MOOR INSIGHTS & STRATEGY

QUANTINUUM

QUANTINUUM UNVEILS ITS NEXT GENERATION QUANTUM COMPUTER

SUMMARY

Quantinuum recently released its second-generation quantum computer, the System Model H2 with an advanced ion trap shaped like an oval racetrack.

Like Quantinuum's earlier quantum computer models—the H0, H1, and H1-2—the new H2 system uses an isotope of ytterbium to create qubits for computation and barium ions for cooling. Like the previous models, it also uses a trapped-ion architecture in a quantum charged coupled device (QCCD).

In 2018, Quantinuum became the first company to use QCCD in a commercial quantum computer. Dr. David Wineland and his NIST group developed the design more than twenty years ago. In 2012, Dr. Wineland received the Nobel Prize in physics for the QCCD architecture and its ability to trap and manipulate atoms and ions efficiently.

Quantinuum's current QCCD performs quantum operations by moving a few ions at a time into one of four zones located in strategic locations along the oval racetrack. Moreover, these zones allow multiple quantum operations to be performed in parallel, which increases algorithm speed and efficiency.

Implementation of QCCD is difficult and extremely complex, but after building three models of quantum computers with different versions of the architecture, Quantinuum makes it look easy. Its developers have created the right combination of software and hardware and the right backend to run complex quantum circuits with high fidelity.

STEALTH RESEARCH PRODUCES UNEXPECTED RESULTS

Quantinuum has also been secretly using its German research team to perform topological research on non-Abelian anyons. Google also published a paper[1] describing the creation of topological ordered states using semiconductors shortly after Quantinuum announced its discovery. Only recently Microsoft also announced its intentions to build a quantum computer using a hardware form of Majorana topological qubits[2].

Research into topological quantum qubits began back in the early 1990s, when Alexei Kitaev proposed using quasiparticles called anyons for qubits with the potential to create error-free quantum computers. Over the years there has been much research by Google and Microsoft on quantum-related topology, but with only marginal progress.

H2's advanced architecture and features made it possible for Quantinuum and its partners to create a topological state to control its properties in real time. Researchers were thus able to demonstrate the creation, braiding and measurement of non-Abelian anyons. The research results were published in May [3].

BENCHMARKING

Quantinuum always runs a comprehensive battery of tests on new systems and improvements and publishes the results to validate its claims. That has been a longstanding policy of Tony Uttley, who has been president and COO of Quantinuum.

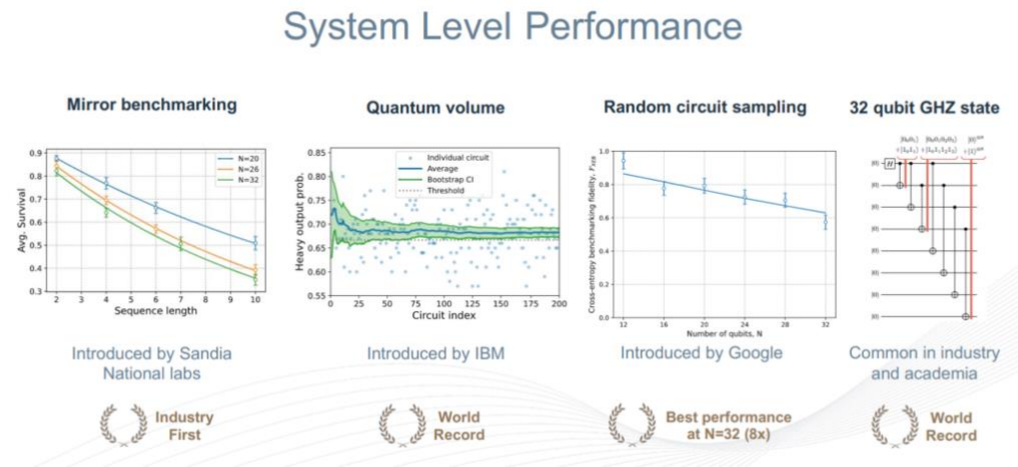
H2 was subjected to even more than Quantinuum's usual benchmarking this time. Here are the algorithmic, component and system benchmark tests performed on the H2.

