time** metabolic imaging


Innovative MRI diagnostic technology

Realization of the introduction of MRI examinations into health checkups and evaluation of the effects of cancer treatment

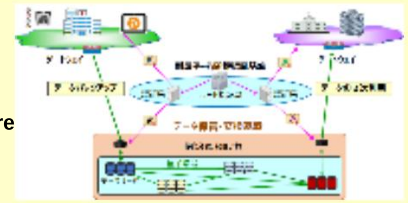
Quantum life technology contributes to the realization of a healthy and long-lived society and the innovation of environmental technology!

Quantum fusion innovation area (3) Image of quantum security technology

•In recent years, studies have been conducted on post-quantum computer cryptography, which is difficult to decipher even with quantum computers, and technology to migrate from the current public key authentication Active. In addition, secret sharing and secret computation for cloud services are being put to practical use.

•By integrating these technologies with quantum cryptography, it is possible to realize "quantum security technology with ultra-long-term confidentiality, tamper resistance, availability, and computational capabilities," and build a cyberspace with robust security into the future. be able to.

quantum secure cloud

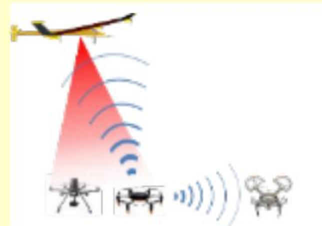


(Source: NICT)

ü **Integrates quantum cryptography, secret sharing, secure computation, and post-quantum computer cryptography** ü Prevents eavesdropping and tampering in the future, and executes calculations while maintaining confidentiality

Realize data backup with business continuity and safe secondary use of data, reduce social security costs, and create new services

Adaptive physical layer cryptography



ü **Development of wireless cryptographic communication technology based on the quantum and electromagnetic properties of light and radio waves**

Provide services that enable IoT devices, drones, etc. to perform high-speed and secure communication anytime, a

Quantum

Cryptographic Uncertainty Principle, Physical Random Numbers

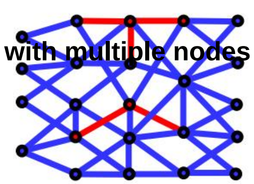
×

Information Security

Modern Cryptography, Computer Science, Network Theory

Optical/quantum network encryption

ü **Integrate quantum cryptography, secret sharing, and network** theory ü **Develop optical/quantum network encryption technology for distributed encoding/encryption communication with multiple nodes and links**



Realization of a scalable secure communication network with excellent denial-of-service attack resistance and availability

Quantum secure mobile communication netwo

(Source: NICT)

ü Implement quantum security technology in mobile objects such as **satellites, drones, and connected cars** ü **Develop** mobile communication technology with excellent mobility, connectivity, and security **realization of a mobile communication network**

Build a cyberspace with permanent security using quantum security technology!

Machine Translated by Google

Image of quantum technology innovation base (international hub)

• In Europe and the United States, the formation of bases for industry-academia collaboration on quantum technology is progressing rapidly (Netherlands Delft University of Technology (QuTech), Canada University of London, Oxford University in the UK, etc.) functions as a stage setting to attract excellent researchers from Japan and abroad.

• **From the perspective of securing and strengthening Japan's international competitiveness, we will gather human resources and technologies mainly in the technical fields where we have strengths, and will conduct everything from basic research to technology demonstration, open innovation, intellectual property management, etc. should form an international collaboration**

Form of base (example)

Open platform type

Open platform type that deepens and strengthens collaboration between universities/research institutes and companies

(e.g. Tohoku University cies)

Center -formation type

that secures independent management with a high degree of freedom even though it is placed under the umbrella of an independent

university/research institution (e.g. WPI center)

In-house center type In-

house **center type** developed and strengthened as an organization of research division under the umbrella of a

research institute (e.g. strategy centers of RIKEN, AIST, e

Center requirements

• **Japan must be in a technological field with outstanding internationally acclaimed researchers and internationally competitive core technologies, etc. • Japanese universities,** research institutes, companies, etc. have high potential Technology areas that are expected to have dramatic developments in future industries and innovations •

Technologies that are expected to

attract large investments from overseas companies, etc., or attract excellent human resources from overseas It is an area • **It is a technical area where it is beneficial and efficient to integrate human resources, technology, budget,** etc.

Center scheme (proposed) •

Project period is about 10 to 15 years (set clear milestones and change or cancel depending on evaluation results)

Set up a gate and gradually increase the proportion of private investment)

• **Establish a board to supervise the entire project in the national government, and** implement detailed progress management through hands-on support, etc. •Appoint a director at each base, and perform necessary **base functions** such as management, research, intellectual property, and commercialization **and build a management system**

Centers

• Superconducting Quantum Computer Research Center • Quantum Device Development Center • Quantum Software (Quantum AI, etc.) Research Center • Quantum Life (Bio) Research Center • Quantum Materials Research Center • Quantum Inertial Sensor Center • Quantum Security Research Center, etc.

Image of human resource development

• **As international competition over quantum technology intensifies, the number of researchers and engineers involved in research and development of quantum technology in Japan is small compared to other countries. Risk of lagging behind** •In order to dramatically improve the quality and depth of human resources in fields related to quantum technology, we will strategically improve the education and research environment at the higher education level. **need to apply**

Image of efforts

Create a roadmap

ü **Clarify what kind of human resources are required for each major technology area, and create a roadmap for strategically training and securing researchers and engineers (Examples of items that need to be identified) academic knowledge and skills, requirements for centers, measures necessary for training and securing, etc.**

Establishment of bases and program development

ü The national government collaborates and cooperates with universities, research institutes, etc. to develop human resource development bases corresponding to major technical areas ü **Development of common educational programs (teaching materials, curriculum, etc.)**

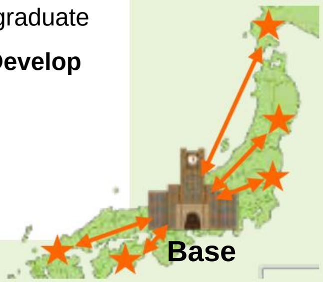
Providing the developed educational programs to desired universities nationwide

strategic initiatives

<Human resource development base> üDevelop human resources using the developed education program **üCollaborate** with universities nationwide that utilize the developed education program **and follow up on areas that cannot be handled by universities in each region alone** (intensive lectures, tutors, etc.)

alignment

<Universities and Graduate Schools in Various Regions> Educational programs developed by ü bases are utilized in undergraduate and graduate education at each university. **Develop an environment to provide specialized** education on quantum technology



Strategically train and secure outstanding researchers and engineers to maintain and improve Japan's research and development capabilities