

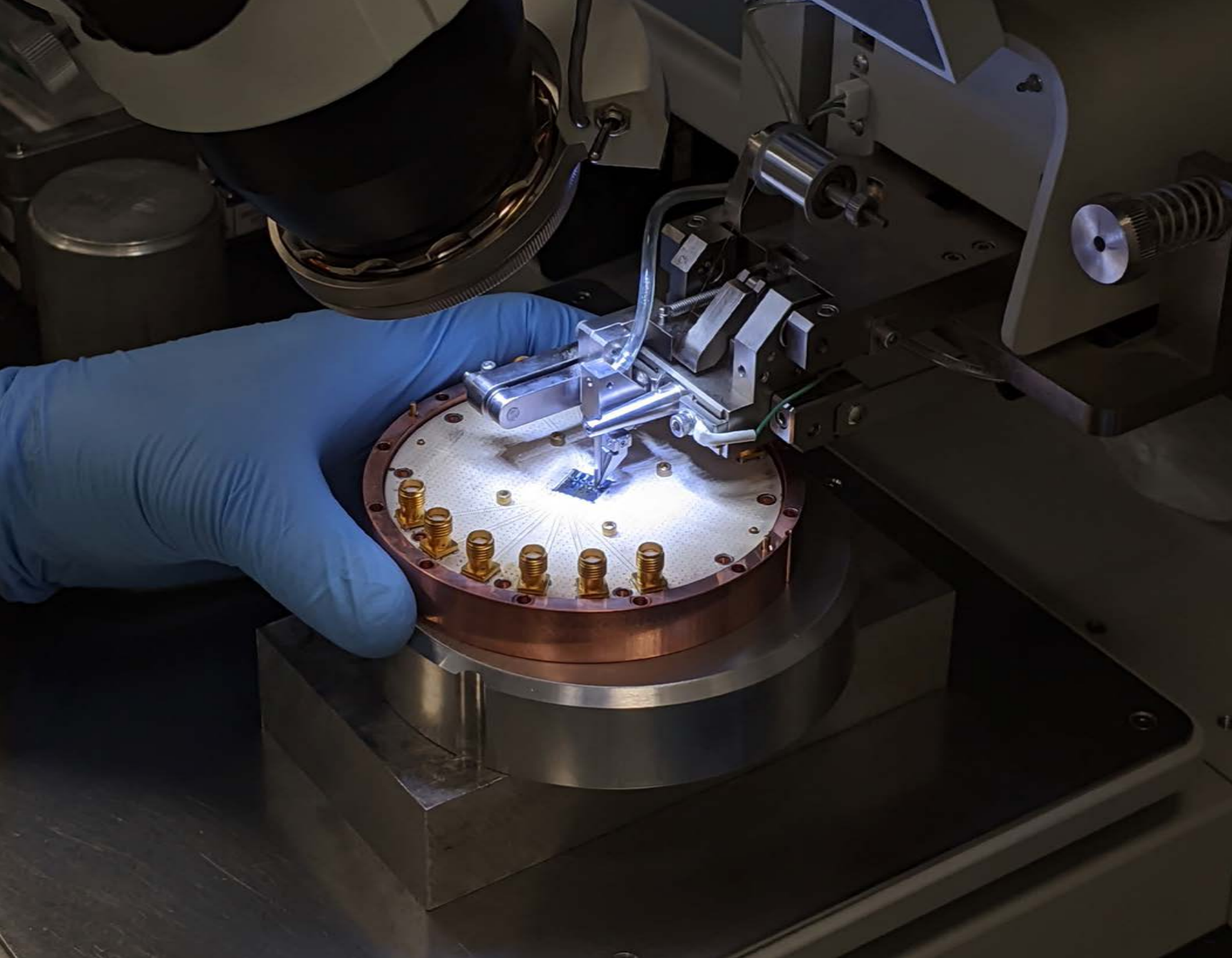
JUNE 2022

# Progress Report

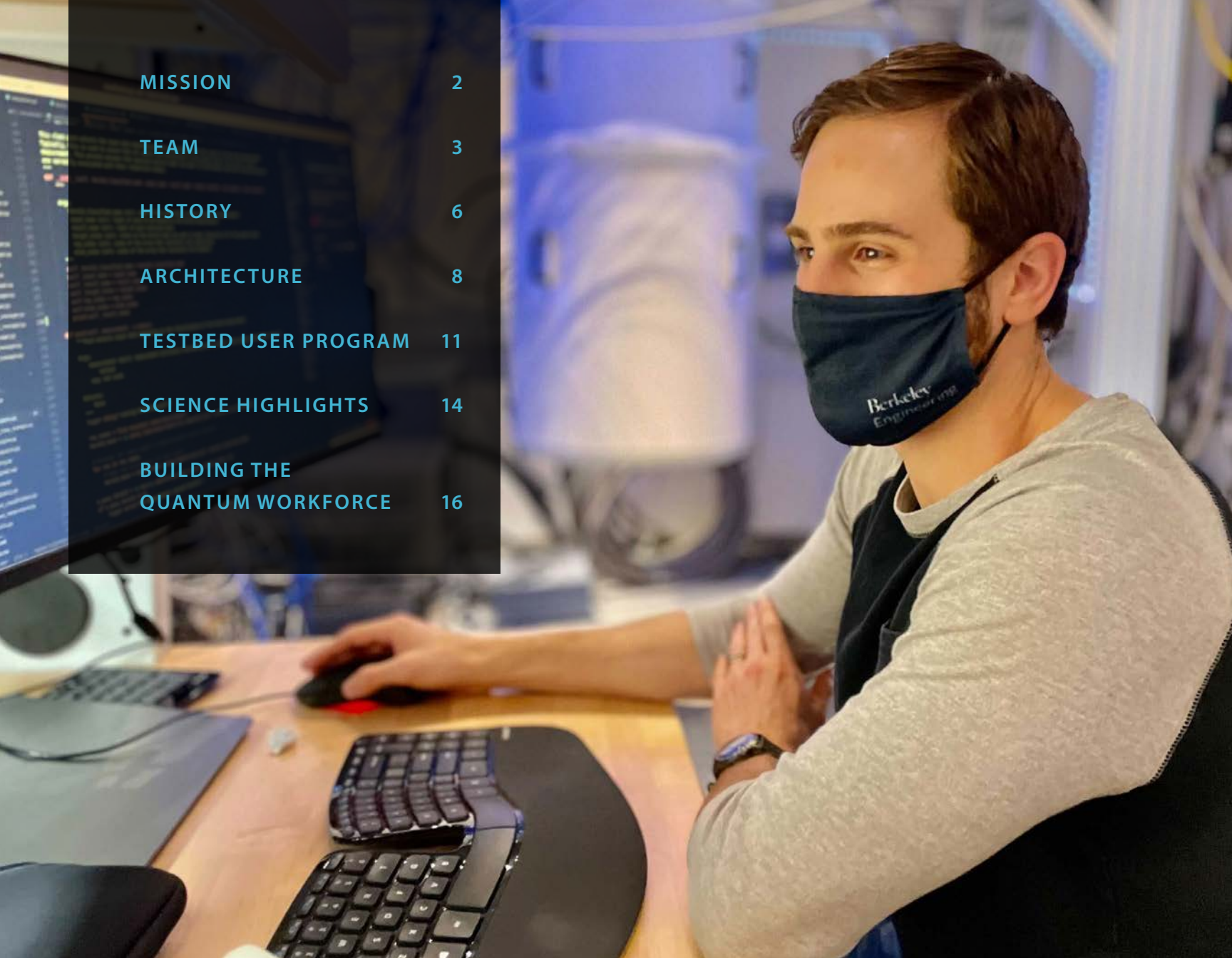
The Advanced Quantum Testbed  
Lawrence Berkeley National Laboratory



Office of  
Science



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## Mission

*AQT Head of Measurement, Ravi Naik, examined the main cryogenic dilution refrigerator.*

The Advanced Quantum Testbed (AQT) at Lawrence Berkeley National Laboratory (Berkeley Lab) is a state-of-the-art collaborative research laboratory funded by the U.S. Department of Energy Office of Science Advanced Scientific Computing Research program. The laboratory operates an open-access experimental testbed, based on superconducting quantum hardware, designed for deep collaboration with external users from academia, National Laboratories, and industry.

These interactive collaborations allow broad exploration of cutting-edge science with systems engineering suitable for the scientific applications that rely on gate-based quantum computing. AQT brings together a team of multidisciplinary researchers focused on the design, fabrication, and operation of superconducting quantum processors, as well as the development of the full control stack

consisting of classical electronics, firmware, and software to enable the execution of quantum algorithms.

Through the research opportunities it offers, AQT is training the next generation of scientists and engineers in quantum computing. The testbed allows early-career scientists to access world-class quantum computing hardware and software systems, establishing a unique environment for active mentoring, open discussion, and networking between different stakeholders in the quantum ecosystem. Testbed users are selected through a peer-reviewed proposal process, gaining full low-level access to AQT hardware and software, including detailed data on architecture, operation, and performance. Users participate in the testbed's evolution and share results to maximize the utility of nascent quantum hardware.