[1] Satzinger, K., et al (2023). Realizing topologically ordered states on a quantum processor. *Science*, *374*(6572), 1237-1241. https://doi.org/DOI: 10.1126/science.abi83

[2] Nayak, C. (2023). Microsoft achieves first milestone towards a quantum supercomputer. *Microsoft Azure Blog*. https://cloudblogs.microsoft.com/quantum/2023/06/21/microsoft-achieves-first-milestone-towards-a-quantum-supercomputer/

[3] Iqbal, M., et al (2023). Creation of Non-Abelian Topological Order and Anyons on a Trapped-Ion Processor. *Arxiv*. https://arxiv.org/pdf/2305.03766.pdf

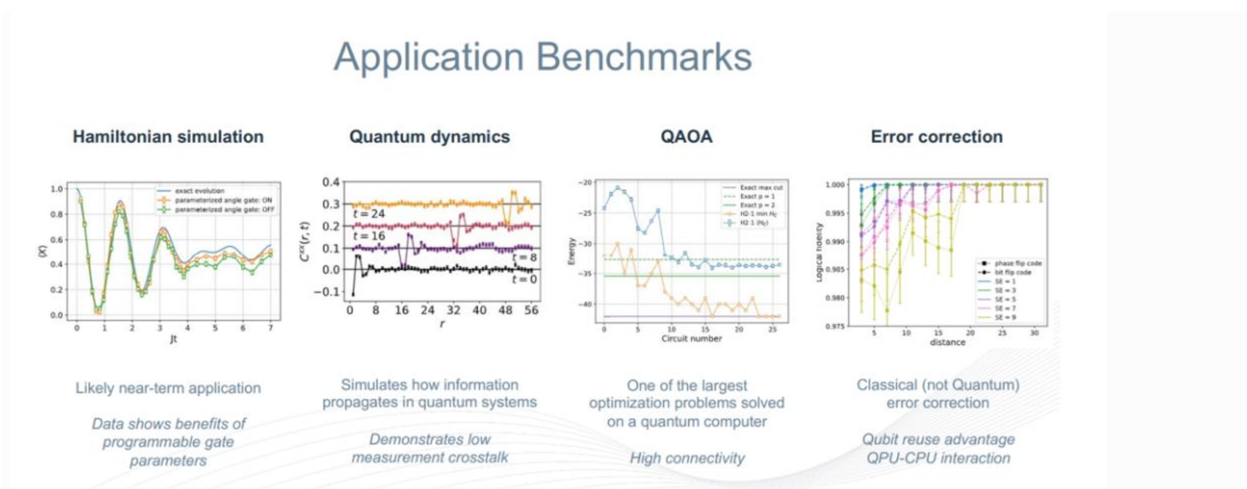
FIGURE 1



Source: Quantinuum

Quantinuum evaluated H2 system-level performance with mirror benchmarking, linear cross-entropy benchmarking, quantum volume and the creation of 32-qubit entanglement in a Greenberger–Horne–Zeilinger (GHZ) state. The GHZ state is an entangled quantum state with extremely non-classical properties, indicating a quantum computer's performance. The H-2 set a record for GHZ states by entangling all its qubits.

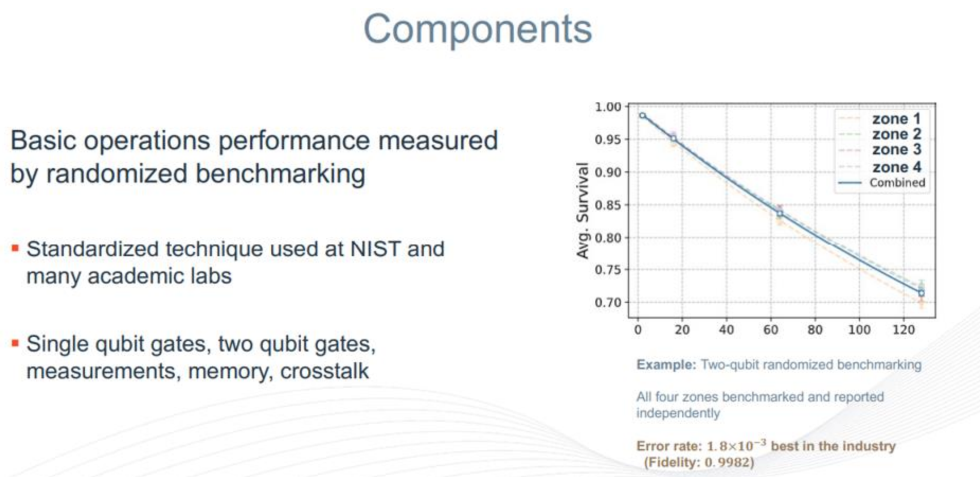
FIGURE 2



Source: Quantinuum

Application benchmarks consisted of well-known algorithms so third parties could easily compare the H2 and other quantum computers. These applications included Hamiltonian simulation, quantum approximate optimization algorithm (QAOA) tests, error correction on a repetition code, and dynamic simulations using qubit reuse.

