Quantum leaps in Japan create opportunities for the Netherlands

Rob Stroeks, Senior Advisor Innovation, Science and Technology, Netherlands Embassy in Tokyo

Outline

Japan is an important player in the area of quantum technology, and a leader in translating technology into applications for society. The country has a pro-active government policy that places quantum as a key element in its future vision for social transformations in energy, life science, digitalization and others. Providers and users of quantum related solutions are working together towards such future. Industry and research organizations are collaborating in multiple programs and joint testbeds to develop quantum computers based on advanced software and precision hardware. Importance is placed on new industries and startups, innovation hubs and the development of human resources through public-private partnerships.

This article will shortly introduce different quantum technology related programs in Japan, including the national quantum strategy (Cabinet Office), Q-Leap (MEXT), Moonshot Goal 6 (JST), RQC (RIKEN), G-QuAT (METI and AIST) and Q-Star (business consortium led by Toshiba). These programs show the country's high (fundamental) research level, well developed cooperation between companies and research institutes, proactive government policies with long term objectives, strong focus on real-life benefits and applications, as well as excellent environment for international collaboration.

The vast number of these recent activities in Japan give various excellent opportunities for Netherlands-Japan cooperation over the whole value chain, and indeed several cooperations are ongoing. This article ends with activities by the Netherlands Embassy in Tokyo to further identify and realize such opportunities.

National Strategy

In April 2023, the Cabinet Office of the Japanese government published the Strategy of Quantum Future Industry Development, a vision document about a future society with quantum-based applications. The vision combines 1) research, 2) vision and 3) industry:

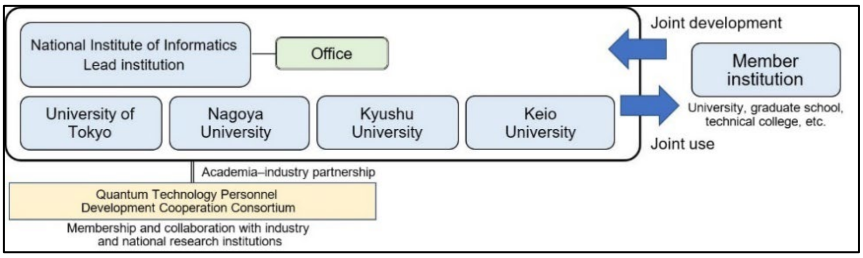
1. Research is based on an innovation strategy of 2020, that leads to priority areas for quantum computers, sensors, communication, cryptography, the establishment of international innovation hubs for research and education, and international frameworks for cooperation with US and EU.
2. Vision is based on a strategy of 2022, that foresees societal impact, places importance on economic security and anticipates opportunities for the Japanese industry to realize growth in areas like mobility, finance, energy and health. The Vision describes measures to gear up activities for quantum computers, software, security networks, metrology, sensing, materials and devices.
3. Industry is involved by support mechanisms for (international) industrial collaboration, the creation of start-ups and unicorn companies, the development of industrial human resources, public-private partnerships (e.g. Q-Star), standardization, strategic supply chains, innovation hubs etc.

The goals of this new Strategy for 2030 include to realize 10 million quantum technology users in Japan through new use cases and testbeds, increase quantum technology related production value to 350 billion euro (50 trillion yen) and create unicorn companies for future markets.

Quantum related national strategies in Japan (source: Cabinet Office)

Q-Leap (MEXT)

The Ministry of Education, Science, Culture, Sport, Science and Technology (MEXT) supports an extensive long-term program on quantum technology under the name Q-Leap, running from 2018 until 2027. This R&D program consists of multiple flagship projects in the field of quantum computers, quantum metrology & sensing and next generation laser technology. It has a special Human Resource Development Program nurture future oriented leaders for next generation quantum technologies, including a new Quantum Academy of Science and Technology (Q-Acadamy) to establish higher education standards and curricula.