# Team Leadership



## **Irfan Siddiqi, Director**

A professor of physics at the University of California, Berkeley (UC Berkeley), Siddiqi is a fellow of the American Physical Society. He is the director of the Quantum Nanoelectronics Laboratory at UC Berkeley and a faculty scientist in the Quantum Information Science & Technology (QuIST) group within Berkeley Lab's Applied Mathematics and Computational Research Division. Currently, he also serves as director of the Quantum Systems Accelerator, one of five Department of Energy National QIS Research Centers, which is also led by Berkeley Lab.



## **David I. Santiago, Science and Technical Lead**

Santiago is the group leader for QuIST and AQT technical lead. Prior to joining AQT in 2018, Santiago served as a scientific consultant in the Defense Advanced Research Projects Agency and the Intelligence Advanced Research Projects Activity, and participated in the research and development programs producing early technological advances in quantum information devices.



## **Christopher Spitzer, Quantum Program Manager**

Spitzer is the program manager for QuIST, helping lead programs that include AQT and the Quantum Systems Accelerator. He was previously the lead for physical sciences and engineering in UC Research Initiatives' grant-making programs and has worked in the U.S. Senate and the Department of State. He received his Ph.D. in physics from the University of Washington and has conducted research in beyond-the-standard-model particle phenomenology.



