Quantum Testbeds Update

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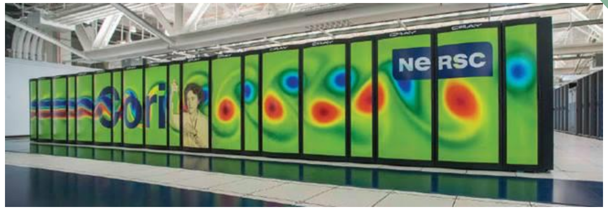
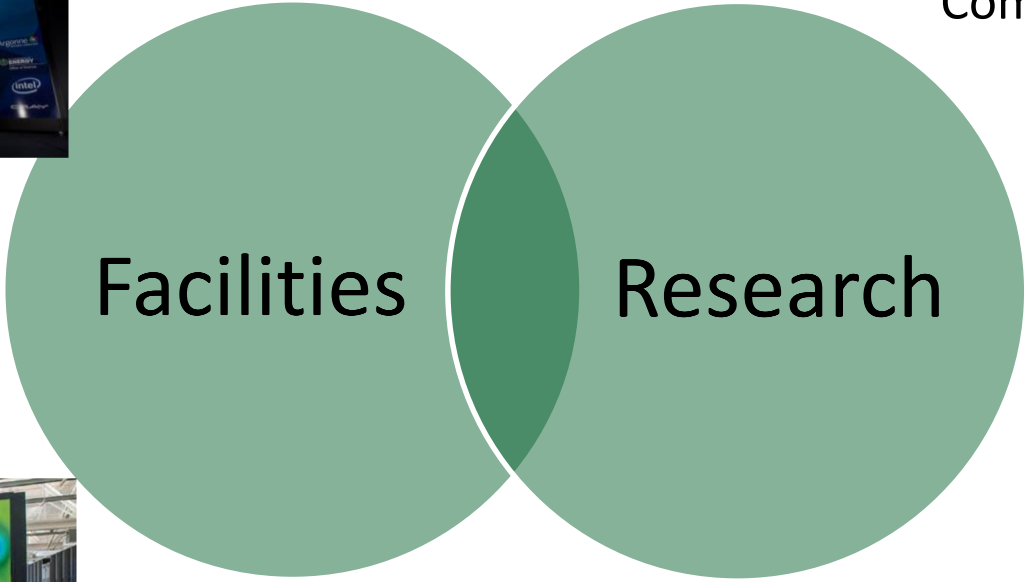
DOE/ASCR Quantum Testbed Stakeholder Workshop (2017)

In addition to identifying technical challenges, strategies for developing and engaging a user community, and noting the role a testbed could play in workforce development, workshop discussions yielded the following key points:

- ***DOE labs have significant capabilities/expertise that can accelerate quantum computing (QC) for science, e.g., in materials characterization, device developments, manufacturing infrastructure, and user facility operations***
- ***Depth of expertise in QC varies widely across the labs***
- ***QC is a rapidly moving field – flexibility and agile management will be essential to keep a testbed relevant***
- ***Multi-scale co-design spanning from materials science to applications and programming has the potential to significantly advance QC for DOE***
- ***A first-generation testbed will be most useful for learning how to build better devices; later generations will be useful for software and algorithm development, which can proceed in parallel***
- ***There is inherent value in maintaining diversity among qubits – emerging qubit candidates may leapfrog ions an SC circuits; different types of qubits coule\d be best-suited to different purposes***
- ***A DOE testbed can serve as focal point for building an SC-QC community and a bridge between sectors to:***
    - *Encourage transparency as precompetitive technologies are developed*
    - *Establish a common vocabulary for QC across diverse disciplines*
    - *Develop and refine interface and other relevant standards*
    - *Define performance metrics and benchmarks to allow fair comparison of different devices*

The ASCR Ecosystem





Computational Science Partnerships

Networking

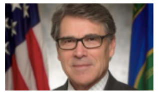
Applied Math

Computer Science

Requirements Reviews

Codesign Partnerships

Podcast: DoE Awards $258 Million for Exascale to U.S. HPC Vendors



Today U.S. Secretary of Energy Rick Perry announced that six leading U.S. technology companies will receive funding from the Department of Energy's Exascale Computing Project (ECP) as part of its new PathForward program, accelerating the research necessary to deploy the nation's first exascale supercomputers. "Continued U.S. leadership in high performance computing is essential to our security,

What Do We Need to Make Informed QC Facilities Investments?

- **An improved understanding of:**
  - The DOE-relevant application space
  - The relationship between characteristics of a quantum processor and application performance

- **Characterizing protocols, metrics, and benchmarks that:**
  - Facilitate improvement of hardware/control/use of hardware
  - Are good indicators of application performance
  - Allow non-experts to understand the factors that are relevant for quantum performance
  - Are straightforward to assess independently

ASCR Tools: Quantum Testbeds Pathfinder

Purpose: To provide decision support for future investments in quantum computing (QC) hardware and increase both breadth and depth of expertise in QC hardware in the DOE community.

Emphasis: Research in the relationship between device architecture and application performance, including development of meaningful metrics for evaluating device performance. Focus is on applications of QC relevant to the Office of Science.

FY 2017: DOE National Laboratory Announcement; 2 awards; total investment of $9.4M over 5 years:

- Advanced Quantum-Enabled Simulation (**LBNL**, LLNL, UC Berkeley)
- Methods and Interfaces for Quantum Acceleration of Scientific Applications (**ORNL**, IBM, IonQ, Georgia Tech, Virginia Tech)

FY 2018: DOE National Laboratory Announcement + companion FOA; 3 awards; total investment of $9.1M over 5 years:

- Quantum-hardware-focused Application Performance Benchmarks (**Virginia Tech**, Duke)
- Efficient and Reliable Mapping of Quantum Computations onto Realistic Architectures (U of Maryland)
- Quantum Performance Assessment (SNL)

Performance assessment of testbeds shows the path forward

Current quantum computers are too noisy for useful computations.

