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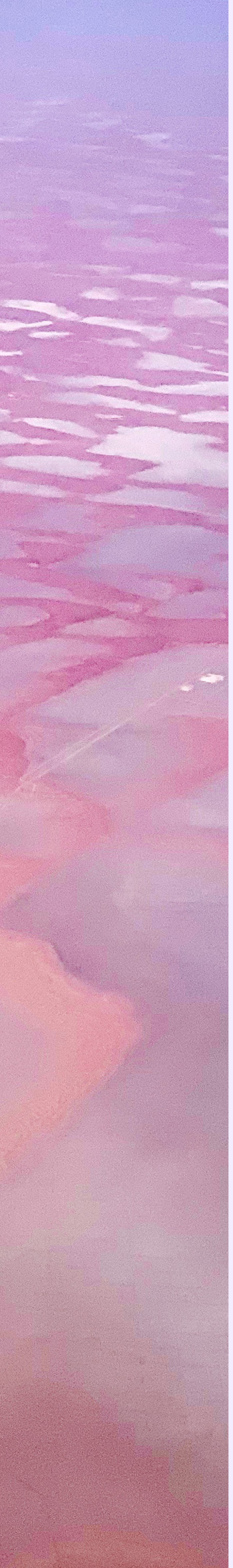
Exploring quantum use cases for the aerospace industry

Accelerating development of new products and advanced materials



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Foreword

Since the dawn of aviation, designing and building vehicles that can fly has pushed the limits of technology. In less than a century, powered flight made the leap from the sands of Kitty Hawk to interstellar space, propelled by innovation, ingenuity, and a continuing quest for greater speed and higher performance.

But just as aircraft performance eventually reaches limits set by the physical laws of nature, the aerospace industry is reaching the limits in what classical computers can do to solve extremely difficult problems, such as simulating chemicals and materials and computing wing turbulence.

Quantum computers harness the unique physics of the very tiny. Instead of storing information as binary bits, quantum computers use quantum bits, or qubits, which can exist in multiple states at the same time. With more qubits, the number of computational states represented in a quantum computer scales exponentially.

IBM demonstrated quantum utility in 2023.[1] Quantum utility is when a quantum computer is able to perform reliable computations at a scale beyond brute force classical computing methods that provide exact solutions to computational problems. Previously, these problems were accessible only to classical approximation methods.

IBM is working with enterprises around the world to explore the capabilities of quantum computers in areas as diverse as advanced materials, life sciences, finance, and engineering.

Not too long ago, many experts doubted that an aircraft could break the sound barrier. Nevertheless, Chuck Yeager and his team proved that supersonic flight was possible.[2] Now, with the maturation of quantum computing, we are on the threshold of breaking through computing barriers that were once thought impossible to breach.

Please take a moment to read and consider our insights on the applicability of quantum computing solutions to the aerospace industry. The use cases that follow only begin to scratch the surface of quantum computing's potential for aerospace. Meeting the challenges and delivering on the opportunities of our industry will require new thinking and new approaches to problem solving—a pioneering mindset that has always defined the aerospace community.

This pioneering mindset has been inherent in the aerospace industry from its inception and I'm confident that this spirit will continue with further identification of impactful applications of quantum computing beyond the following use cases. As President Kennedy noted in his 1961 inaugural address, "the problems of the world cannot possibly be solved by skeptics or cynics whose horizons are limited by the obvious realities. We need men who can dream of things that never were and ask why not?"

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Quantum computing technology is approaching takeoff speed for transformational aerospace applications.