## **Ravi Naik, Head of Measurement**

Naik is a research scientist in QuIST and measurement lead at AQT. His current research efforts focus on two-qubit gates in multi-qubit superconducting processors and noise in quantum algorithms. He received his Ph.D. at the University of Chicago for his research on multimode circuit quantum electrodynamics with Professor David Schuster.



## **Kasra Nowrouzi, Head of Hardware**

Nowrouzi is a research scientist at AQT, where he oversees the development and deployment of full-stack systems for collaborative quantum computing experiments on superconducting platforms. He received his B.S. in electrical engineering and computer sciences and Ph.D. in applied physics from UC Berkeley. His dissertation work with Professor Roger Falcone included the development of an ultrastable computational x-ray microscope for operando phase-retrieval imaging of nanomaterials for the COSMIC beamline at Berkeley Lab's Advanced Light Source.

# Team **Members**

AQT's diverse and growing team at Berkeley Lab includes staff and post-doctoral researchers specialized in firmware and software, quantum algorithms, quantum processing units, and controls, as well as experts, graduate students, and undergraduate interns from UC Berkeley. Collaborating scientists at AQT include researchers from MIT Lincoln Laboratory.

“AQT provides an incubator to co-design innovative quantum computation technologies by assembling a national community of scientists and engineers. It was built from the ground up to support projects from external teams through access to both the full quantum computing platform and to the expertise of AQT scientists to maximize the testbed’s potential.”

**IRFAN SIDDIQI**, *Director*





# History

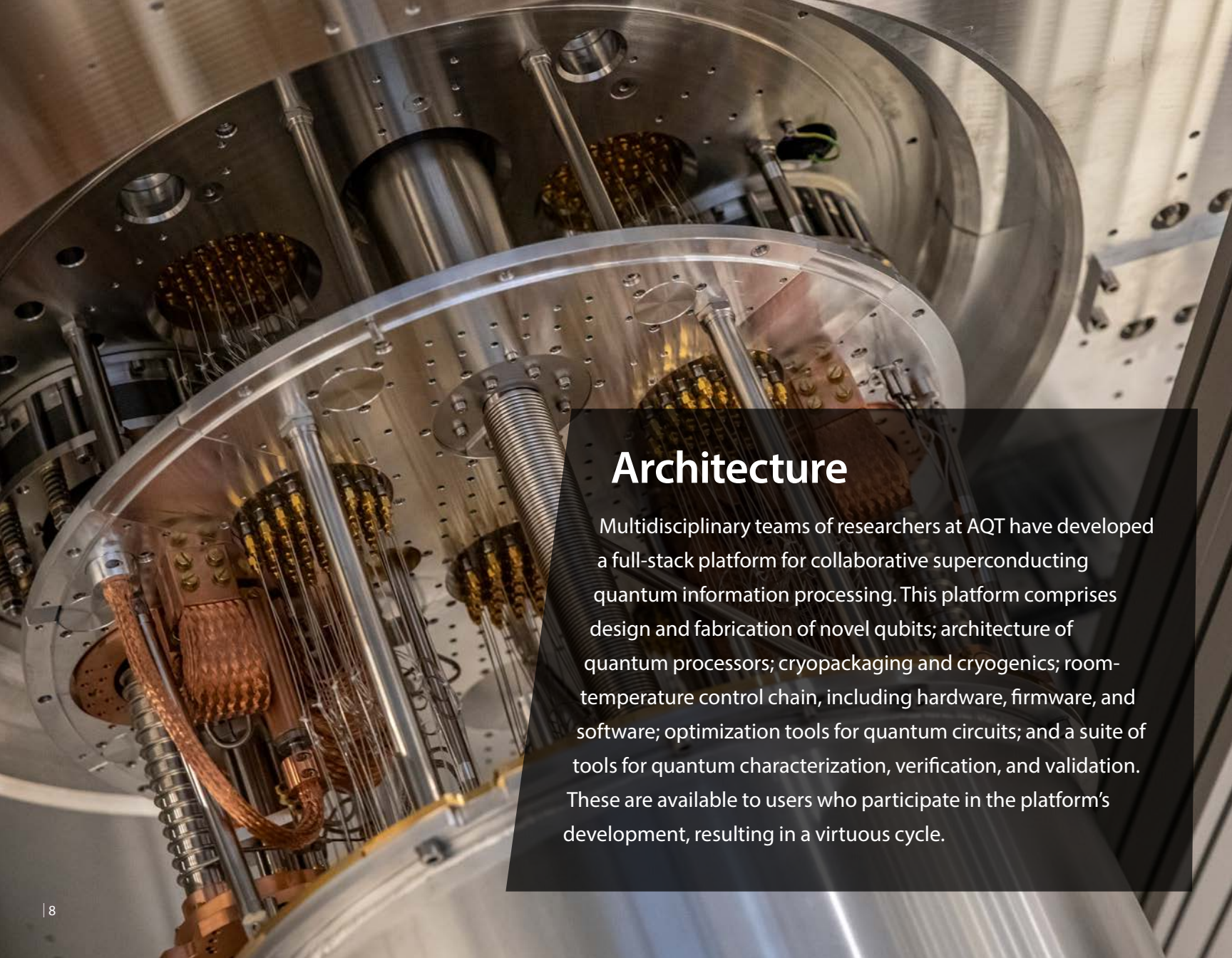
*A superconducting quantum processor unit at AQT*

AQT builds on the research and development at Berkeley Lab and benefits from DOE's Office of Science investments in Berkeley Lab. Launched in 2018, the first phases focused on the deployment and integration of state-of-the-art superconducting hardware and the development of novel quantum benchmarking techniques. This included verification and validation, noise detection, suppression, and mitigation.