- Quantum computers are still in the early stages of development, and current devices are subject to a broad range of failure modes
- Useful computations will only be possible if errors are sufficiently suppressed and/or mitigated

To progress we need to understand how & why current devices fail

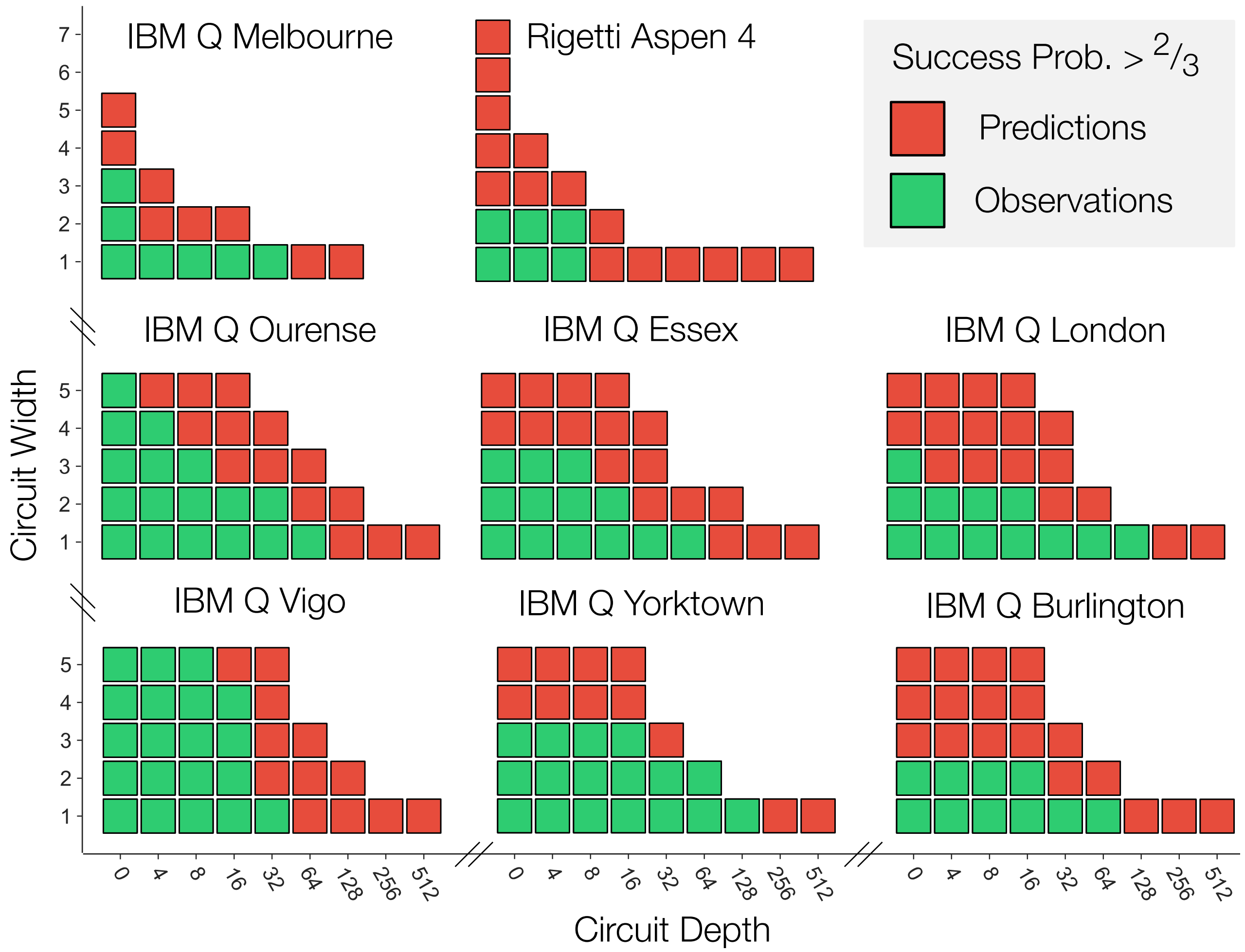
- This is a surprisingly hard task!
- We urgently need to develop methods for comprehensively assessing the performance of current & near-term quantum computers

Understanding how current devices fail shows the path forward

- There are many choices still to be made in the development of quantum computation, from low-level device physics through to algorithmic advances.
- A detailed understanding of current devices will inform the developments needed for quantum computing solutions to DOE-relevant problems.

Describing the Quality of a Quantum Computer is Complex

- Error rates are often quoted for devices with the implication that all circuits smaller than around *1 / the error rate* will succeed and all others will fail
- Plots at right show the results of experiments designed to probe the worst-case performance
- Running carefully designed benchmarking circuits reveals that predictions based on standard error rates can differ significantly from real-world performance
- This is particularly true for structured programs, like algorithmic circuits.



ASCR Tools: Quantum Testbeds for Science

Purpose: To provide the research community with novel, early-stage quantum computing resources and advance our understanding of how to use these resources for advancing scientific discovery.

Motivation: Researchers will need low-level access to quantum computing devices, and even the ability to modify these devices, to experiment with different implementations of gates and circuits, explore programming models, and understand the practical consequences of device imperfections. (2017 Quantum Testbed Stakeholder Workshop Report)

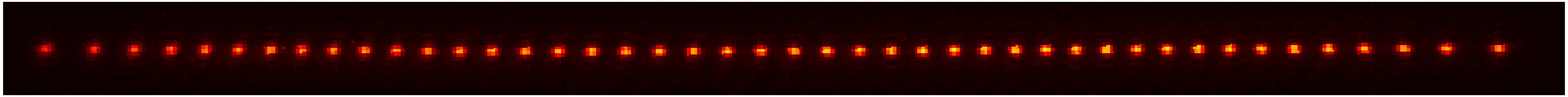
Details: Quantum Testbed for Science (QTS) Laboratories will function as small collaborative research facilities that host experimental quantum computing resources on site, provide external researchers with access to and support in using these resources, and sponsor community engagement activities. Research performed at the QTS Laboratories will inform the design of next-generation devices, ensuring that tomorrow's quantum computers will be capable of running quantum algorithms in support of DOE's science and energy mission.