FIGURE 3

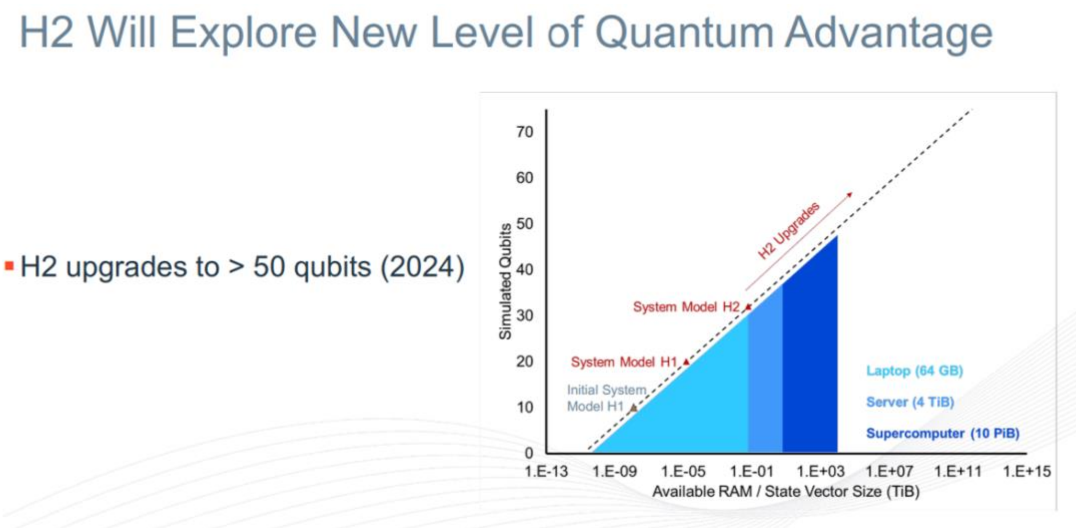


Component benchmarking was done with randomized benchmarking (RB) to estimate error rates of component operations in quantum circuits. RB repeatedly creates a gate and measures its state after each procedure to calculate the component's error rate. RB was used to measure H2's error rate for single-qubit gates, two-qubit gates, measurements, memory, and crosstalk errors.

BENCHMARKING INSIGHTS

In addition to providing performance metrics, benchmarking also allows comparisons to be made between different models of the same companies, but also between quantum computers from different companies. Benchmarks also help identify areas that need improvements and which components and systems are underperforming. As mentioned later, benchmarks helped Quantinuum to identify areas contributing the most system errors.

FIGURE 4

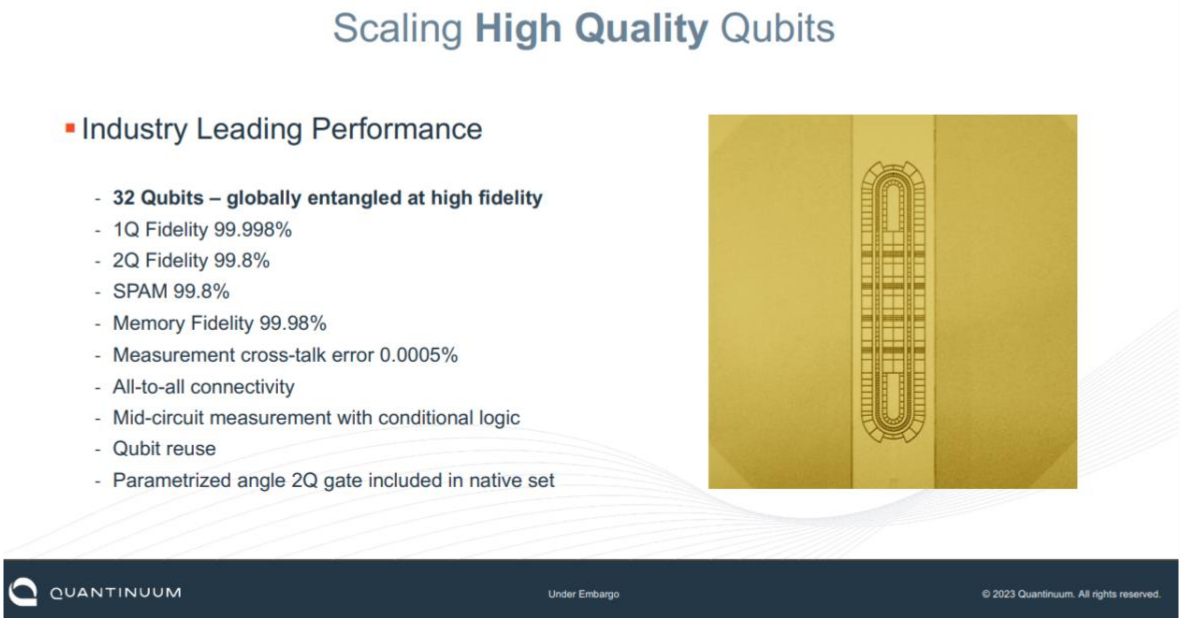


Source: Quantinuum

Assuming researchers can maintain or improve H2's fidelity and create workable solutions for all its known issues when scaling exceeds 50 qubits, future H2 releases will have a good chance of achieving quantum advantage.