In 2020, AQT opened the testbed for broad user engagement and has received dozens of research proposals from users in academia, National Laboratories, and startups to explore a variety of topics, including algorithms, simulations, characterization, validation, control hardware, firmware, software, and processor architectures. In its initial three years, AQT performed a variety of demonstrations, including quantum simulation, optimization, quantum chemistry and condensed matter, nuclear physics, and high-energy physics.

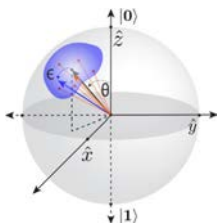






## Architecture

Multidisciplinary teams of researchers at AQT have developed a full-stack platform for collaborative superconducting quantum information processing. This platform comprises design and fabrication of novel qubits; architecture of quantum processors; cryopackaging and cryogenics; room-temperature control chain, including hardware, firmware, and software; optimization tools for quantum circuits; and a suite of tools for quantum characterization, verification, and validation. These are available to users who participate in the platform's development, resulting in a virtuous cycle.



## SOFTWARE STACK

Includes a versatile software stack compatible with a variety of open quantum circuit formats and equipped with a set of evolving tools for algorithmic performance optimization, including efficient compilation techniques and approaches that mitigate error. The stack provides users low-level access and can support non-standard software needs for testbed users.



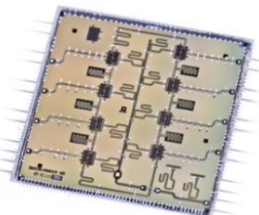
## COMMERCIAL AND CUSTOM CONTROLS

Includes commercial and in-house electronic controls. The in-house control stack, QubiC, accommodates custom needs of testbed users. Close collaboration between users and AQT scientists enables considerably more flexibility than is typically available in commercial quantum computing platforms.



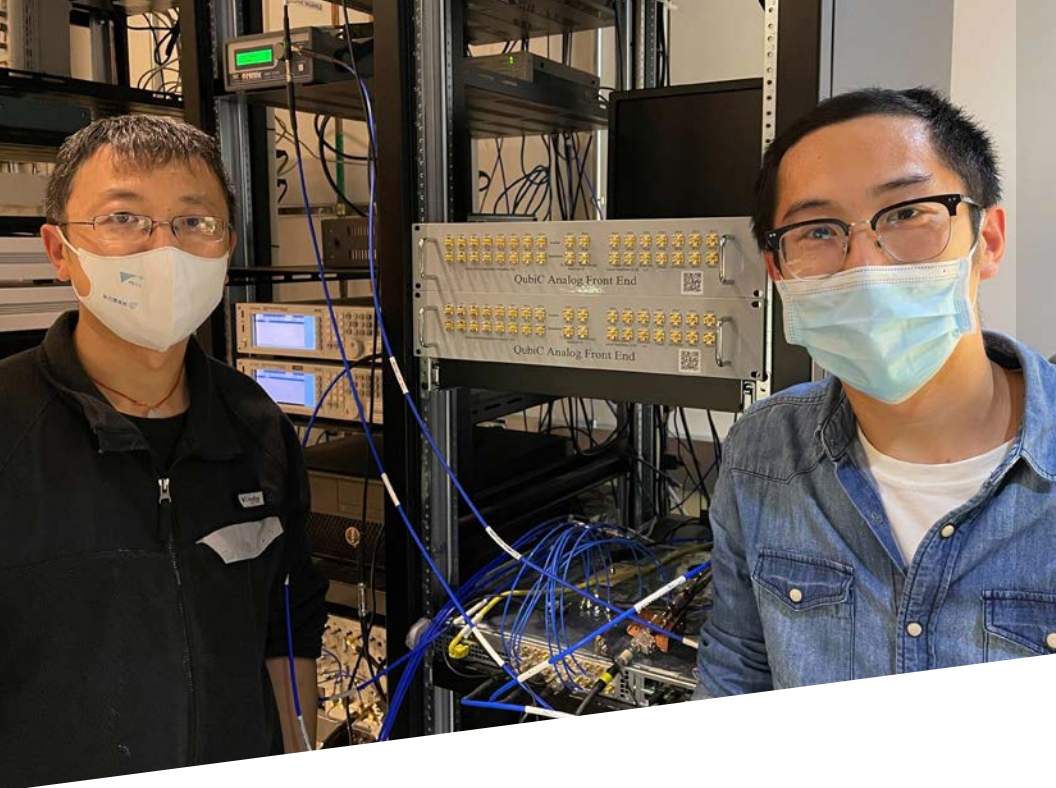
## CRYOGENIC PLATFORM

Includes a Bluefors dilution fridge, "Blizzard," outfitted with 160 RF lines and operating at 10mK. Blizzard was developed in partnership with Berkeley startup Bleximo to include an experimental stage that accommodates modular and extensible sets of experiments and cryopackaging for improved electromagnetic hygiene. The platform provides control and readout for a total of 128 qubits, and it accommodates multiple quantum processors.