Overview of the Quantum Academy of Science and Technology (Source: Q-Acadamy)

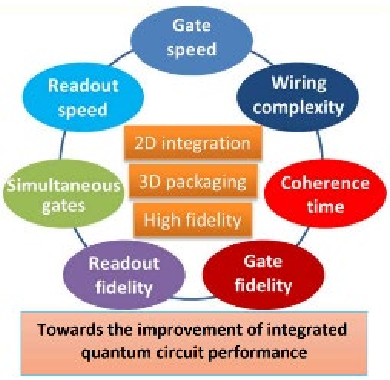
The governing board of Q-Leap is chaired by Prof. Makoto Gonokami, President of RIKEN, and further consists of leaders in industry and research institutes. For all the projects (see overview and links below), consortia are formed with multiple partners from industry and research institutes. Applications range from quantum computers with over hundred qubits integrated in 3D packaging to cloud based applications, from quantum software to AI applications, quantum sensors for applications in life science (neuro-imaging, biosensors, novel MRI etc.) to batteries and power devices, high-performance lasers to create accurate cyber-physical spaces (CPS) and precision measurements.

Overview of the Q-Leap programs

Quantum information technology (Quantum simulator, Quantum computer)
Program Director: prof. Kohei Ito, Keio University

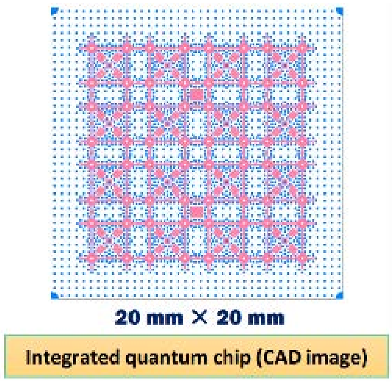
Flagship programs

1. Research and Development of Superconducting Quantum Computers

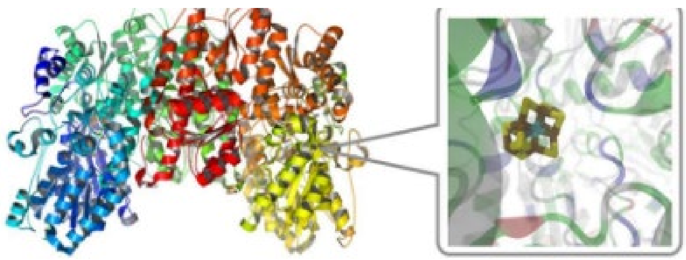


Goals

- Integration of 100 or more qubits into a three-dimensional package
- Readily accessible applications available on a cloud-based service



2. Development of quantum software by intelligent quantum system design and its applications



M. Reiher et al., PNAS 114, 7555-7560 (2017)

Nitrogen-fixing enzyme (left) and its center (right).

- Construction of software/architecture to intelligently elicit the performance of NISQ devices. Working toward implementation in superconducting quantum computers
- Provide users with applications that take advantage of quantum advantage. Analysis of real-world problems by quantum AI.

Research programs:

- Development of cold-atom based quantum simulators by optical control with precisions on the attosecond temporal and nanometer spatial scales and their applications to quantum computing
- Multi-degree-of-freedom complex quantum simulator using cooled ions
- Architecture and applications for small to large scale quantum computation
- Development of quantum software applications by fast classical simulator of quantum computers
- Large scale integration of silicon qubits to realize quantum computer
- Quantum software

[Quantum metrology & sensing](#)

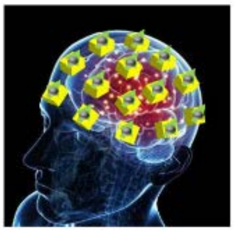
Program Director: prof. Yasuhiko Arakawa, the University of Tokyo

Flagship programs

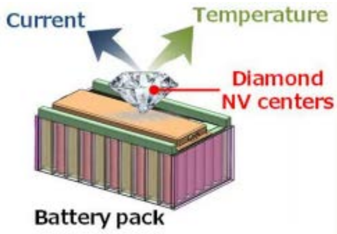
1. Development of innovative sensor systems by highly sophisticated control of solid quantum sensors

Goals

- Development of prototypes for magnetoencephalography with high sensitivity and high spatial resolution
- Development of prototypes for systems that monitor the current and the temperature in batteries and power devices.



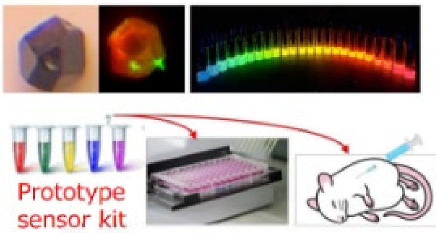
Magnetoencephalography



Battery/power device monitoring

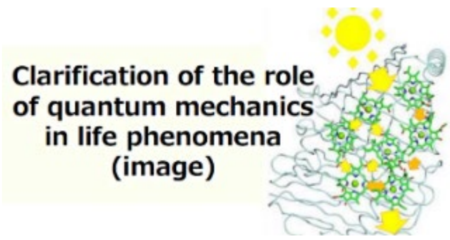
2. Innovations Medicine and Life Sciences through the Application of Quantum Technology