Executive summary

Now is the time to get ready for quantum computing

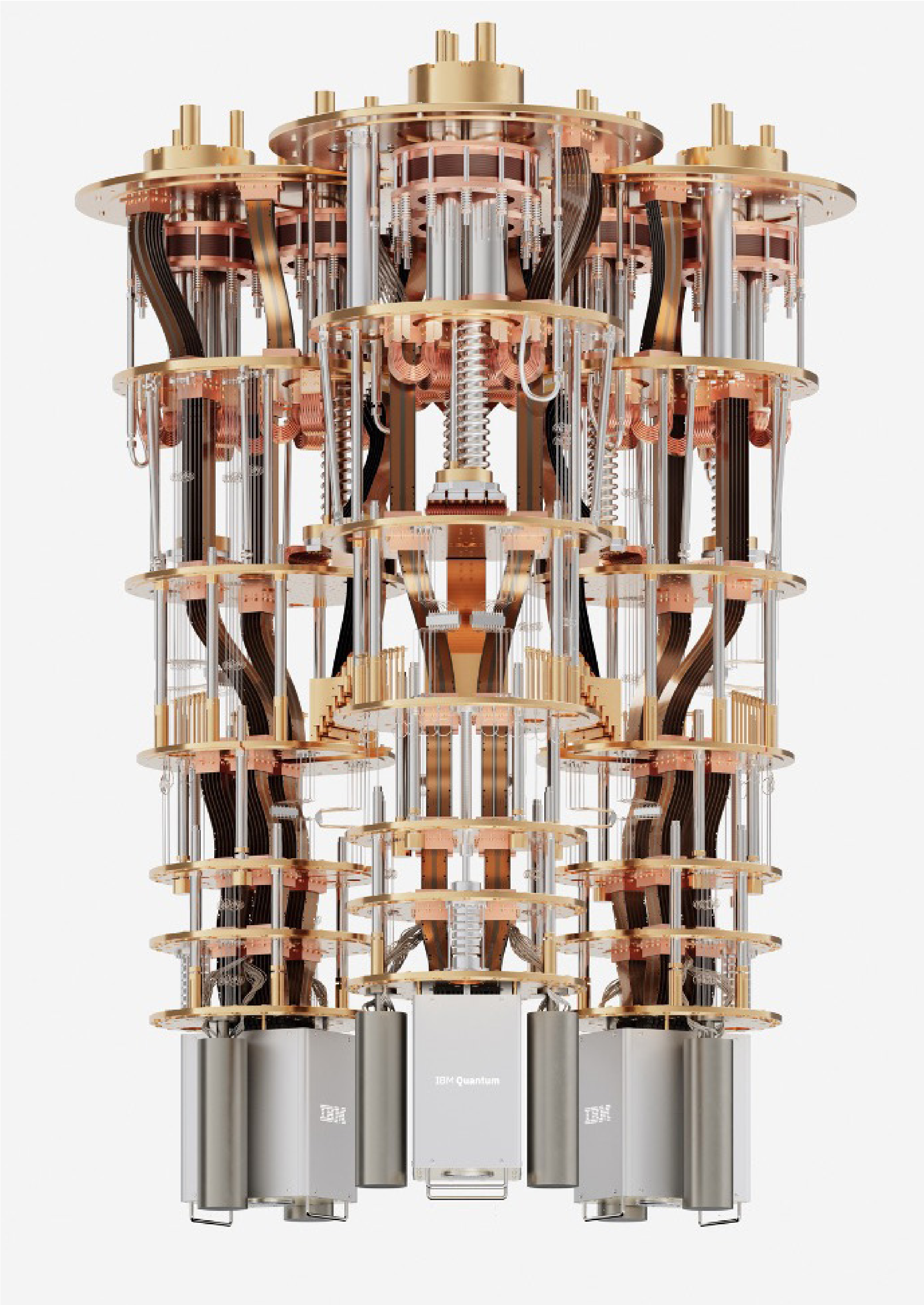
- By achieving quantum utility in 2023, quantum computers can provide reliable, accurate solutions to problems beyond the reach of brute force classical computing approaches. Previously, these problems were accessible only to classical approximation methods—usually problem-specific approximation methods carefully crafted to exploit the unique structures of a given problem.
- The first quantum applications are potentially expected before the arrival of quantum error correction (QEC), which is planned for 2029 on the IBM Quantum Roadmap (see Figure 1 on Page 6). Once QEC is available, the applications space is expected to greatly expand.
- Taking advantage of these quantum capabilities requires developing new workflows and a quantum-ready workforce. Based on a multi-year learning and development curve, organizations starting now can position themselves to intercept the window for first applications.

First movers are expected to capture most of the value

- Quantum computers are complex, state-of-the-art machines that require specialized teams to operate. When these computers start executing the first compelling applications, demand is expected to be high, and access is expected to be limited.
- When demand exceeds supply, organizations that have not already established access to quantum computers may face long waits. Without access, applying quantum methods, developing and attracting quantum-ready talent, innovating and securing intellectual property may not be possible with this potentially game-changing technology that can lead to competitive advantage.[3]

Quantum computing has high potential to disrupt the aerospace industry

- The business impact of quantum computers is expected to go beyond simply reducing computational runtimes.
- Quantum computers have the potential to accelerate product development and advanced materials development by replacing current time and labor-intensive experimental methods with faster, more efficient computational methods enabling numerous virtual checks on manufacturability and supportability concerns.
- The scope of this potential disruption requires reexamining assumptions and identifying high impact quantum use cases for aerospace organizations.



