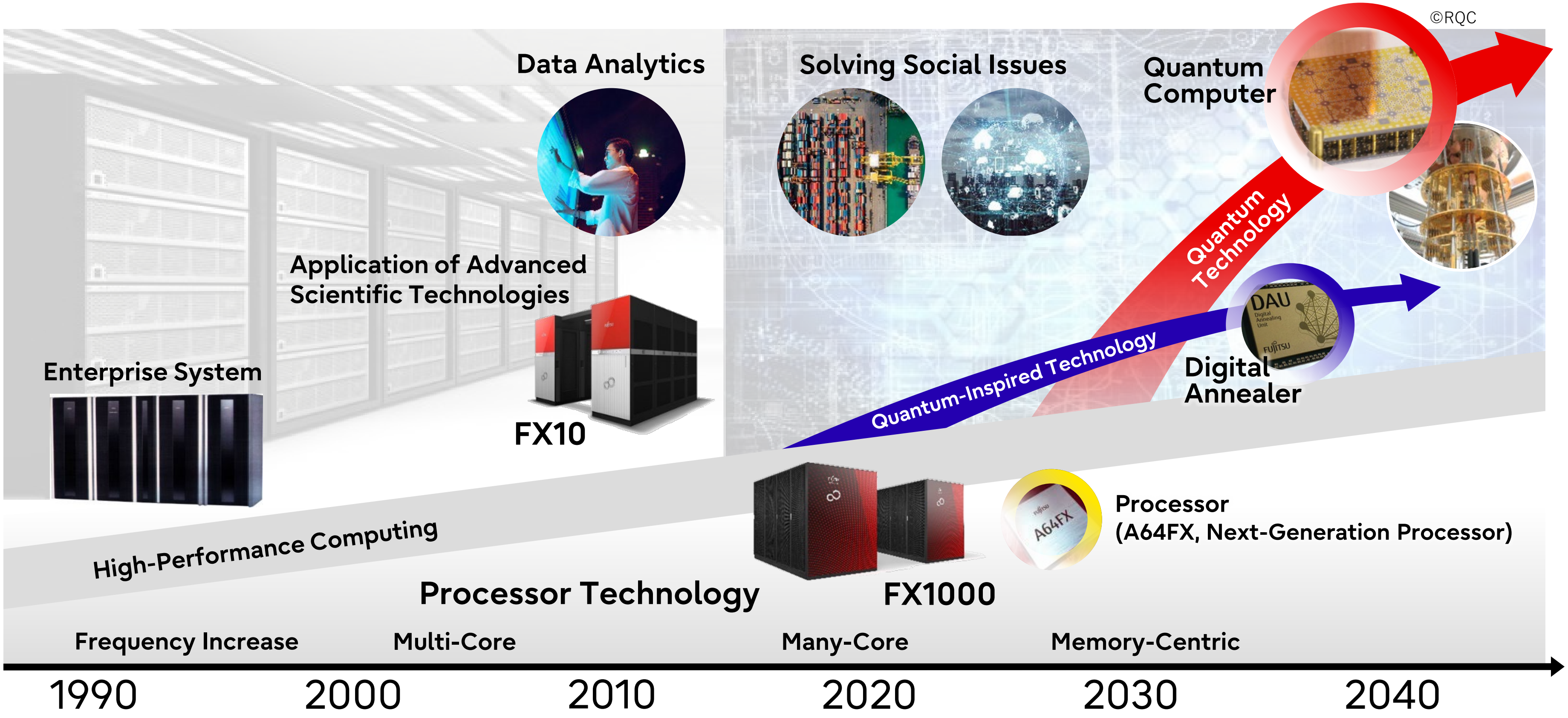
Updates of Quantum Computing Research at Fujitsu

Shintaro Sato

Fellow SVP, Head of Quantum Laboratory
Fujitsu Research, Fujitsu Limited

Dec. 6, 2023

Computing Technology at Fujitsu



Computing as a Service Vision

FUJITSU

Provide the top-class Computing Technologies "as a Service"

Application

Finance | Material | Energy | Medicine | Meteorology | Disaster Prevention

Platform

AI | Simulation | Data Analytics

Computing as a Service

Low power consumption | Great computing power | Trust platform

Available on Public Cloud

Middleware

OS

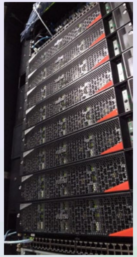
Hardware

High Performance Computing (HPC)