- Development of nanoscale biosensor systems with the ability to make simultaneous measurements over a wide field-of-view at high resolution
- Development of ultrasensitive MRI/NMR equipment based on quantum technology such as hyperpolarization and quantum coding, and novel long-life hyperpolarized molecular probes of low toxicity
- Explication of the quantum-theoretical mechanisms of biological functions that have not been clarified to date; to be achieved through the development of high-precision quantum-coherence measurement and spectrographic analysis technologies that enable us to explore quantum effects (e.g. photosynthesis, magnetoreception) in living creature.



Nanoscale/quantum biosensors (image)

Ultrasensitive MRI/NMR (image)



Research programs:

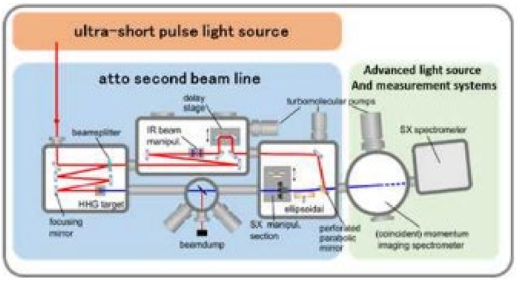
- Establishment of earthquake early alert methods using high-sensitivity gravity gradiometer
- Development of photon-number-resolving quantum nano-photonics
- Development of quantum atomic magnetometer with dual quantum noise squeezing
- Development of Spectroscopic techniques based on cutting-edge quantum optics
- Research on quantum sensing devices using quantum entangled photons
- Material science of complex defects for highly-sensitive quantum sensors
- Development of next generation high-performance inertial quantum sensors

Next generation laser

Program Director: prof. Kiminori Kondo, National Institute for Quantum and Radiological Science and Technology (QST)

Flagship program

1. Advanced Laser Innovation Center (ALICe)



Prototypes of an advanced light source and a measurement system

Goals

- Science and theory enabling intelligent laser manufacturing (STELLA). Development of CPS laser manufacturing (simulator) capable of proposing the optimal processing parameters based only on simulation in cyberspace.
- Attosecond lasers for next frontiers in science and technology (ATTO). Development of high-repetition and high-intensity attosecond-pulse lasers and laser-based advanced measurement system.

Research programs:

- Development of attosecond light functions of strongly correlated quantum materials
- Developing guidelines on materials strengthening and toughening based on mechanism of atomic scale damaging under ultrashort pulsed laser processing
- Operando measurements using advanced beams to study the mechanism of fine structure formation
- Research on basic technologies for a high-repetition attosecond pulse source driven by a free electron laser

Human resources development program

Program Director: prof. Kohei Ito, Keio University

Core program

1. Development of the Standard Program for Quantum Science and Technology Goals
   a. Establishment of a curriculum
   b. Development of course teaching materials
   c. Implementation of lecture courses
   d. Implementation of internships

Sub programs:

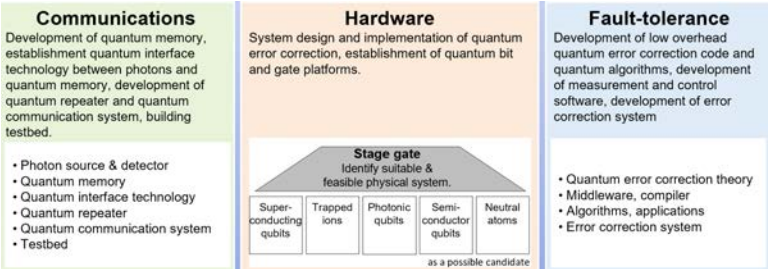
- Fostering Quantum Natives through Practical Research and Development
- Quantum Education for future technologies
- A hands-on program for fostering quantum-based thinkers among emerging engineers in various disciplines

Moonshot Goal 6 (JST)

A challenge of quantum computers is that the sensitive nature of quantum superpositions is easily affected by its environment, leading to errors that accumulate as calculations continue, resulting in a lower accuracy. The Moonshot Goal 6 research program, coordinated by the Japan Science and Technology Agency (JST), aims to solve this issue with big breakthroughs to realize a quantum computer by 2050 that can correct such errors: a so-called fault-tolerant quantum computer. To achieve this, the program focuses on different aspects, such as increasing the number of physical qubits, the development of a correction mechanism, verification systems and scaleup methods. The program consists of three components: hardware, networks and software. For the hardware, research is conducted on four types of quantum mechanisms: superconductivity, ion trap, photonics and silicon (semiconductors). A network is being developed to connect multiple medium-scale quantum computers into a large powerful one. For the software, correction codes and algorithms are being developed, as well as measurement and control software.