FY 2017: DOE National Laboratory Announcement; 2 awards; total investment of $56.3M over 5 years:

- Advanced Quantum Testbed (**LBNL**, MIT-LL): multiple novel superconducting qubit architectures
- Quantum Scientific Computing Open User Testbed (**SNL**): room-temperature and cryogenic trapped ion platforms

Both testbeds will give users access to low-level control parameters and complete information about their QC platforms. The testbeds are expected to be available to users by the end of FY 2019, and will be upgraded throughout the award term.

QSCOUT DOE Quantum Testbed Laboratory



Testbed systems designed for open access to support scientific applications

- High-fidelity operations $\#gates \propto (\#qubits)^2$
- Gate-level access
- Open system with fully specified operations and hardware
- Low-level access for optimal control down to gate pulses
- Open for comparison and characterization of gate pulses
- Open for vertical integration by users

https://qscout.us
https://qscout.sandia.gov

QSCOUT

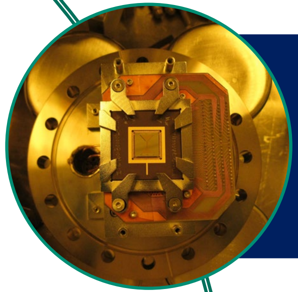
Duke UNIVERSITY

Ken Brown et al.

Tufts UNIVERSITY

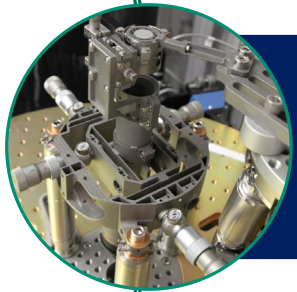
Peter Love et al.