A64FX Technology

Quantum-Inspired Technology

Digital Annealer



Quantum Simulator

Quantum Technology

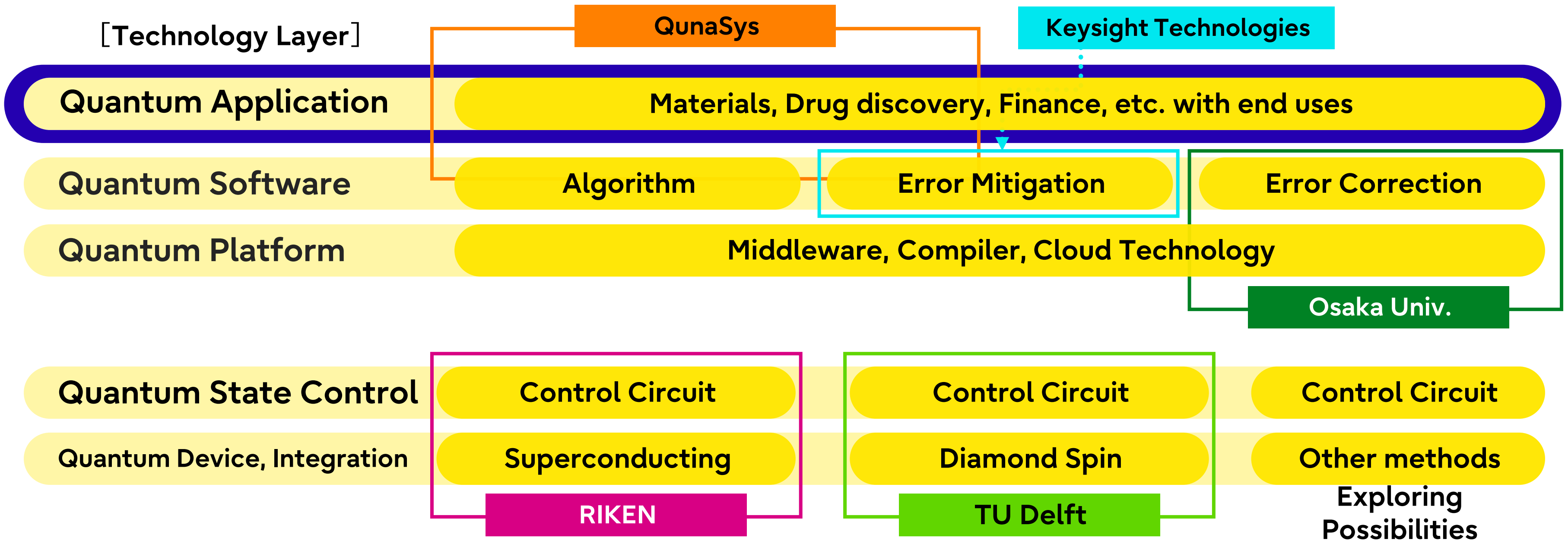
©RQC

Superconducting Qubit
Diamond Spin Qubit

Fujitsu's Strategy for Quantum Computing

FUJITSU

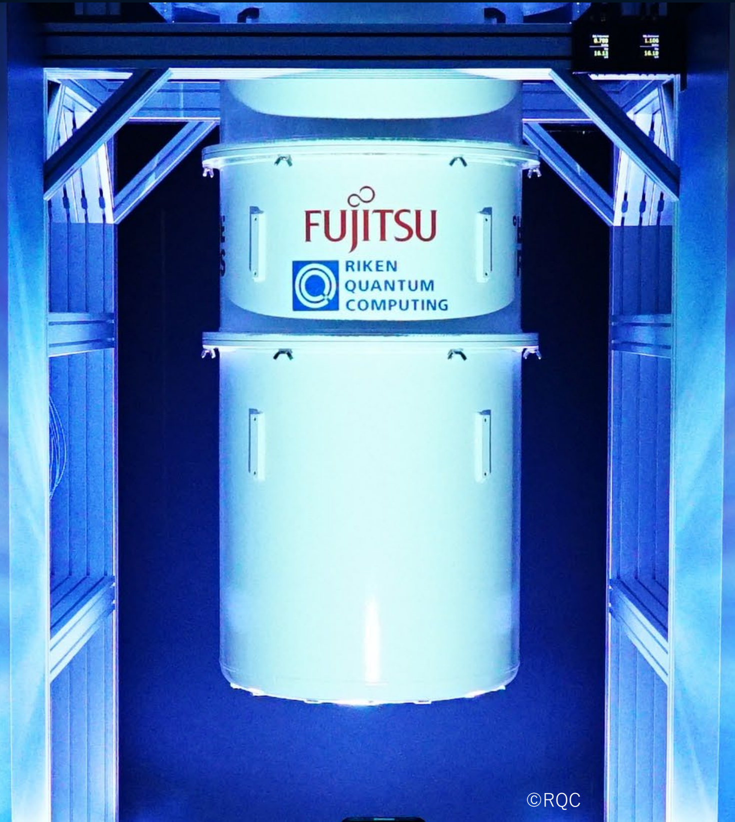
- Cover all the technology layers with the world's leading research institutions
- Put emphasis on software technologies, while working on several types of hardware
- Develop applications with end users by using a newly-developed quantum simulator



Release of a 64-qubit System (Oct. 5, 2023)

- Collaboration with Prof. Nakamura

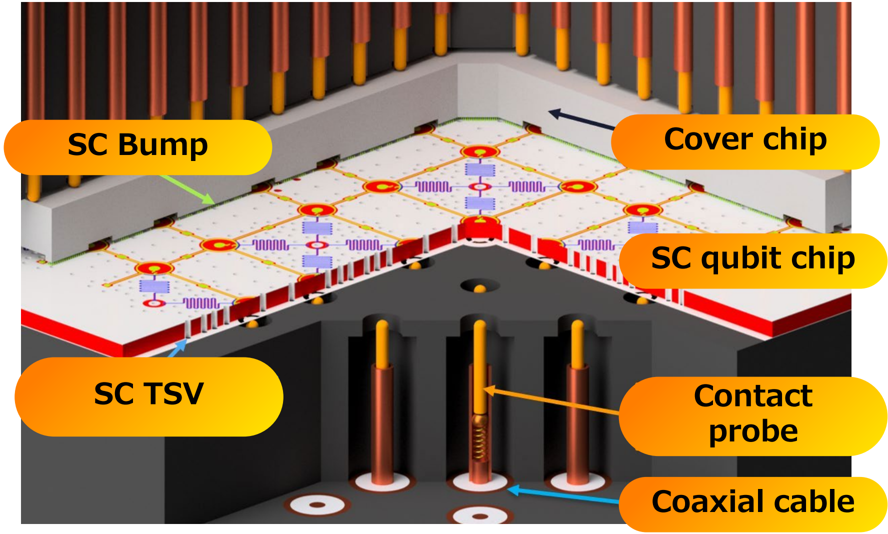
- Developed Japan's second domestic quantum computer at RIKEN RQC-Fujitsu Collaboration Center
- Plan to develop applications with end users mainly in the industry using this system