The program defines three milestones: develop an intermediate NISQ (Noisy Intermediate-Scale Quantum Computer) with error correction by 2030, set up a network of distributed NISQ computers by 2040, and realize a final universal fault tolerant quantum computer by 2050.

A clear picture of the total budget of the program is difficult: the funding system is complex and not officially published in its totality. The Cabinet Office mentions an initial budget for 2020-2025 of ten billion yen (about 70 million euros), but substantial additional budgets have been granted after that.



Scheme of Moonshot Goal 6 (source: JST)

In the current first phase of the program (2020-2025), there are twelve projects running. Preparations are ongoing for the next phase (2026-2030), with an important goal to increase the number of physical qubits from current 100 to one million 1,000,000 in next five years to make 100 or more logical qubits.

Overview of the current projects within the Moonshot Goal 6 Program (https://www.jst.go.jp/moonshot/en/program/goal6/).

- **Research and Development of Theory and Software for Fault-tolerant Quantum Computers**
  Construct a co-design model including qubit design, fault-tolerant architecture, and compilers and programming languages.
- **Development of Quantum Interfaces for Building Quantum Computer Networks**
  Develop a quantum interface in which quantum memory is combined with an optomechanical crystal, in order to connect the superconducting qubit and the communication photon. https://moonshot.ynu.ac.jp/en/index.html
- **Fault-tolerant Quantum Computing with Photonically Interconnected Ion Traps**
  Develop ion trap devices that facilitate building large-scale systems beyond the limitations posed by conventional approaches. The new approach is based on a novel idea of photonically interconnecting multiple ion traps. https://www.oistmoonshot.jp/en/
- **Development of Large-scale Fault-tolerant Universal Optical Quantum Computers**
  Develop a “quantum look-up table” that works at room temperature. https://optical-quantum-computers.jp/en/
- **Large-scale Silicon Quantum Computer**
  Large-scale integration of silicon qubits by utilizing silicon semiconductor integrated circuit technology, leading to low power consumption.
- **Quantum Cyberspace with Networked Quantum Computer**
  Develop elemental technologies for networking quantum computers with photons, atoms, semiconductors and so on, aiming to network small and medium quantum computers. https://qcnqc.jp/en/
- **Development of Integration Technologies for Superconducting Quantum Circuits**
  Develop hardware technologies required for scaling up the circuit of superconducting qubits in order to accelerate R&D of superconducting quantum computers. https://ms-iscqc.jp/en/
- **Large-scale quantum hardware based on nanofiber cavity QED**
  Develop novel quantum-computing hardware based on nanofiber cavity QED.
- **Large-scale and high-coherence fault-tolerant quantum computer with dynamical atom arrays**
  Implement a “dynamical qubit array” in which a large number of cold-atom qubits are assembled with optical tweezers. In close cooperation with industry, all components will be integrated and packaged to achieve high stability and usability. http://ms-ohmoripm.ims.ac.jp/en/
- **Development of a Scalable, Highly Integrated Quantum Error Correction System**
  Find technical breakthroughs for algorithms and scalable backends for classical hardware for error correction, scalable quantum-to-classical input/output frontends, semiconductor chips for backend/frontend, and cryogenic operation of optical integrated circuits for high bandwidth and low power quantum-classical input/output. https://www.greenlab.kit.ac.jp/qubecs/en/index_en.html
- **Development of scalable Silicon quantum computer technology**
  Develop scalable technologies for Silicon quantum computer, with the use of sparse integration and medium-distance quantum coupling. This is to lead to a unit structure of qubits that enable scale up. Cooperation with semiconductor industry.
- **Scalable and Robust Integrated Quantum Communication System**
  Build a testbed for a general-purpose quantum communication network, a key technology for distributed large-scale quantum computers and quantum Internet. Integrate hardware and software to demonstrate the principles and technologies of communication architectures and protocols with a view to actual operation.