## SUPERCONDUCTING QUANTUM PROCESSORS

AQT's processor portfolio includes an array of different architectures with varying connectivity and native gate sets. The standard processor for user experiments so far has been an 8-qubit transmon ring with high-coherence qubits ( $T_1$  and  $T_2 > 100 \mu\text{s}$ ) and high-fidelity gates (99% for two-qubit gates). A novel 8-qubit QPU (quantum processing unit) with arbitrary dynamically reconfigurable (up to all-to-all) connectivity is currently under development. AQT also collaborates with MIT Lincoln Laboratory to introduce new processor designs into the library available to users.



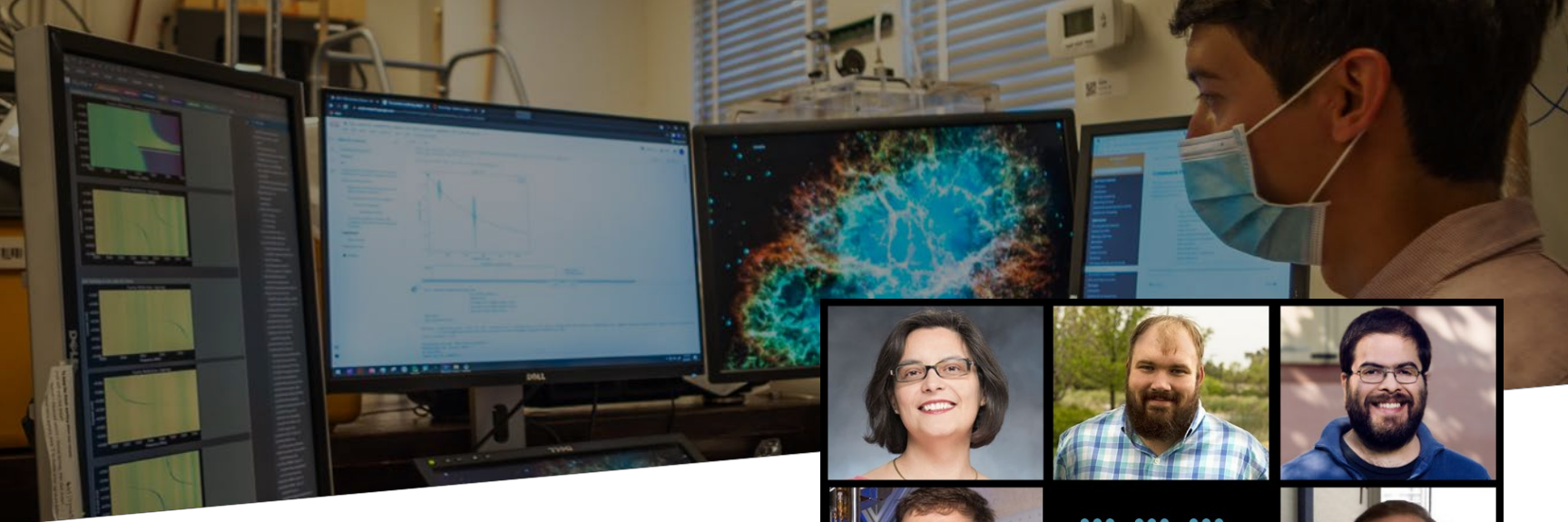
## Notable Hardware Advancement in the Last Year: **QubiC**

AQT leverages Berkeley Lab's robust and longstanding research and development in particle accelerators for its in-house control stack. An important hardware advancement is a novel FPGA-based control and measurement system - QubiC - that is modular and open source. QubiC is capable of the efficient upload and execution of quantum experiments with minimal overhead, can be customized to accommodate unique needs of users, and has demonstrated fast feedback. AQT scientists have used QubiC to develop and implement automated calibration of two-qubit gates.

*Above: Researchers Gang Huang and Yilun Xu led the QubiC design leveraging robust research and development for particle accelerators at Berkeley Lab.*

"Newer control electronics are not tailored for quantum processors, so quantum researchers purchase more instruments as the control hardware needs become more complex. However, the cost for control hardware should not be linear or exponential, and that's where we try to come in. By building QubiC as a more accessible and affordable system from the ground up, we really know what happens underneath for further integrations and try to scale the design."

**GANG HUANG,  
BERKELEY LAB'S ATAP DIVISION,  
CO-LEADER OF QUBIC DESIGN**



## Testbed **User Program**

AQT functions as an open testbed encouraging research proposals from a broad range of teams in academia, industry, and National Laboratories. The platform is a key tool that enables research to support DOE's science and energy mission. AQT offers easily accessible, deep expertise to refine project ideas for the highest potential impact, often bringing new approaches and carrying them out.

AQT is establishing its user community, enabling the exchange of ideas and building a body of shared knowledge. More than half the user projects in FY20-21 were collaborations with National Laboratory groups. Testbed users have also included industry partners such as Quantum Benchmark (acquired by Keysight Technologies) and Super.tech (acquired by ColdQuanta), jointly publishing in the scientific literature with AQT researchers.