QSCOUT Systems engineering



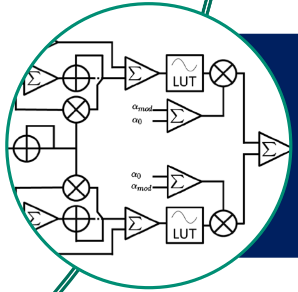
Reducing background collisions

Vacuum technology



Individual addressing

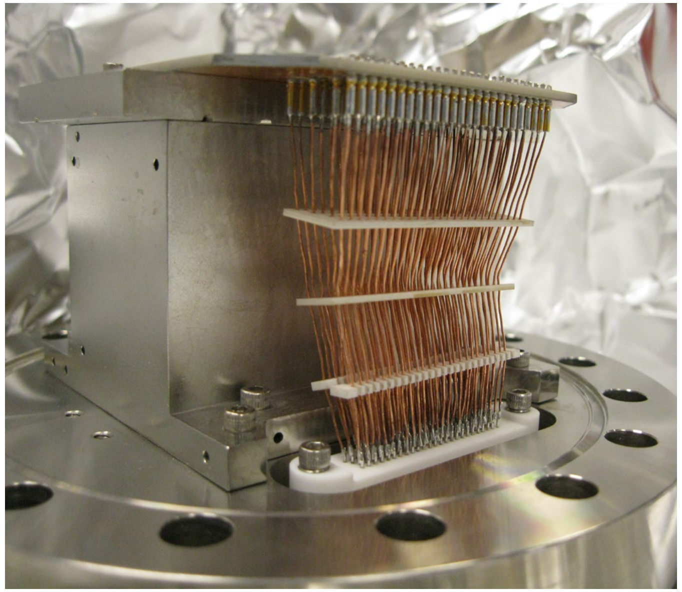
Optical and mechanical engineering



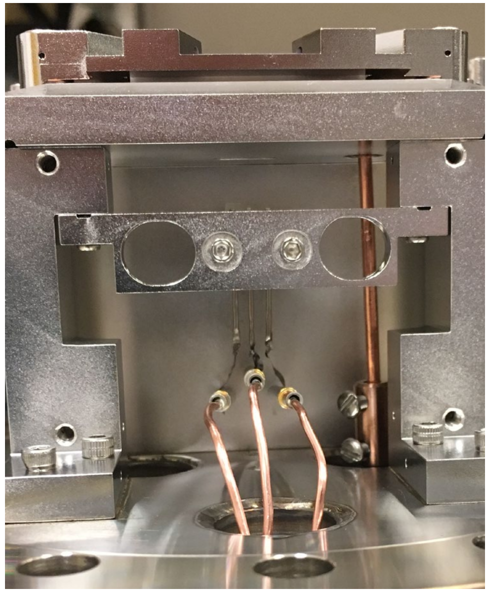
Coherent Pulse control

Electrical engineering

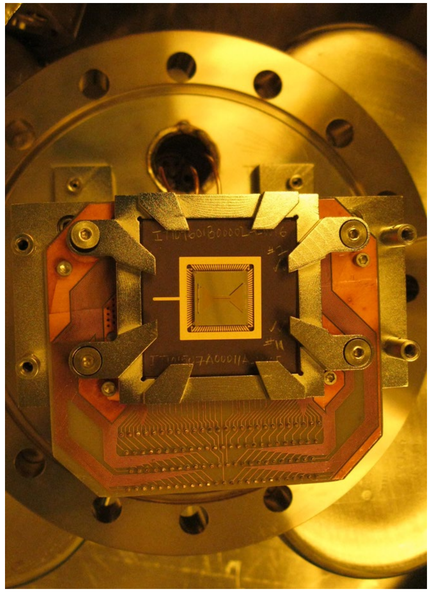
QSCOUT: Vacuum system engineering



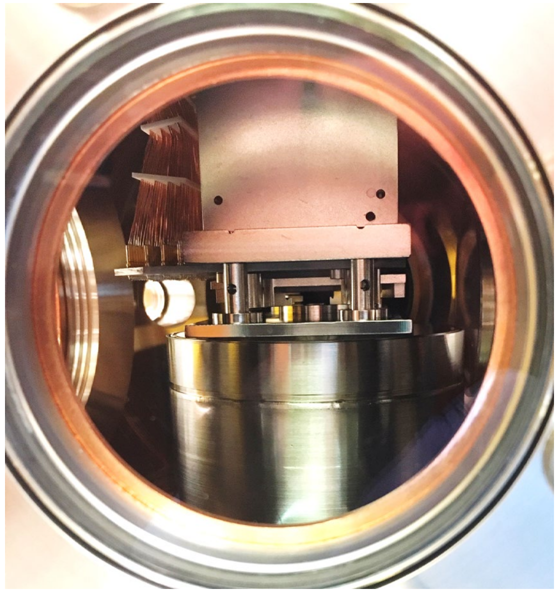
Bare copper wires with Al_2O_3 spacers



3 Yb ovens (loading slot, Peregrine loading hole, HOA loading hole)



Trap installed for final bake



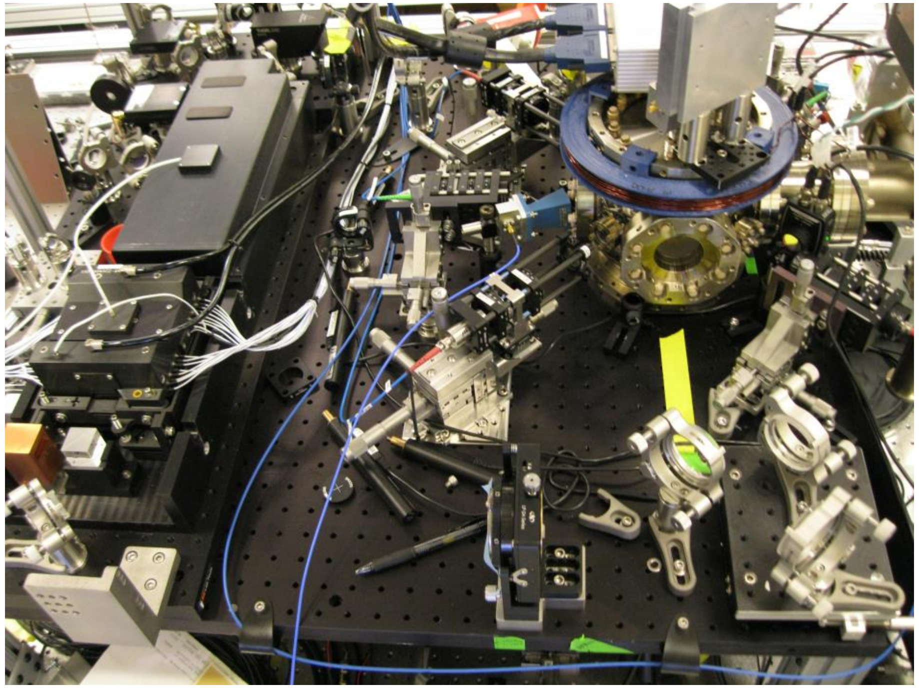
Trap platform in chamber, both re-entrants visible

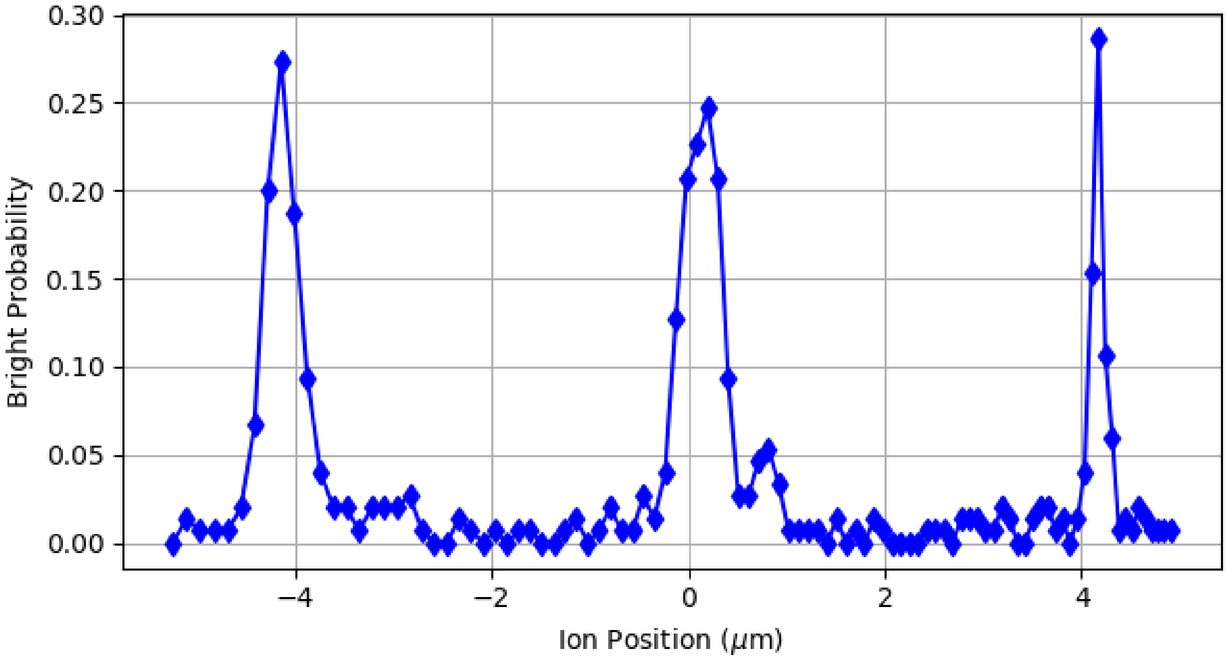
Features (hydrogen and organic mitigation):

- 316L stainless steel subjected to high-temp bake process for UHV performance
- Organics free: Ceramics replacements
  - MACOR fuzz button spacer & Micro-D connector shell
  - AlN and Al_2O_3 circuit board
- Bare copper wires for RF and DC voltages