The program is yielding published research results in different areas of above-mentioned projects, for example:

- Area: Photonics.
  "Over-8-dB squeezed light generation by a broadband waveguide optical parametric amplifier toward fault-tolerant ultra-fast quantum computers", Prof. Akira Furusawa, publication in Applied Physics Letters, June 23
  https://pubs.aip.org/aip/apl/article/122/23/234003/2894851/Over-8-dB-squeezed-light-generation-by-a-broadband
- Area: semiconductors.
  "Fast universal quantum gate above the fault-tolerance threshold in silicon", Prof. Seigo Tarucha, publication in Nature, January 2022
  https://www.nature.com/articles/s41586-021-04182-y
- Area: semiconductors.
  "Quantum error correction with silicon spin qubits", Prof. Seigo Tarucha, publication in Nature, August 2022
  https://www.nature.com/articles/s41586-022-04986-6
- Area: software.
  "Hunting for quantum-classical crossover in condensed matter problems", Prof. Nobuyuki Yoshioka, publication in arXiv of Cornell University, October 2022
  https://arxiv.org/abs/2210.14109

The overall Program Director of Moonshot Goal 6 Prof. Masahiro Kitagawa of Osaka University, who gave a presentation during a Netherlands Roadshow Event as part of the Innovation Mission to Japan on quantum-photonics in October 2022, comments: "We are making good progress with the twelve projects in the Moonshot Goal 6 Program, addressing different aspects to realize a fault tolerant quantum computer by 2050. International collaboration is crucial to achieve this goal, which is why we host international symposia with prominent researchers from the world. The Netherlands is one of the most active countries in the field, for example, QuTech/TU-Delft, and has lots of activities such as Quantum Delta NL and innovative startups. We also want to increase collaboration with industry, both Japanese and international."

Prof. Lieven Vandersypen, Director Research at QuTech, who gave a lecture during the Moonshot Goal 6 International Symposium in Tokyo in July 2023, comments as follows: "At QuTech we work with novel materials and new concepts to better control qubits and upscale solutions for quantum computers. These are complex developments that cost time, which is why it is important to have long term goals. Here the Japanese Moonshot Program is a good example, with a goal of 2050 to realize of a fault-tolerant universal quantum computer. We collaborate with Japanese counterpart on several aspects, for example with RIKEN."

RIKEN and Quantum Innovation Hubs

The national research institute RIKEN is the centre of many quantum related activities in Japan. The RIKEN Center for Quantum Computing (RQC) was established in 2021 to integrate domestic research and development, and is the head quarter of the network of Quantum Technology Innovation Hubs (QIH). In March 2023, RQC released Japan's first domestic quantum computer, putting Japan on the international map, together with US and European countries.

Prof. Yasunobu Nakamura, Director RIKEN Center for Quantum Computing, comments as follows: "As Headquarter of 10 leading Japanese Quantum Technology Innovation Hubs, RIKEN is in the centre of quantum related research and developments in the country. We are working a lot with foreign partners, including from the Netherlands. I see a lot of potential to further increase these collaborations."

- **RIKEN Center for Quantum Computing (RQC)**: RQC is focusing on research in the areas of superconductivity, optics, atoms, electrons, semiconductors and theoretical research. In March 2023, RQC announced Japan's first domestically produced quantum computer, joining the US and European countries that released similar machines in recent years. Outside users can access the new computer via the cloud, enabling new research and development to start actually solving a broad variety of issues using the power of a quantum computer. The new machine, that was developed in cooperation with Fujitsu and NTT, runs on 64 quantum bits based on superconductivity to create the quantum effect. This makes it more powerful than IBM's 27-qubit quantum computer that was set up in Japan in 2021.

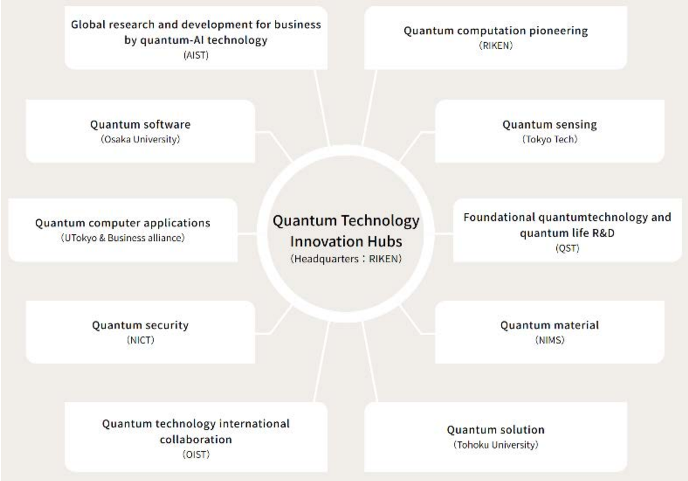
  Like other countries, RIKEN is working on new releases with more qubits: linking the activities to RIKEN's supercomputer Fugaku, RQC is working to complete a next version with over hundred qubits in 2025. RQC is also assisting Fujitsu to further commercialize the technology and develop a version with over thousand qubits in 2026.