In October 2021, AQT launched its second open call for user project proposals, receiving applications across a broad range of topics. This



*User project led by Lawrence Livermore National Laboratory and the University of Trento on "Near-term Quantum Simulations for Nuclear Physics."*

included executing algorithms for scientific computation, benchmarking of NISQ (noisy intermediate-scale quantum) hardware, and co-designing next-generation architectures and algorithms. AQT continues to accept research proposals on a rolling basis for time-sensitive or high-priority projects, serving as an experimental laboratory for the fast-growing QIS community.



“I think the most significant value to startup entrepreneurs is that AQT’s platform is designed to be modified, forked, and flexible.”

**PRANAV GOKHALE**

*VP of Quantum Software at ColdQuanta,  
Super.tech former CEO and Co-Founder*

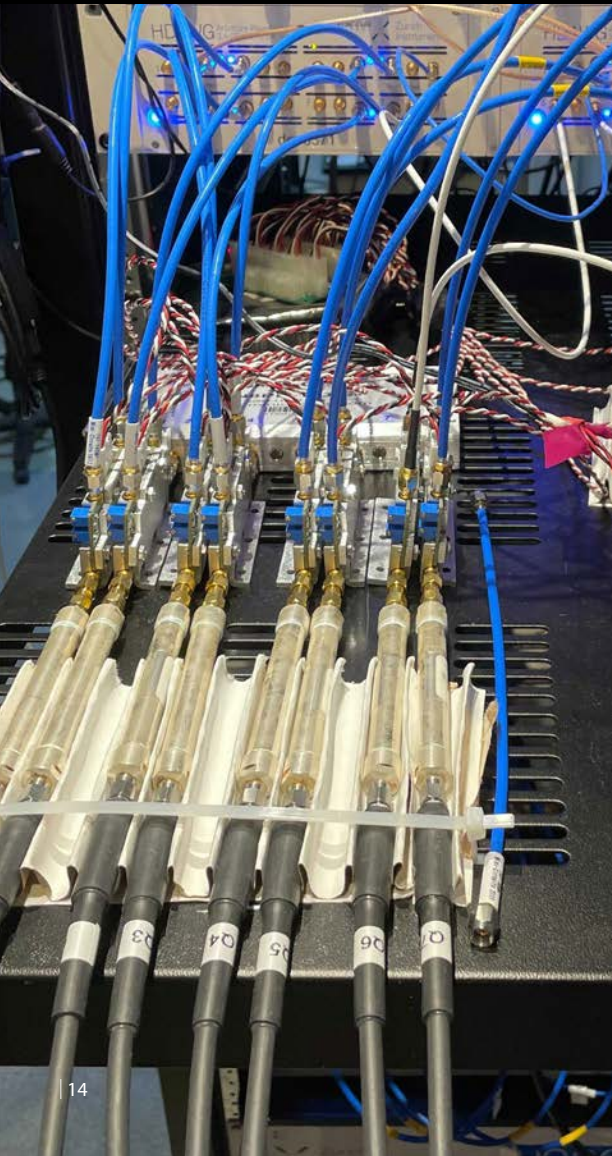


“In the context of a testbed user meeting, we learned about other techniques that we were not aware of. So this user meeting sparked new ideas for our research. At the same time, our research also provides feedback to the hardware specialists.”

**SOFIA QUAGLIONI**

*Deputy Group Leader of the Nuclear Data &  
Theory Group in the Nuclear and Chemical  
Sciences Division at Lawrence Livermore  
National Laboratory (LLNL)*

Since its inception, AQT has enabled a number of advances in a broad range of topics in quantum information science and technology. These advances touch upon a breadth of areas, some of which are highlighted below.



## High-fidelity iToffoli Gate

This project resulted in the first experimental demonstration of the high-fidelity iToffoli gate (~98%) by driving three superconducting qubits at the same frequency using simultaneous microwave excitation. The simplicity of the experiment implemented the iToffoli gate in a linear chain without decomposition into 1- and 2-qubit gates, making the gate calibration straightforward and showing how the gate can be implemented on any microwave-based superconducting quantum processor efficiently. This 3-qubit gate demonstration completes the necessary gate set for universal quantum computation paving the way for more efficient quantum circuit executions.

*Nature Physics* (2022). DOI:10.1038/s41567-022-01590-3

## Error Characterization in Qutrits Through Randomized Benchmarking

Processors based on three-level qutrits could store exponentially greater information and implement algorithms with more efficient quantum circuits in comparison to two-level quantum systems. AQT's team developed and demonstrated performance benchmarking tools on qutrit-based processors, enabling error characterization and efficient evaluation of qutrit circuit fidelity. The researchers invented and implemented randomized benchmarking and cycle benchmarking of single-qutrit and two-qutrit gates.

*Physical Review Letters* 126, 210504 (May 2021)

## Improving QITE Algorithm Accuracy

AQT scientists built upon the randomized compiling project and extended the technique to the hybrid quantum-classical Quantum Imaginary Time Evolution (QITE) algorithm. Furthermore, the researchers developed a novel, scalable purification-based error mitigation strategy that improves the accuracy of QITE and is applicable generally to NISQ-era algorithms. The project also utilized the QSearch quantum circuit optimizer developed at AQT for dramatic improvement in QITE circuit fidelity.