Individual addressing characterization on single ion

- Co-propagating Raman transitions
- Three central beams are illuminated expected separation 4.5µm
- A single ion is moved through the beam
- For each position the probability to flip the spin in measured



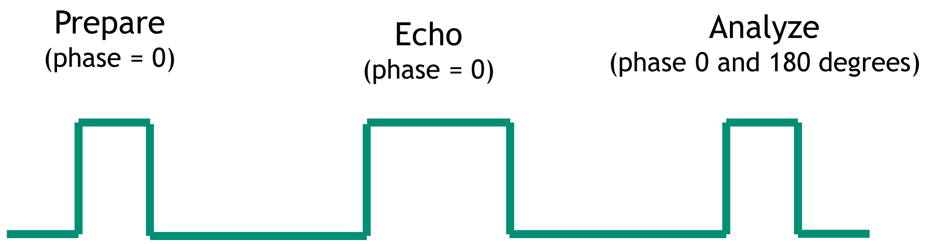


- Focal size as expected or slightly smaller
- Clear separation of individual beams
- Appears to be stable

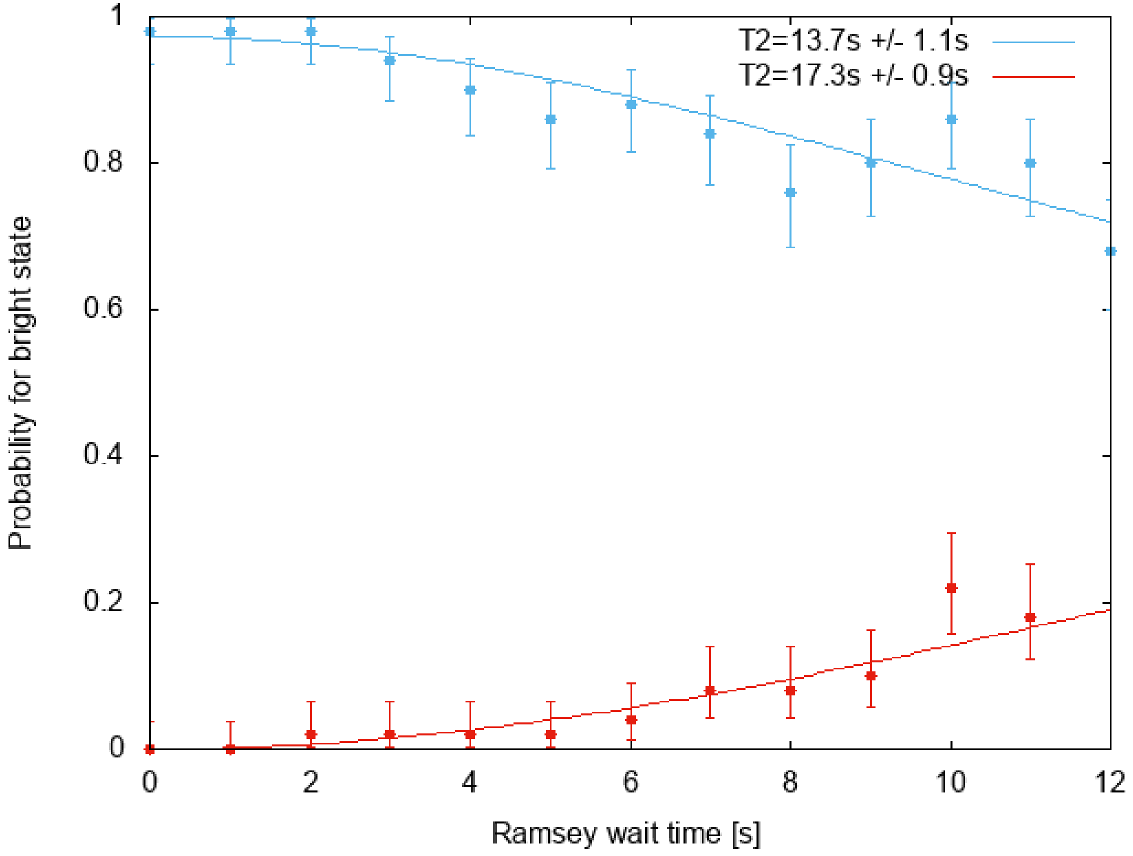
Microwave Coherence Time Measurement

- QSCOUT apparatus
- Microsemi Cs clock and Ultra-stable oscillator
- RFSoC output single-sideband mixed with Microwave Dynamics 12.6GHz source
- No explicit magnetic field shielding or stabilization