Research at RIKEN Center for Quantum Computing RQC (source: RIKEN)

- **Quantum Technology Innovation Hubs (QIH)**: With RIKEN as its headquarter, the national network of Quantum Technology Innovation Hubs (QIH) brings together quantum related research and educational activities all over Japan, develops (international) cooperation between academia, industries and governments, and coordinates between relevant graduate schools for educational purposes. QIH coordinates these activities through four committees: international cooperation, intellectual property & standardization, industry-government-academia cooperation and human resources development.

Next to RQC, the QIH network mainly consists of the following innovation hubs:

- G-QuAT at AIST is aiming for a global business ecosystem utilizing quantum computer technology, as described later in this article.
- QIQB is the Centre for Quantum Information and Quantum Biology at Osaka University. QIQB consists of six research groups: Quantum Computing, Quantum Information Fusion, Quantum Information Devices, Quantum Communications and Security, Quantum Measurement and Sensing, and Quantum Biology.
- The **Quantum Sensing research group** at Tokyo Institute of Technology, focusing on cold atom interferometer and NV centres (Nitrogen-vacancy (NV) centres in diamond can be used as quantum sensors to image the magnetic field with nanoscale resolution).
- QII, the Quantum Innovation Initiative with head quarter in the University of Tokyo, is a consortium of research institutes (the University of Tokyo, Keio University and RIKEN) and companies (e,g, Sony, Suntory, Toshiba Toyota, IBM, Hitachi) that focus on quantum computer software and applications.
- QST, the National Institute for Quantum Science and Technology, is focusing on quantum materials and their functionalities.
- NICT, the National Institute of Information and Communications Technology, is focusing on quantum cryptography, quantum networks and communication.
- NIMS, the National Institute for Material Science, is focusing on single crystal growth, diamond chemical vapor deposition for quantum device applications and semiconductor optics.



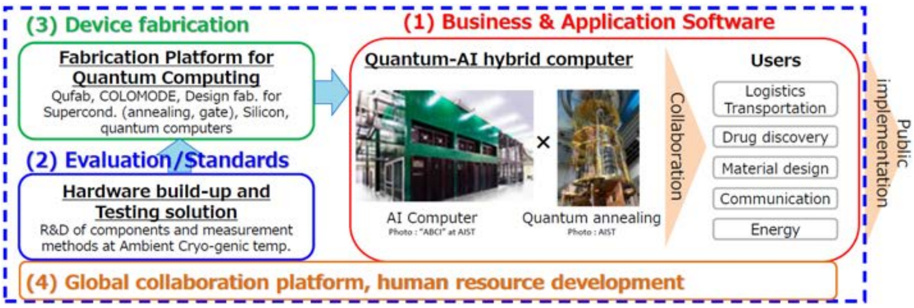
Quantum Technology Innovation Hubs (source: RIKEN)

G-QuAT (AIST)

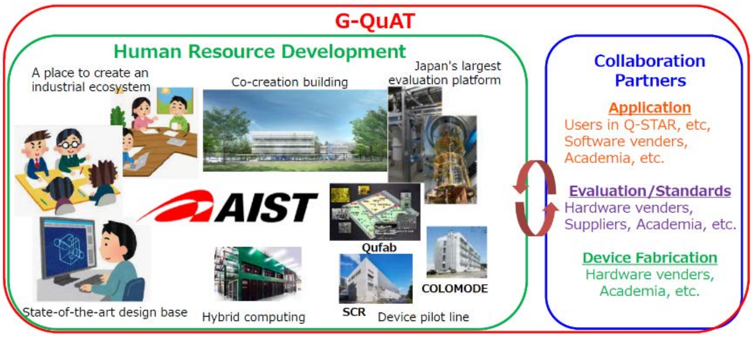
The Global Research and Development Center for Business by Quantum-AI Technology (G-QuAT) is a new centre that was established in July 2023 as part of a global R&D strategy for business by quantum AI technology (described in the introduction of this article). The group focusses on practical use cases that combine quantum computing technology and classical computing technology and investigates possibilities to increase the number of qubits to realize quantum devices. G-QuAT is located at AIST, the National Institute of Advanced Industrial Science and Technology, and linked to the Ministry of Economy, Trade and Industry (METI) and their strategies on quantum, AI and economic security. G-QuAT has an annual budget of about 200 million euros (32 billion yen). The centre is running testbeds in close connection to industry and is open for quality evaluation by for example the Q-Star consortium described elsewhere in this article. G-QuAT has established an international advisory board.