*arXiv preprint arXiv:2104.08785*



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## Optimized ZZ SWAP Networks

Chicago-based Super.tech used AQT's platform to experimentally validate a project optimizing the execution of fermionic SWAP networks on four qubits. The fermionic SWAP network offers a promising path forward for coping with limited qubit connectivity by enabling a qubit routing sequence that can be used to efficiently execute the Quantum Approximate Optimization Algorithm (QAOA). The project used an overcomplete set of native hardware operations to decompose the relevant quantum gates and SWAP networks, minimizing circuit depth and maximizing gate cancellation. The project also introduced Equivalent Circuit Averaging, which randomizes over degrees of freedom in the quantum circuit compilation to reduce the impact of systematic coherent errors.

[arXiv preprint arXiv:12111.04572](#)

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## Error Mitigation Through Randomized Compiling

AQT's team, in collaboration with Quantum Benchmark/Keysight Technologies, demonstrated the Randomized Compiling (RC) protocol for the first time, suppressing coherent errors and increasing quantum algorithm fidelity on an AQT quantum processor. The experiment showed that RC enables accurate predictions of algorithm performance from measured qubit error rates. AQT researchers showed performance gains under RC for essential algorithms such as the quantum Fourier transform.

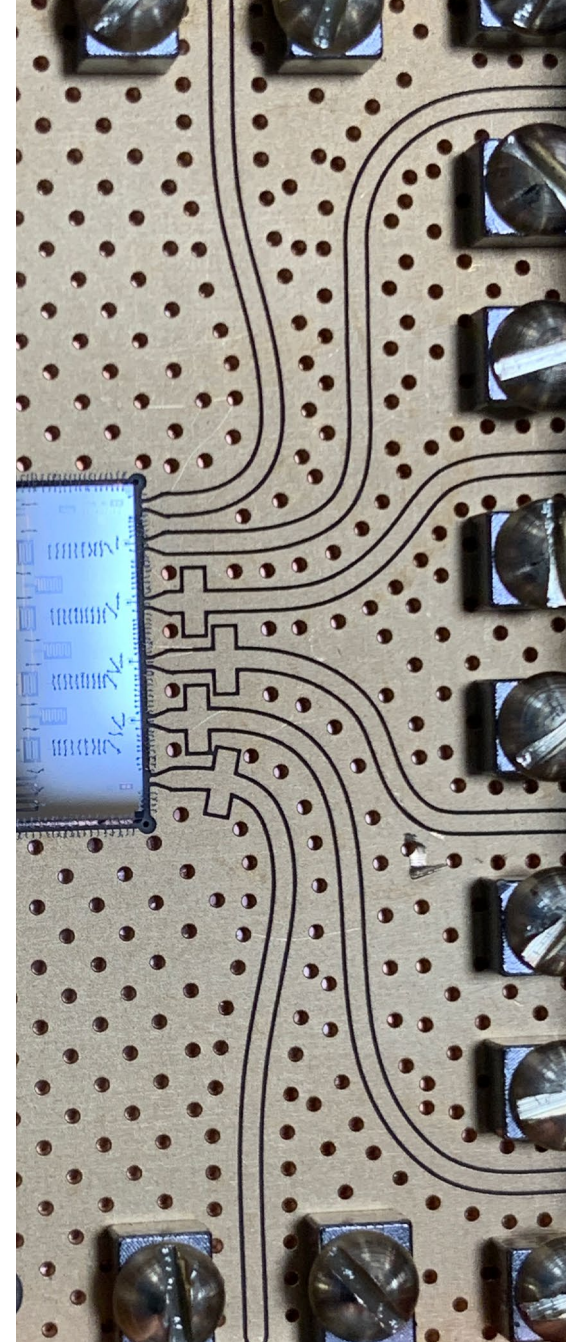
[Physical Review X .11.041039 \(November 2021\)](#)

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## Efficiently Improving NISQ Hardware Performance

Researchers at Keysight Technologies, in collaboration with AQT, developed and experimentally validated two efficient error mitigation protocols – Noiseless Output Extrapolation and Pauli Error Cancellation. The researchers combined popular mitigation strategies such as probabilistic error cancellation and noise amplification with efficient noise reconstruction methods so that protocols can mitigate a wide range of noise processes. Researchers observed significant improvements in the performance of both structured and random circuits with up to 86% improvement in variation distance over the unmitigated outputs. Their experiments demonstrate the effectiveness of the protocols to drastically enhance the performance of quantum circuits composed of noisy cycles of gates.

[arXiv preprint arXiv: 2201.10672](#)



# Building the Quantum Workforce

Since its foundation, AQT has incorporated scientists from different backgrounds and fields to become a collaborative hub for the broader national and international community and to train the quantum workforce.

AQT hosts undergraduate students for extended thesis projects, often for a year or more. It also offers an ideal training laboratory for graduate students and postdocs to engage with projects from materials and fabrication to quantum algorithms and applications. In the process of training on AQT projects, students and postdocs collaborate with researchers from National Labs and industry, integrating them into the wider quantum information research community.