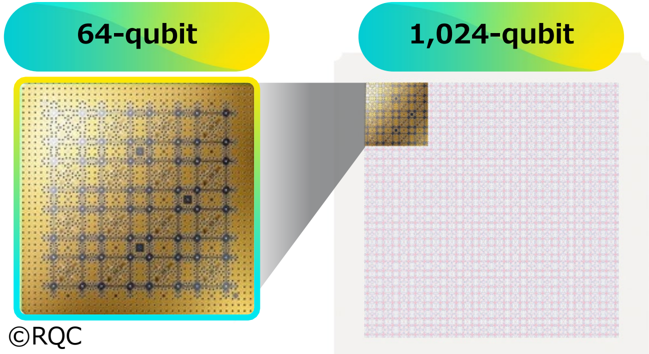
Superconducting Qubit Technology: Scalable Qubit Chip Design

RIKEN QUANTUM COMPUTING FUJITSU

3D Contact structure



3D Contact to Superconducting qubits ©RQC



©RQC

Can scale up by tiling basic units

sample holder

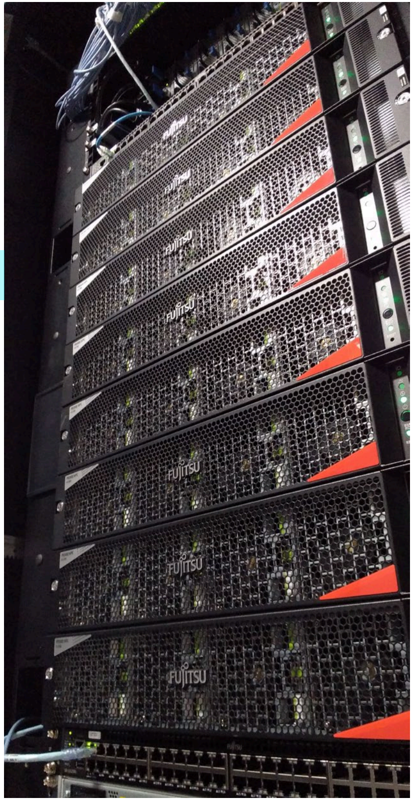
We also work on the improvement in wafer-scale uniformity of characteristics of Josephson junctions.*

*T. Takahashi, et. al. *Jpn. J. Appl. Phys.* **62**, SC1002 (2023)