The six research teams at G-QuAT focus on the following three R&D topics and a special role for human resources:

- **Quantum-AI hybrid computer.** To converge computational technology, G-QuAT is setting up a new supercomputer ABCI-Q to run from 2024. This machine will integrate quantum annealing research with the existing AI supercomputer ABCI (AI Bridging Cloud Infrastructure, which was developed together with Fujitsu and is running since 2018 with some 2500 users).
- **Evaluation.** To realize a resilient supply chain and stimulate commercialization, G-QuAT has prepared an evaluation system at low temperatures for large-scale quantum hardware, including quantum annealing machine/quantum computer for up to thousand quantum bits, and a platform user companies.
- **Device.** To increase the number quantum bits, G-QuAT is preparing platforms to produce quantum prototype devices and quantum annealing machines, as well as 3D packaging technologies for more than 100 quantum bits by three-dimensional packaging technique.
- **Human resources.** G-QuAT has a special role in developing industrial human resources and start-up companies.



Scheme of G-QuAT (source: AIST)



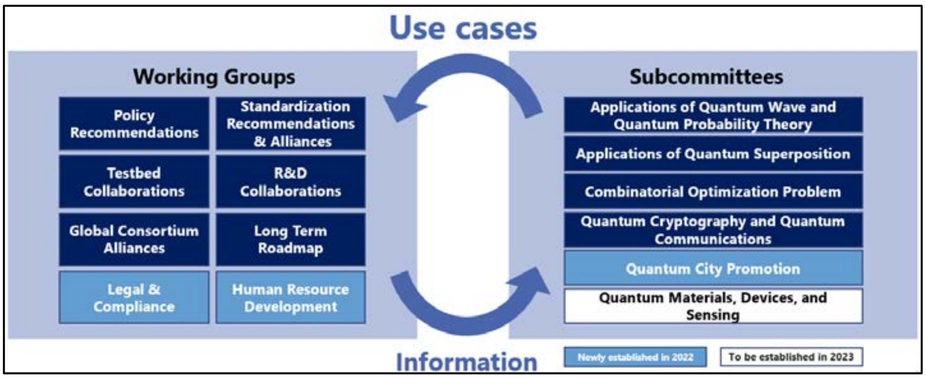
Human Resources Development scheme of G-QuAT (source: AIST)

Q-Star

Q-Star is a business consortium of 84 members, mainly divided into two categories: vendor companies and user companies. The vendors are suppliers of quantum related technologies, and the users are delivering products and services in areas like finance, mobility and chemistry. Q-Star working groups and subcommittees result in actual use cases, in which the consortium brings together possibilities and needs to realize the use of quantum technology in society. Q-Star aims to contribute towards Japan as a "quantum technology innovation nation" by creating industries that deliver services in such areas as materials, devices, measurement technologies, computers, communications and simulation technologies.

After establishment and preparations in 2022, Q-Star entered the Demonstration Phase in 2023. The number of members grew from 11 founding members to current 84 members (79 companies and five research institutes). Chair of the Board is Taro Shimada, President and CEO of Toshiba Corporation.

In January 2023, Q-Star signed an MoU with the Quantum Industry Canada (QIC), the US based Quantum Economic Development Consortium (QED-C), and the European Quantum Industry Consortium (QuIC) to form an International Council to enable and grow the global quantum industry.



Working groups and subcommittees at Q-Star (source: Q-Star)

The six subcommittees have a role as follows (see here for more details):

- **Applications of Quantum Wave and Quantum Probability Theory**: Exploring the creation of new industries, starting with the financial sector.
- **Applications of Quantum Superposition**: Businesses creation applying quantum superposition in with focus on certain areas as future pillars that span multiple industries.
- **Combinatorial Optimization Problem**: Using new computing technology (e.g. quantum annealing technology or quantum inspired technology) to solve industrial optimization challenges.
- **Quantum Cryptography and Quantum Communications**: Business cases for the use of quantum cryptography communication.
- **Quantum City Promotion**: Use cases related to social infrastructure development, demonstration experiments and practical implementation.
- **Quantum Materials, Devices, and Sensing**: Industry-Academia cooperation to apply novel quantum materials, devices, and sensing techniques in practice.