AQT offers additional educational opportunities for high school and undergraduate students. Over the past year, the Head of Hardware Kasra Nowrouzi hosted a visit from UC Davis undergraduate students in the summer National Science Foundation REU (Research Experiences for Undergraduates). AQT also partnered with Berkeley Lab's K-12 STEM Education and Outreach program for a career talk featuring Head of Measurement Ravi Naik.



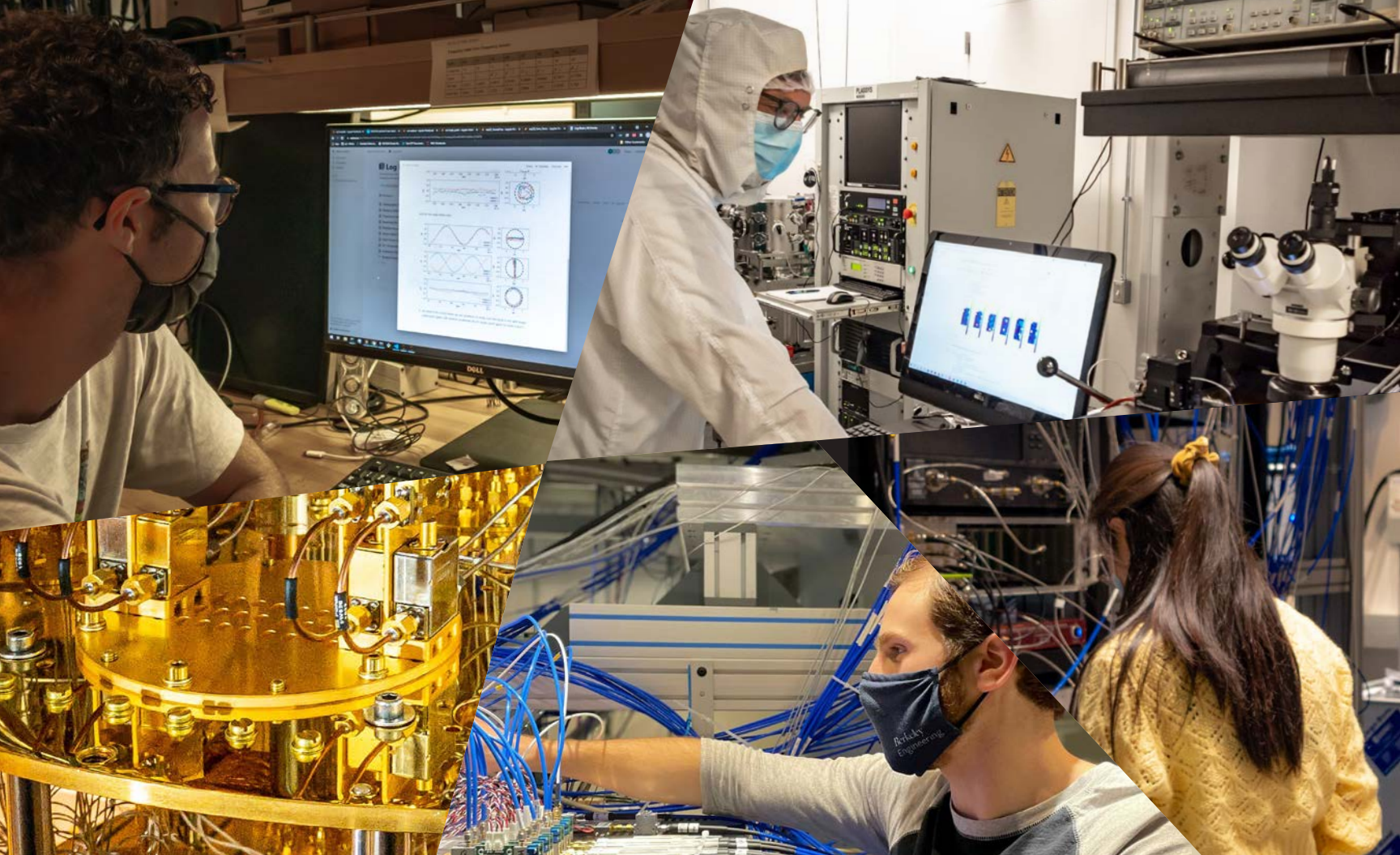
*Zahra Pedramazi, AQT project scientist, and Long Nguyen, postdoctoral researcher.*

AQT students and graduate alumni have taken positions in prominent research institutions and companies worldwide, including Google, quantum startup Alice & Bob, the Korea Institute of Science and Technology, the Yale Quantum Institute, and the University of Rochester.



“Being part of such a large community with such a range of research interests means there is always someone whose work can inform yours and vice versa. There is a constant dialogue between the different research thrusts, which is what enables AQT to be such a vibrant and productive research environment.”

**MERRELL BRZECZEK**, *UC Berkeley alumnus who studied with Siddiqi and AQT staff for her bachelor's degree honor thesis.*



[aqt.lbl.gov](http://aqt.lbl.gov)

Images by Christian Jünger, Akel Hashim, Kasra Nowrouzi, Zahra Pedramazi, Thor Swift, Merrell Brzeczek, Pranav Gokhale, Sofia Quaglioni et al.  
Quantum communications lead Monica Hernandez. Design by Creative Services Division, Berkeley Lab 22-CR-8050.