Quantum Computer Simulator

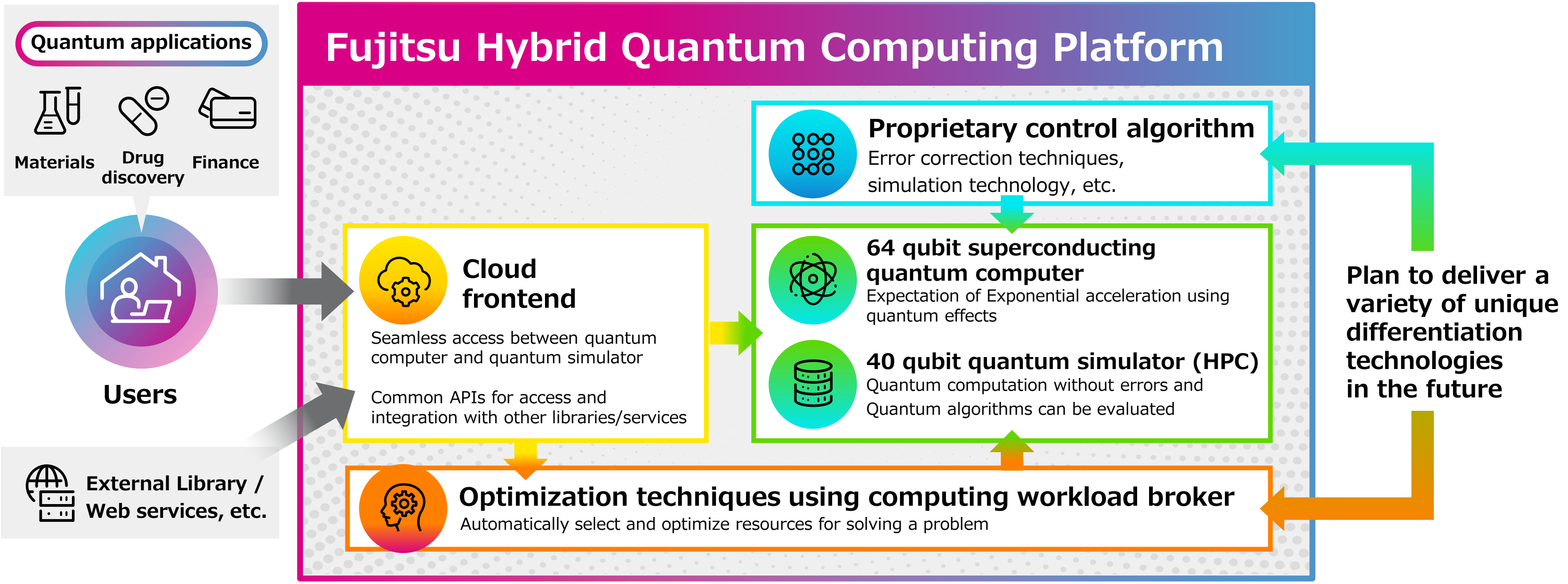
FUJITSU

- **The world largest-class quantum computer simulator as a permanent dedicated system**
  - Qulacs (state vector simulator) on FX700 cluster
  - Continuous enhancement
    36 qubits (64 nodes: FY21) → 40 qubits (1024 nodes: FY23)
- **Collaboration with customers**
  - Material (Fujifilm), Finance (Mizuho-DL Financial Technology)
  - **Quantum challenge**: Application discovery with universities and companies around the world (US, Europe, Asia and Oceania)
- **Research on new-type simulators for larger scale**
  - **Tensor Network simulator** with Barcelona Supercomputing Center
  - **Decision Diagram simulator** with the University of Tokyo



Fujitsu Hybrid Quantum Computing Platform

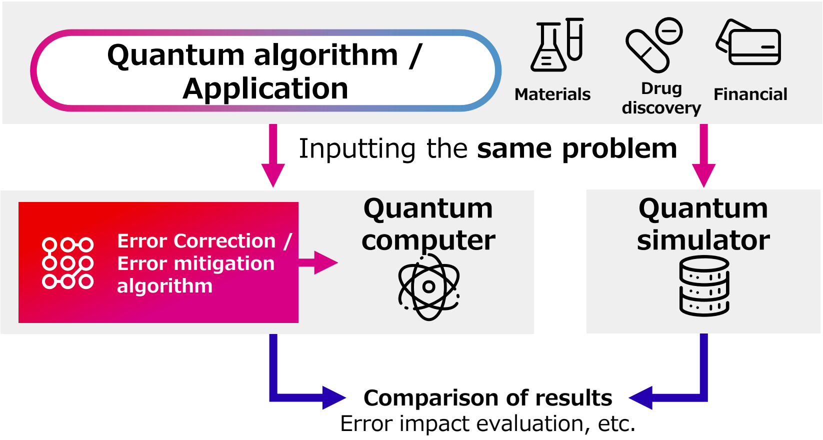
- **Seamless operation between quantum computer and quantum simulator**
- **Development of computational methods that take advantage of both quantum computers and quantum simulators**



Platform Utilization Approach

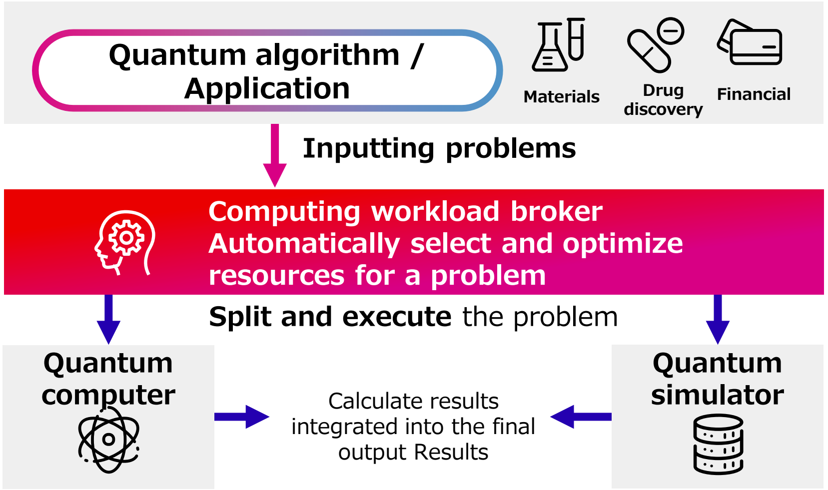
1 Accuracy evaluation of quantum algorithms

- Input the same problem for a quantum computer and quantum simulator
- Evaluate the impact of qubit errors by comparing results
- Expected use for algorithm development of quantum error mitigation and error correction



2 Hybrid algorithm development of quantum computer /simulator

- Split the same problem by condition (Speed priority, accuracy priority, etc.)
- Execution assigned properly to quantum computer and the simulator for a split problem



Development of Applications

FUJITSU

- Fujitsu is already working with customers to develop pioneering quantum applications using quantum simulators
- We plan to accelerate collaboration research using this platform and expand the search for practical hybrid quantum applications in various fields such as materials, finance, and drug discovery.