Use cases are developed in cooperation by vendors and users, using a so-called Quantum Refence Architecture Model for Industry (QRAMI), that was developed to combine aspects in three dimensions: 1) Domain (business area like finance, mobility, materials), 2) Architecture (layers like business, interface, integration and assets) and 3) Hierarchy (quantum aspects like quantum communication, security, sensing, device).

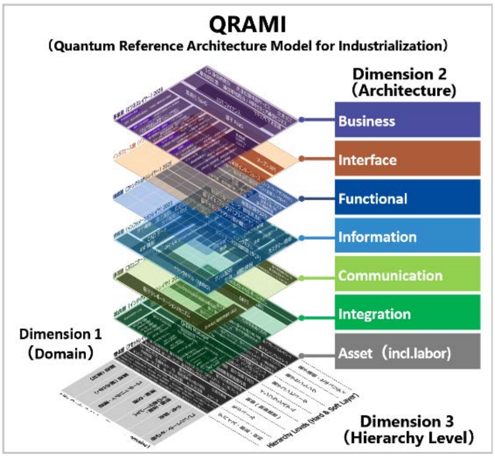
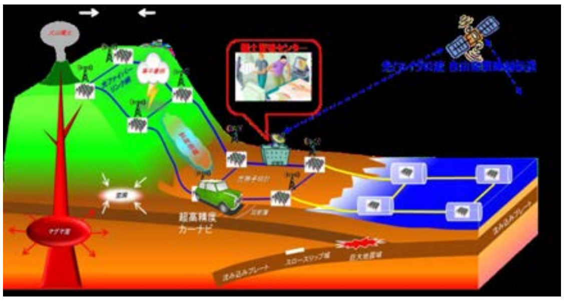


Image of the Quantum Refence Architecture Model for Industrialization QRAMI (Source: Q-Star)

As example, the subcommittee on Quantum Materials, Devices, and Sensing (MDS) under the leadership of Dr. Tetsuomi Sogawa of NTT is developing use cases in different areas, including quantum sensing and devices for high-precision monitoring for environment and disaster management, food security, automated driving and medical applications (MRI, biomarkers etc).



Examples of use case application of quantum sensing, from left to right sub-sea monitoring, MRI and water management (Source: Q-Star)

Image of a future society using quantum technology (source: Q-Star)

Opportunities for Netherlands-Japan collaboration

The vast amount of Japanese activities described above give many opportunities for the Netherlands.
As part of its role and activities to develop bilateral cooperation in the field of quantum technology, the Netherlands Embassy in Tokyo is in close contact with all programs described in this article. Since 2021, these activities are integrated with activities for semiconductors, photonics and nanotechnology (sometimes jointly referred to as 'deeptech'). This is because of the many crossovers in topics and the fact that Japanese organizations are often active in all of these areas and also integrate related strategies and policies.

Therefore, the approach towards Japan is executed in close cooperation with Quantum Delta NL, Photon Delta NL, Hightech NL, central and regional governments, as well as the Netherlands business and science community. Until Summer 2023, the activities were broad and explorative, ranging from fundamental research to commercial applications and policies. In order to give updates and introductions about Netherlands and Japanese programs, policies, stakeholders, we organized multiple online webinars and lab-tours, onsite roadshows and exhibitions, Innovation Missions and matchmake events, reports etc. In total between fifty and sixty Dutch organizations have joint these activities. Bilateral agreements were signed between governments, industries and academia, recognizing each other as important player and partner.

A number of bilateral cooperations are ongoing, such as the QuTech – Fujitsu joint project to develop a blueprint for a scalable quantum computer based on optically linked spin qubits, includes quantum algorithms with error correction codes. New opportunities for research cooperation are for example given by the JST Aspire program of the Japanese government.

This is a publication of:
Netherlands Enterprise Agency
Prinses Beatrixlaan 2
PO Box 93144 | 2509 AC The Hague
T +31 (0) 88 042 42 42
Contact us
www.rvo.nl
Publication number: RVO-146-2025/RP-INT