H2 PERFORMANCE

FIGURE 5



The H2 has 32 high-fidelity qubits, compared to the H1-2's final qubit count of 20. Keep in mind that every qubit added to a quantum computer doubles its power. The H2's 12 additional qubits make it exponentially more powerful than the H1-2.

In addition to increasing the number of qubits, Quantinuum scientists also managed to reduce the physical resources associated with each qubit, and they did it without sacrificing any previous circuit fidelity gains. Its two-qubit gate fidelity is currently the best in the industry.

The H2 has a number of features in common with Quantinuum's previous H-series machines.

All-to-all qubit connectivity is an important feature that allows any qubit to be entangled with any other qubit or all qubits, an important feature for quantum mechanics and for running algorithms.

Mid-circuit measurement with conditional logic allows the outcome of a qubit measurement to control the direction of a computation. It plays a critical role in the execution of many quantum algorithms.

Qubit reuse allows the repeated use qubits in a computation. Deploying it reduces the number of qubits needed and increases computational efficiency.

High Quantum Volume is a hallmark of the H2. H2's QV is 65,536—double that of H1's record-breaking QV of 32,768, announced just a week before the H2 was released.

FIGURE 6

EVOLVING TRAP DESIGN

One of the most interesting features of the H2 is its racetrack geometry. However, other academic researchers have tested ion traps of similar geometries over the years. Even so, the H2's functional design and functionality belong exclusively to Quantinuum researchers. Each part of the trap serves a specific function. The H2 trap creates a highly controlled and coordinated environment to store, move and perform quantum operations on a single ion or pair of ions.

In addition to providing higher fidelities and more qubits, technologies used in the new oval QCCD design will contribute to future developments such as error correction. Per

Quantinuum's roadmap, there will be future dash releases of the H2 and three more whole generations leading up to the H5 by 2030.

It is also important to recognize that Quantinuum researchers have demonstrated that new ion trap designs can increase the number of qubits without sacrificing performance. Quantinuum has been developing the next generation of grid traps for some time now. It has already solved a significant grid problem by enabling ytterbium and barium ions to move through grid intersections together instead of separately. The solution also allows ions to make 90-degree junction turns as pairs without inducing excessive ion motion.

WHY ION TRAPS WITH GRID CONFIGURATIONS ARE NECESSARY

The number of ions that can be put on a chip is limited by the size of the chip. Scaling up the number of qubits means increasing the number of modular chips and linking them together, which forms junctions and intersections. The chips are expected to become smaller over time, allowing more connections to be packed into a single chip and more chips to be packed into a smaller area. If you look at Quantinuum's plans for its following three designs, you can see that the granularity of grids increases for each subsequent design.

FUTURE H2 IMPROVEMENTS

Quantinuum has compiled a list of unresolved issues it plans to address to improve H2's performance. These include additional QCCD scaling, better control of more electrodes, and improved laser light generation, delivery, and detection.

QCCD uses a special shuttle operation to move batches of ions into different trap areas. An improved design is necessary because the shuttle process is slow, and it consumes a large percentage of circuit time. I believe this will likely be one of Quantinuum's highest-priority improvements.

Benchmarking results can also serve to uncover weaknesses within a system. In the instance of the H2, it was determined that the primary source of errors lay in its two-qubit gates. Mind you, it is not uncommon for errors to be more prevalent in two-qubit gates compared to single-qubit gates. Entangling qubits to make two-qubit gates is complex and delicate, making it more vulnerable to noise-induced errors. However, researchers consistently endeavor to minimize errors, regardless of its origin, and I'm sure that Quantinuum's researchers are working hard to improve the performance of the two-qubit gates.

CONCLUSIONS

Quantinuum has published extensive testing data on the H2 and a wealth of information regarding timing, requirements and limitations for future versions. The documentation is comprehensive enough that it might give the impression that by following Quantinuum's steps, it might be possible to duplicate the H2. However, building another H2 from scratch would be very difficult without the cumulative knowledge gained from experiencing previous successes and failures of the step-by-step experimentation that went into its development.

Quantinuum's topological non-Abelian anyon research was made possible by the H2's advanced features, high fidelity and precision control, plus one of its earliest differentiating features—the mid-circuit measurement discussed earlier.

Quantinuum now has two research paths to follow: the quantum path and the topological path. Even though topological and quantum research can cohabit within the physical and quantum construct of the H2, any usefulness of non-Abelian anyon is likely many years away. On the other hand, trapped ions are on track to achieve quantum advantage in just a few years.

Most importantly, both technologies have the potential to achieve the real Holy Grail of quantum computing - fault tolerance.

IMPORTANT INFORMATION ABOUT THIS PAPER

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