Collaboration research partners

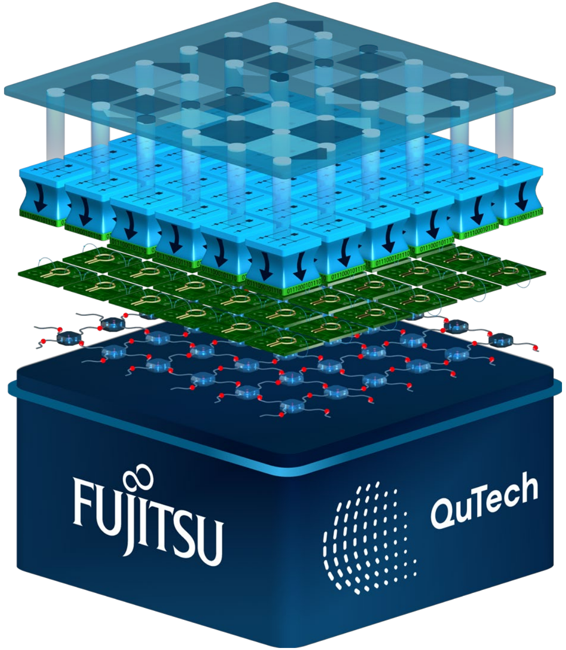
FUJIFILM

MITSUBISHI CHEMICAL GROU

TOKYO ELECTRON

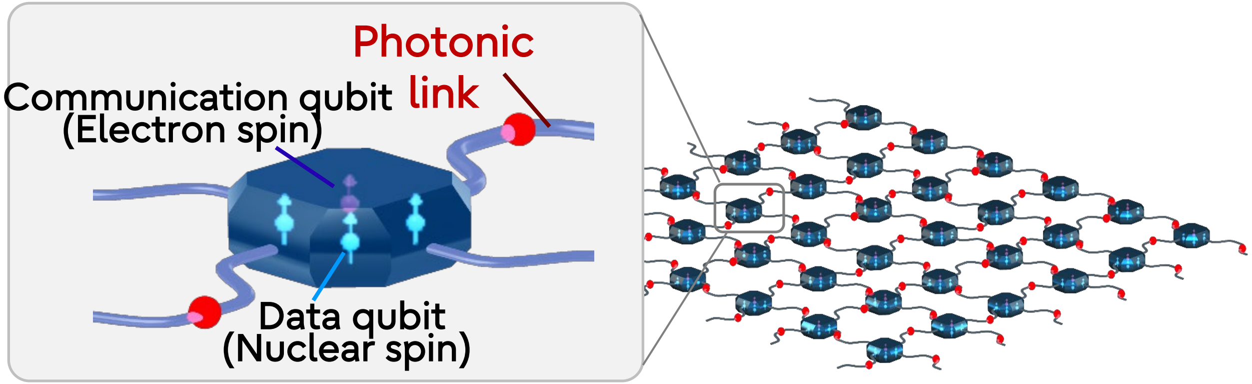
Mizuho–DL Financial Technology

Diamond-Spin Modular Technologies for Scalable Quantum Computer



- Each quantum module consists of an electron spin and nuclear spins in a diamond.
- Quantum modules are connected by photonic links, which can be used as one quantum computing system.
- This approach can allow for high-temperature operation (> 1 K) and good scalability.

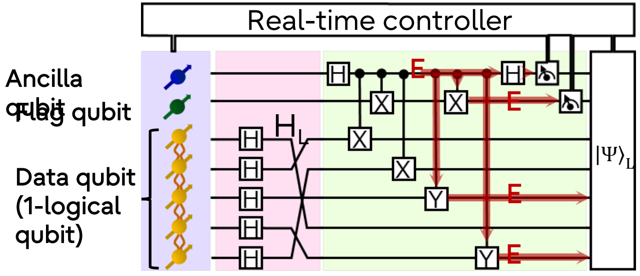
Modular architecture



Diamond-Spin Based Quantum Protocols and Qubit Chips

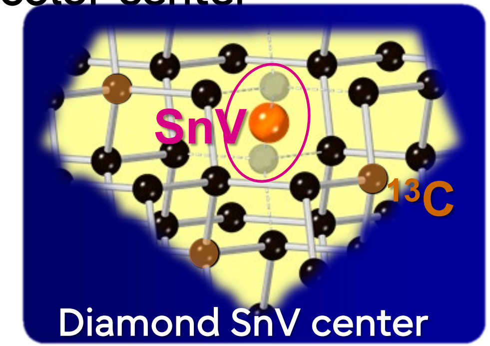
- We are developing quantum protocols and qubit chips in parallel.