Ramsey Sequence

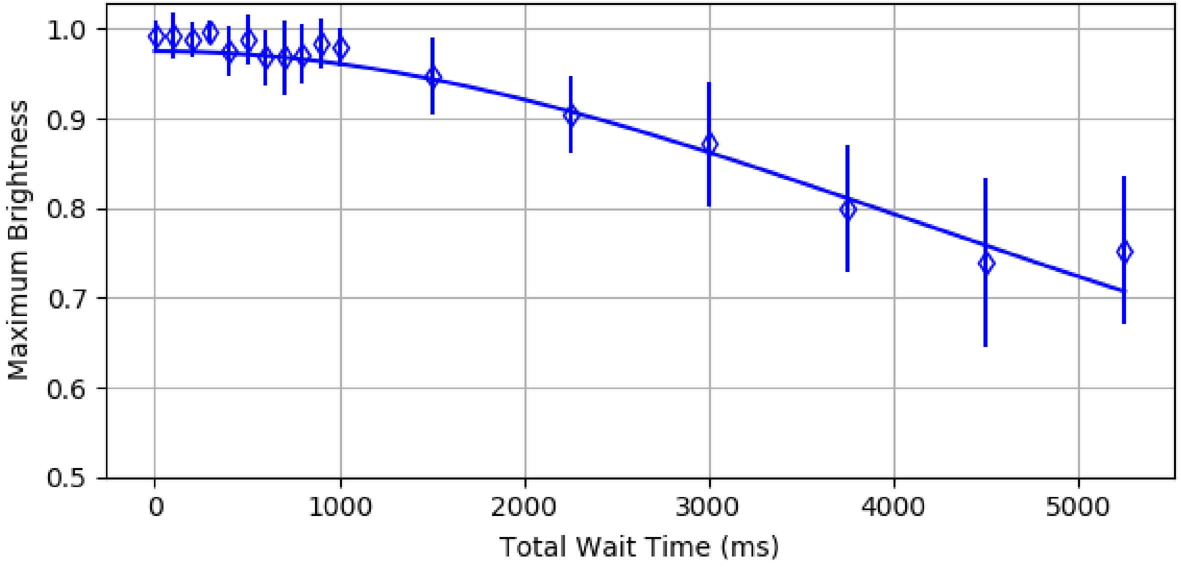


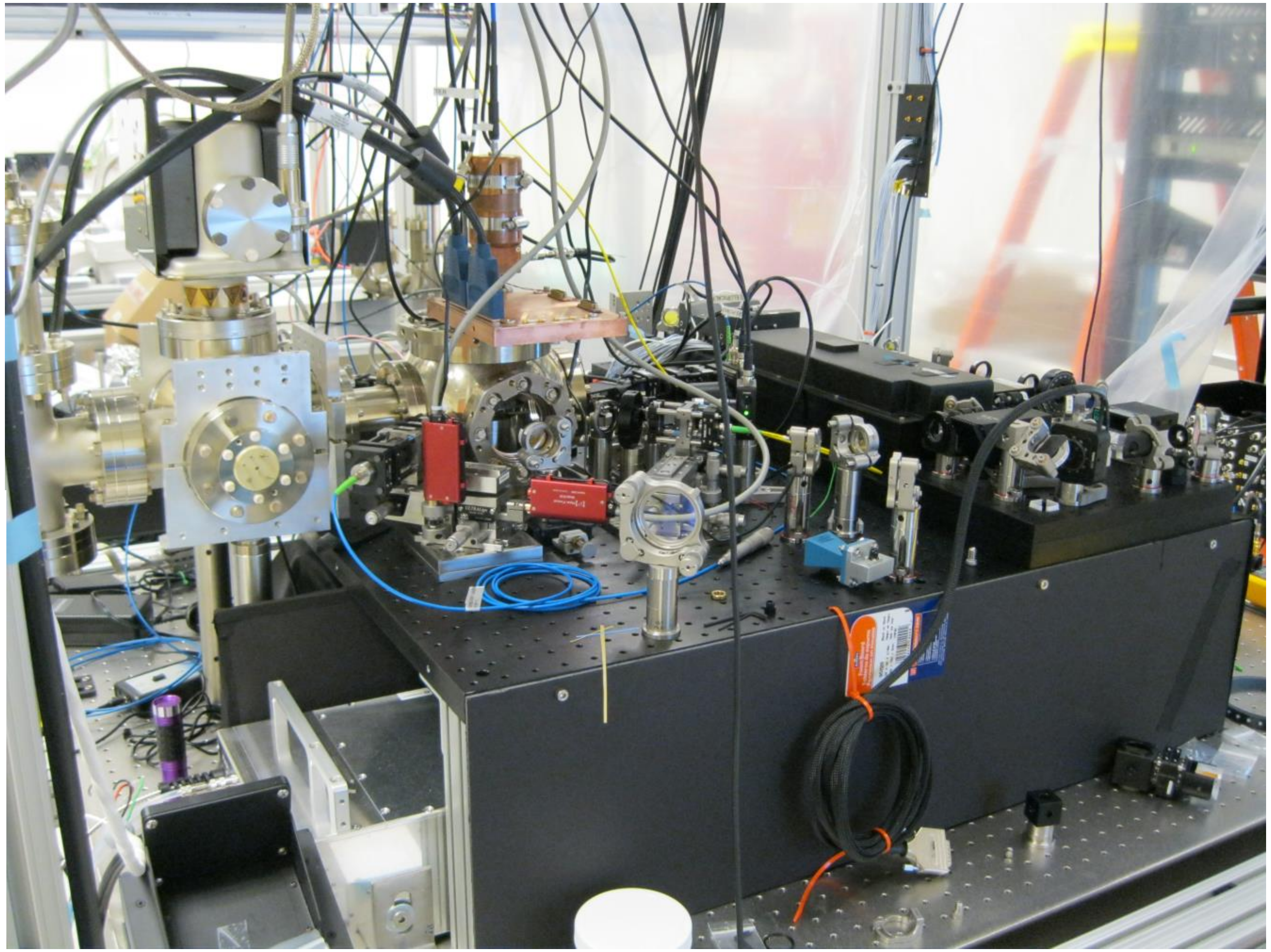
- Measured T_2^* coherence time 13.7s +/- 1.1s
- Bright state limited by ion heating in trap
- Dark state indicates a coherence time (excluding the effect of ion heating) of 17.3s +/- 0.9s