- **Quantum protocol**
  Fault-tolerant operation for error correction

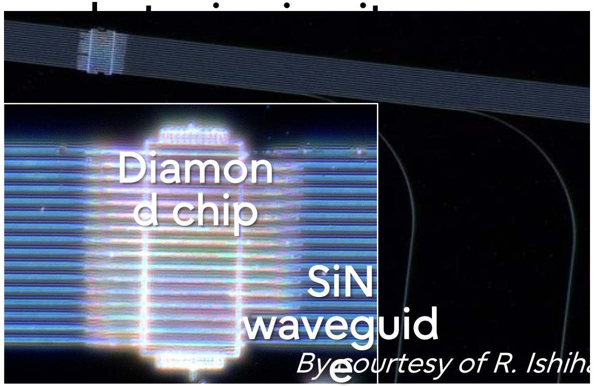


M. H. Abobeih *et al.*,
Nature **606**, 884–889 (2022).

- **SnV qubits**
  Improvement using efficient and robust SnV color center



- **Photonic chip**
  Integration of small diamond chips on SiN

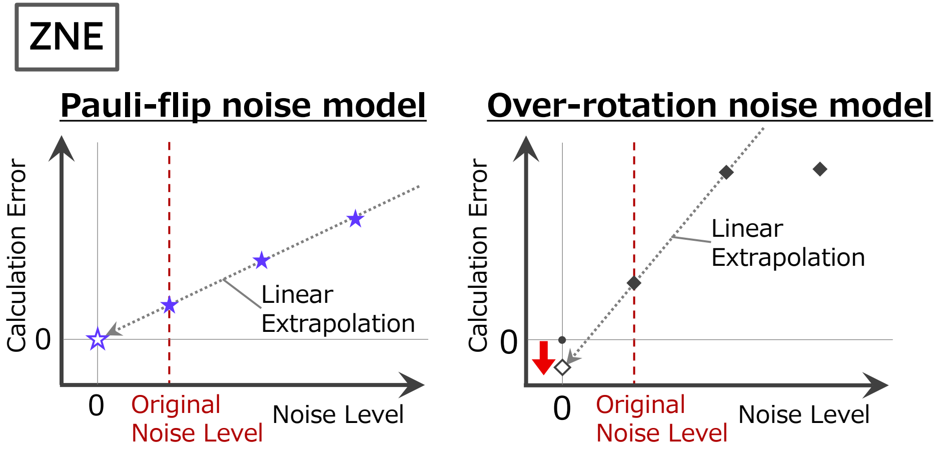


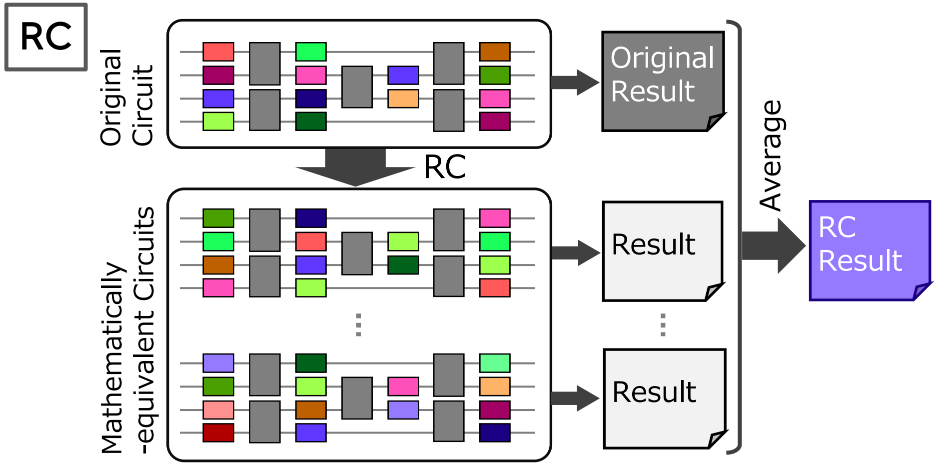
Quantum Error Mitigation Technology

FUJITSU

- Synergetic combination of Zero-Noise Extrapolation (ZNE) and Randomized Compiling (RC)

  Kurita *et al.*, Quantum **7**, 1184 (2023).
  - ZNE is a powerful method, but it is not effective for over-rotation noise.
  - RC is a method of making random circuits which are mathematically equivalent to the original circuit and averaging the calculation results of all equivalent circuits.

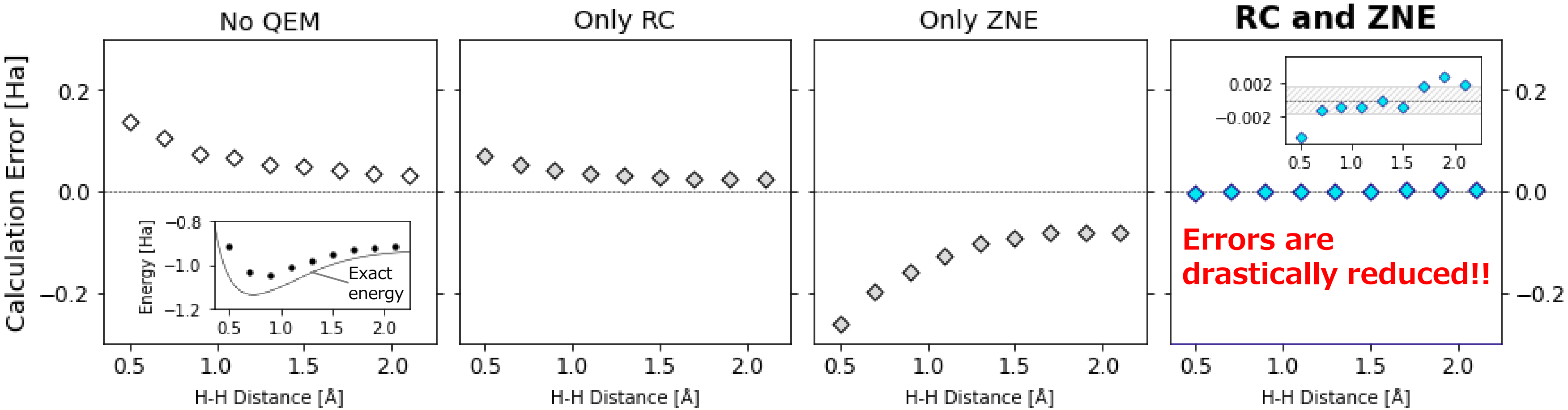




RC "converts" any noise to Pauli-flip noise and makes ZNE effective.

Numerical Results of Our Method

- We apply our method to a practical algorithm for quantum chemistry.
  - Variational quantum eigensolver (VQE), calculating the ground-state energies of H_2
- Although RC or ZNE alone does not improve the energy errors sufficiently, **combination of them drastically reduces the energy errors**.



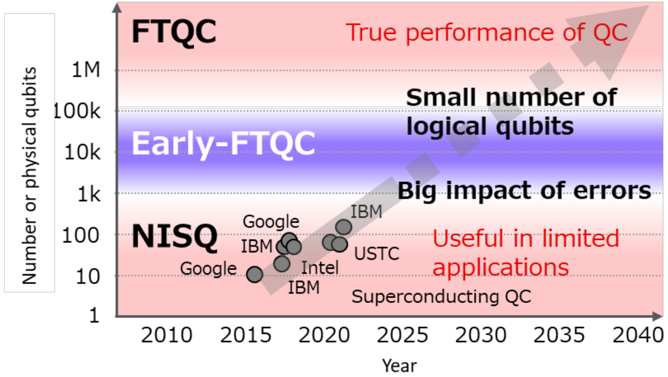
Our method proposed in this work is useful for practical algorithms.

Newly Developed Quantum Computing Architecture

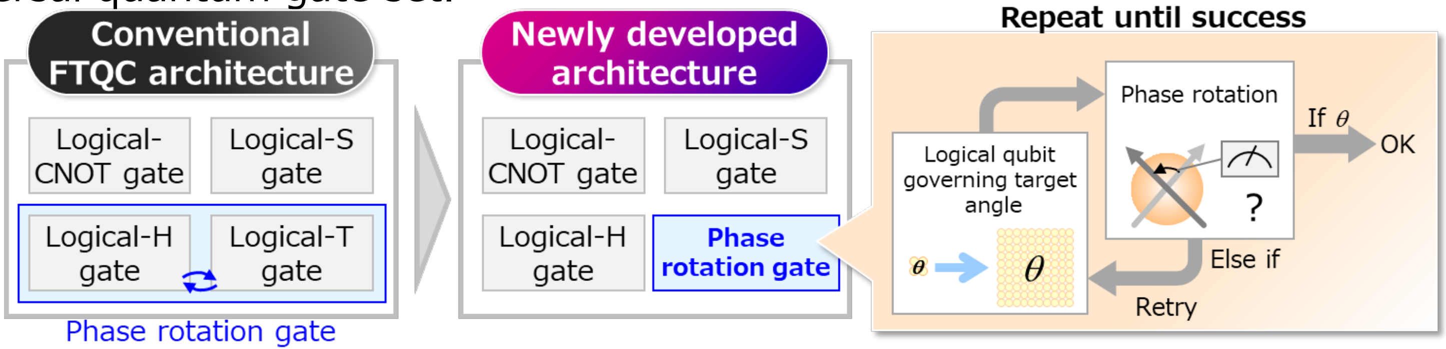
- **Background**
  - In the early-FTQC era, sufficient performance cannot be demonstrated with current approaches to NISQ and FTQC.

    NISQ: Noisy Intermediate-Scale Quantum computer

    FTQC: Fault-Tolerant Quantum Computer



- **New Quantum Computing Architecture**
  - Introducing a new type of phase rotation gate, instead of conventional T-gate, into a universal quantum gate set.