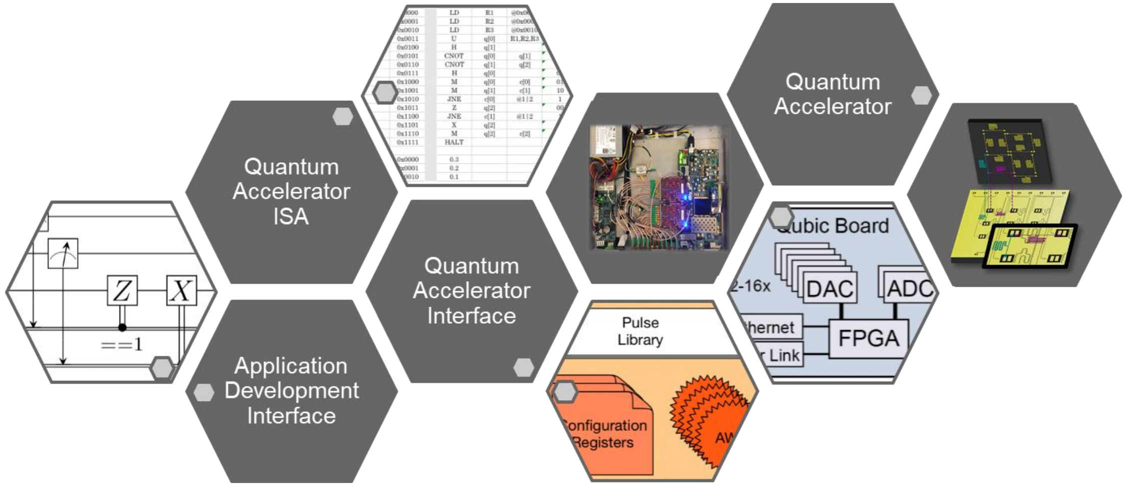
RFSoC Raman coherence time

- Raman transitions using large global beam
- Beat-note lock of Paladin 355nm pulsed laser realized on RFSoC
- RFSoC drives both tones needed to realize Raman transitions
- Coherence time > 5s





Advanced Quantum Testbed



January 2020

Mission

Integrate the current state-of-the-art in superconducting QPUs to answer key questions needed to develop extensible quantum systems

- Perfect select technology pathways

Industry

- Drive new fundamental notions in algorithms and quantum hardware

Academia

AQT

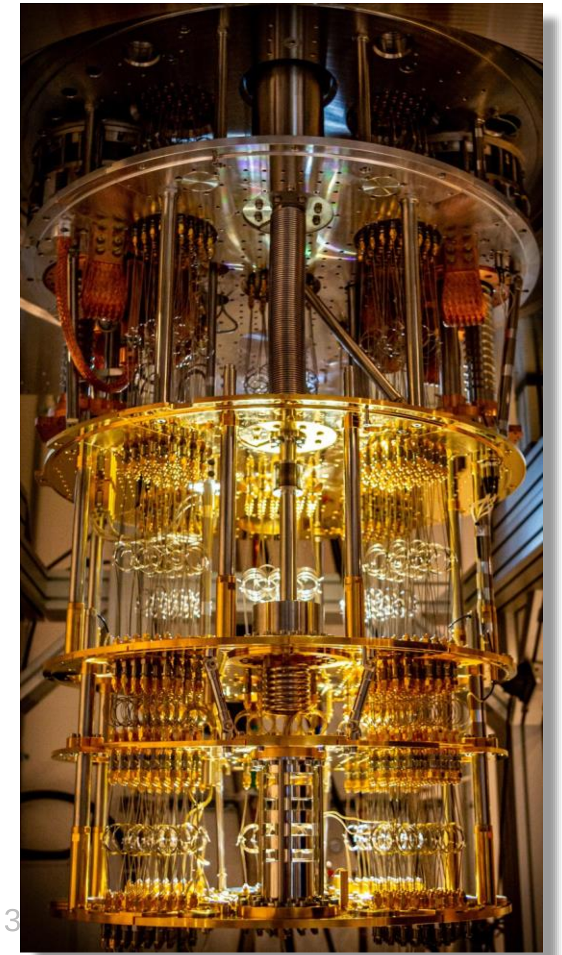
- **Assemble quantum technologies for fundamental scientific collaborations**
  - **Guides the development and enables the deployment of QIS capabilities into the DOE mission space**
  - **Assembles unique, broad-scope scientific capabilities into an adaptive, cutting-edge technology platform**
- **Provides deep scientific interaction to DOE SC scientists**

AQT Capabilities

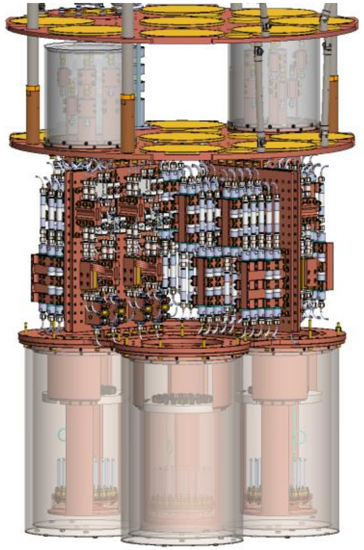
Hardware and Firmware

The Fridge

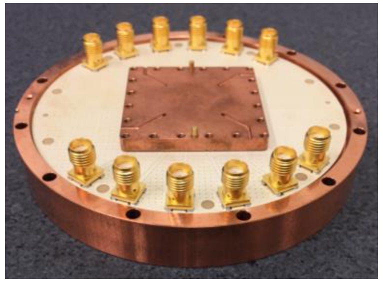
1mW Dilution System



Cold Stage



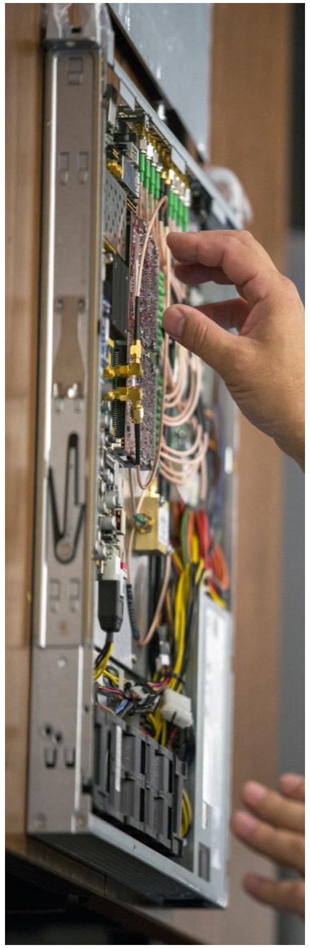
bleximo



The Controls

Commercial Solutions

LBNL ATAP



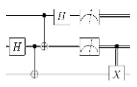
The People

LBNL, UC Berkeley, Bleximo, MIT-LL

Working with the AQT Team

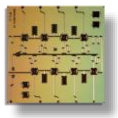
Commissioning Sequence for the Testbed

First Light
Benchmarking quantum systems



Jan 2020

Operation
Integrating the state-of-the-art



Co-design
Defining the path to operate deep circuits

Hardware Deployment

- Phase I: 8 - 32 qubit processors with varied topology; gate / readout fidelities > 95%; coherence > 50 μs
- Continuous hardware improvements leveraging wiring for 128 qubits with 99% fidelity

Trailblazing Computations

- Using circuits to determine quantum capacity: verification/validation, noise detection, suppression, mitigation, fault tolerance, …
- Quantum simulation experiments in optimization, computation, machine learning; materials science; and high-energy physics

Broad User Engagement

- Circuits which yield verifiable quantum advantage
- Defining the next generation architectures and algorithms via co-design.

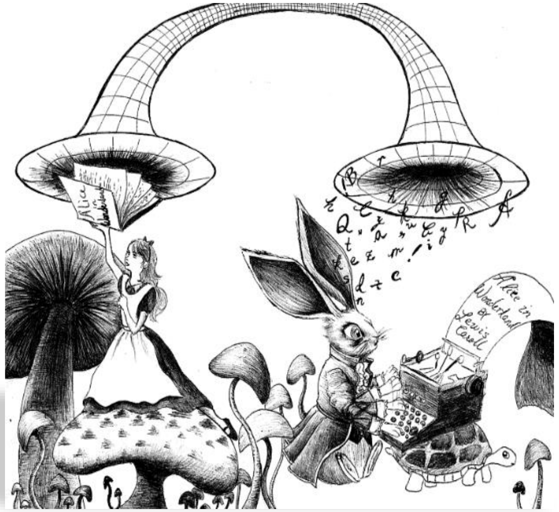
Quantum Simulations

Quantum gravity simulations on the AQT utilize reconfigurable hardware via ternary quantum logic

- Unitary operations model info scrambling in black holes
- Teleportation probes quantum mechanical scrambling (c.f. decoherence)
- Observed teleportation fidelities agree with quantum models of black hole dynamics:

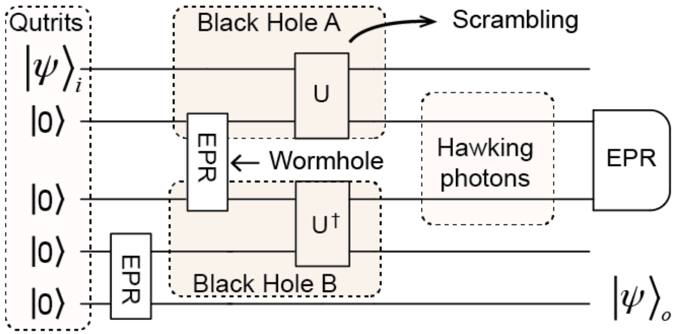
$$U_{Scrambling} = 0.56$$

$$U_{identity} = 0.34$$

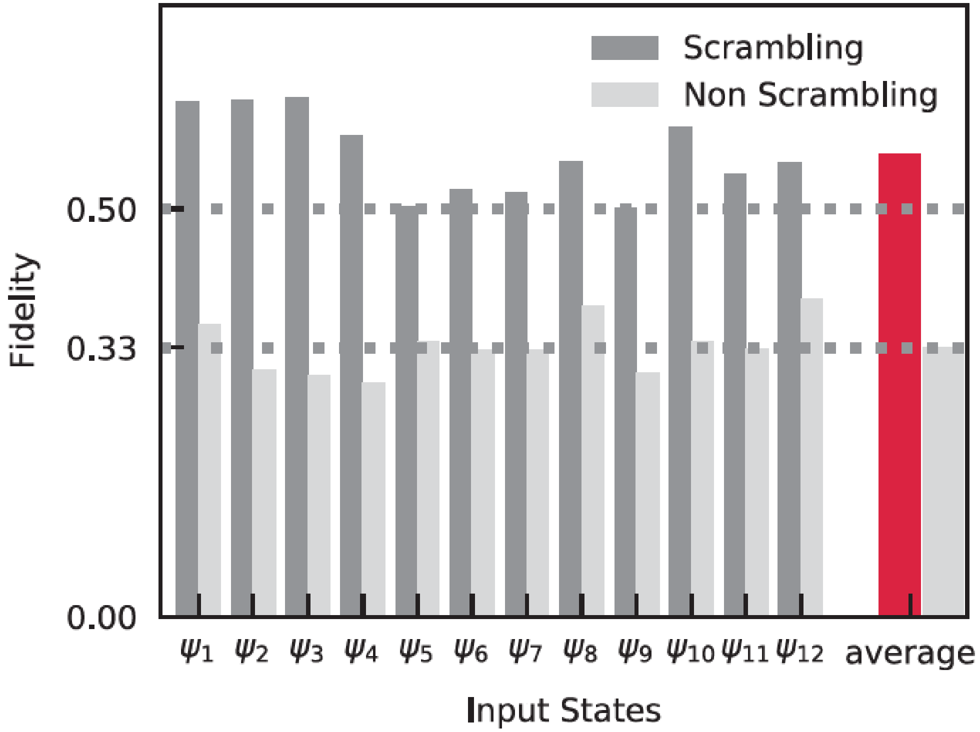


Decoding possible with quantum memory entangled with BH

Hayden & Preskill (2007)



Yoshida & Yao (2018)



AQT Annual Stakeholder Meeting 2020

Lawrence Berkeley National Laboratory April 29-May 1, 2020

Quantum Tutorials – Pre-Meeting

Lectures covering an introduction to gate-based quantum computing. Survey of superconducting qubits, hardware and scalability, program execution, and interfacing with quantum computers

Day One: Superconducting QC Landscape

Invited speakers and panel discussions covering the current status of superconducting QC and on design challenges for superconducting circuits.

Day Two: Advanced Quantum Testbed Program

Status of the AQT and current user projects. Breakout sessions to discuss hardware/firmware integration and algorithm implementation