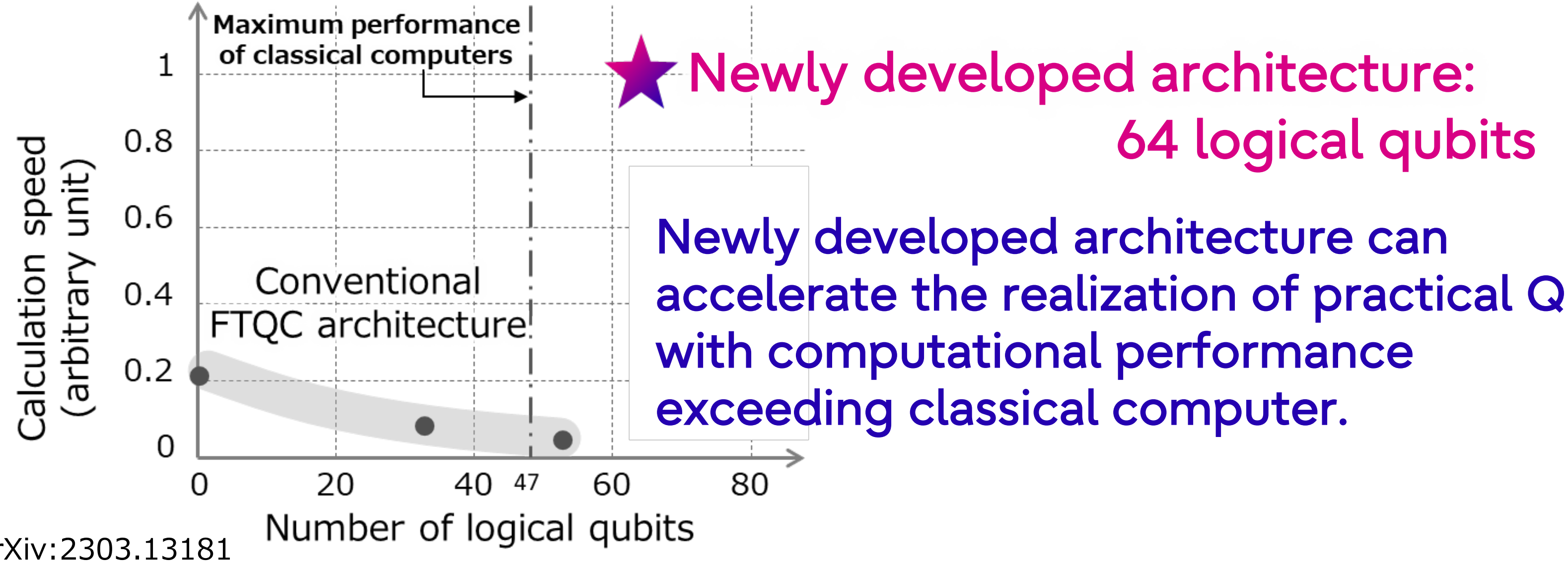


Akahoshi *et al.*, arXiv:2303.13181
https://pr.fujitsu.com/jp/news/2023/03/23.html

Achievement of newly developed architecture

Reduced to approximately 1/10 in number of physical qubits and 1/20 in gate operations, with a slightly noisy logical phase rotation gate.

- **Performance estimation of a QC with 10,000 physical qubits**

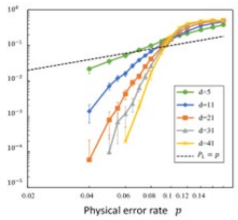


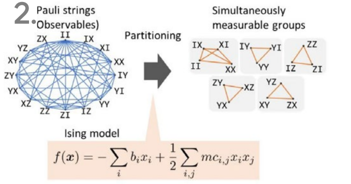
Newly developed architecture can accelerate the realization of practical QC with computational performance exceeding classical computer.

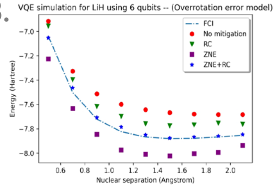
Akahoshi *et al.*, arXiv:2303.13181
https://pr.fujitsu.com/jp/news/2023/03/23.html

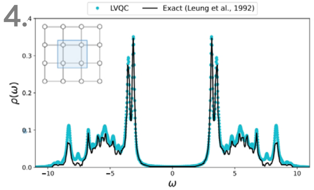
Recent Publications in Quantum Algorithm Area

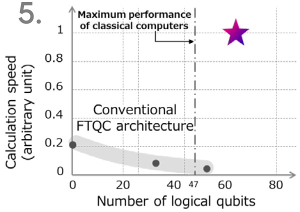
1. **A Practical and Scalable Decoder for Topological Quantum Error Correction with Digital Annealer**
   Fujisaki, Oshima, Sato, and Fujii, Phys. Rev. Research **4**, 043086 (2022).
2. **Pauli String Partitioning Algorithm with the Ising Model for Simultaneous Measurement**
   Kurita, Morita, Oshima, and Sato, J. Phys. Chem. A **127**, 1068 (2023).
3. **Synergetic quantum error mitigation by randomized compiling and zero-noise extrapolation for the variational quantum eigensolver**
   Kurita, Qassim, Ishii, Oshima, Sato, and Emerson, Quantum **7**, 1184 (2023).
4. **Computation of Green's function by local variational quantum compilation**
   Kanasugi, Tsutsui, Nakagawa, Maruyama, Oshima, and Sato, Phys. Rev. Research **5**, 033070 (2023).
5. **Partially Fault-tolerant Quantum Computing Architecture with Error-corrected Clifford Gates and Space-time Efficient Analog Rotations**
   Akahoshi, Maruyama, Oshima, Sato, and Fujii, arXiv:2303.13181
6. **Variational Denoising for Variational Quantum Eigensolver**
   Tran, Kikuchi, and Oshima, arXiv:2304.00549
7. **Splitting and Parallelizing of Quantum Convolutional Neural Networks for Learning Translationally Symmetric Data**
   Chinzei, Tran, Maruyama, Oshima, and Sato, arXiv:2306.07331
8. **Quantum error correction with an Ising machine under circuit-level noise**
   Fujisaki, Maruyama, Oshima, Sato, Sakashita, Takeuchi, Fujii, arXiv:2308.00369

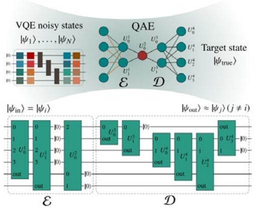
1.


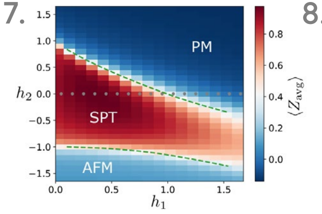
2.


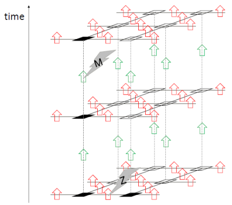
3.


4.


5.


6.


7.


8.


About the Future

FUJITSU

To release large-scale simulators and actual machines successively in order to solve societal problems

2023.7 To release a high-speed and large-scale 40 qubit quantum simulator

2023.10 To release a superconducting quantum computer (64 qubits) at the RIKEN RQC- Fujitsu Cooperation Center

FY2025 To release of a larger-scale superconducting quantum computer (256 qubits), and implement the error correction

FY2026~ To release a superconducting quantum computer with >1000 qubits

FY 2020 — 2030

Thank you