IBM Quantum System Two with Heron Processors

The future of the aerospace industry and the need for speed

Currently growing at one of the most rapid rates in its history, the global aerospace and defense industry is projected to bring in revenues of $1.4 trillion by 2030.[4] In the commercial sector, growth is fueled by increasing demand for air travel. For example, commercial aircraft manufacturers have orders for over 15,700 aircraft and it will take 13 years to address the open order backlog at 2023 delivery rates.[5]

Demand is growing for aerospace products—but so is the time frame for developing more complex aircraft types. For example, increased certification oversight and requirements have extended development cycles for major aircraft manufacturers from five to six years in the 1980s and 1990s to more than eight years today.[6]

Timelines have become even longer in the US defense sector. Between 1945 and 1974, the mean time to develop an aircraft from start to initial operational capability (IOC) was five years. Since then, time to IOC has increased dramatically. The McDonnell Douglas F-18 Hornet program took 11 years, the Northrup B-2 Spirit took 16 years, and the Lockheed Martin F-22 Raptor took 20 years to become operational.[7]

Today, as costs escalate along with longer development cycles, aircraft designers are exploring and adopting cutting-edge technologies, such as autonomous devices, ultralight materials, robotics, alternate fuels, and electric aircraft. However, the scientific and engineering complexity of these technologies and products presents unprecedented design, manufacturing, and qualification challenges.

In a business environment where the maxim “time is money” is more relevant than ever, combining the proven power of classical computing with the growing potential of quantum computing could deliver paradigm-shifting breakthroughs for the aerospace industry.

Perspective

Classical and quantum computing: Combining the best of both computing worlds

While quantum computers can excel at running certain algorithms or simulating natural processes, they will still run alongside classical computers. Together with advances in AI, quantum computing completes a triad of technologies where classical bits, quantum qubits, and AI neurons will create new synergies to drive the future of computing for the aerospace industry.

Introduced in the 1940s, classical computing represents information in strings of zeroes and ones and uses a set of logical operations to manipulate these strings. In 1994, classical computing evolved to the point where the first aircraft to be designed entirely by computer-aided design tools made its first flight, the Boeing 777.[8]

Initial applications for quantum computers were articulated at a conference co-hosted by IBM and MIT in 1982. At this event, theoretical physicist Richard Feynman lectured on the potential advantages of simulating quantum systems with quantum computers. Twelve years later, Peter Shor presented a quantum algorithm that could efficiently factor large numbers that outperform classical algorithms. In 2001, IBM and Stanford University demonstrated the first implementation of Shor's algorithm on a seven-qubit processor.[9]

Quantum computing is based on quantum physics—the science that studies the behavior of subatomic matter. By harnessing the properties of subatomic particles, these computers offer a growing potential to solve problems too big, too complex, or too hard for today's fastest supercomputers.

The increased compute power of quantum computers partially stems from the ability of quantum particles to exist in superposition—in multiple states at the same time—as well as their ability to link through a phenomenon known as quantum entanglement. Superposition allows a quantum computer to make large numbers of calculations simultaneously—a quantum superpower that can enable exponentially greater computing speed and capacity than the binary bits used by classical computing.

The quantum continuum: Moving from utility, to advantage, to transformation

At the start of this decade, quantum computers were experimental devices and primarily used to study quantum computing itself. But that changed in June 2023, when IBM and UC Berkeley published "Evidence for the utility of quantum computing before fault tolerance."[10] This marked the arrival of quantum utility, which means that quantum computers can perform reliable computations at a scale beyond brute force classical computing methods.

After quantum utility, the next step is to identify the hard problems that are valuable to industry and solvable with quantum computation. IBM anticipates that the first instances of quantum advantage will come from engaging with a quantum ecosystem of partners from academia and industry.

Quantum advantage occurs when a computing task of interest to business or science can be performed more efficiently, more cost effectively, or with better quality by using quantum computers. This is the inflection point where quantum computers, combined with classical systems, can perform significantly better than classical systems alone.

The next few years will be critical on the hardware side of quantum development. Qubits in today's machines have limited coherence times and can only be kept in quantum states for short periods. This instability creates "noise" resulting in the accumulation of faults during quantum calculations. Currently, these faults are addressed by error handling methods such as quantum error mitigation—post-processing techniques that allow researchers to counteract the effects of noise after computations are complete.

Quantum error correction is a future capability that can allow quantum computers to correct errors as they appear during computations. Steady progress in error correction is projected to lead to the demonstration of an error-correcting quantum computer by 2029, according to the extended IBM quantum roadmap (see Figure 1).[11]

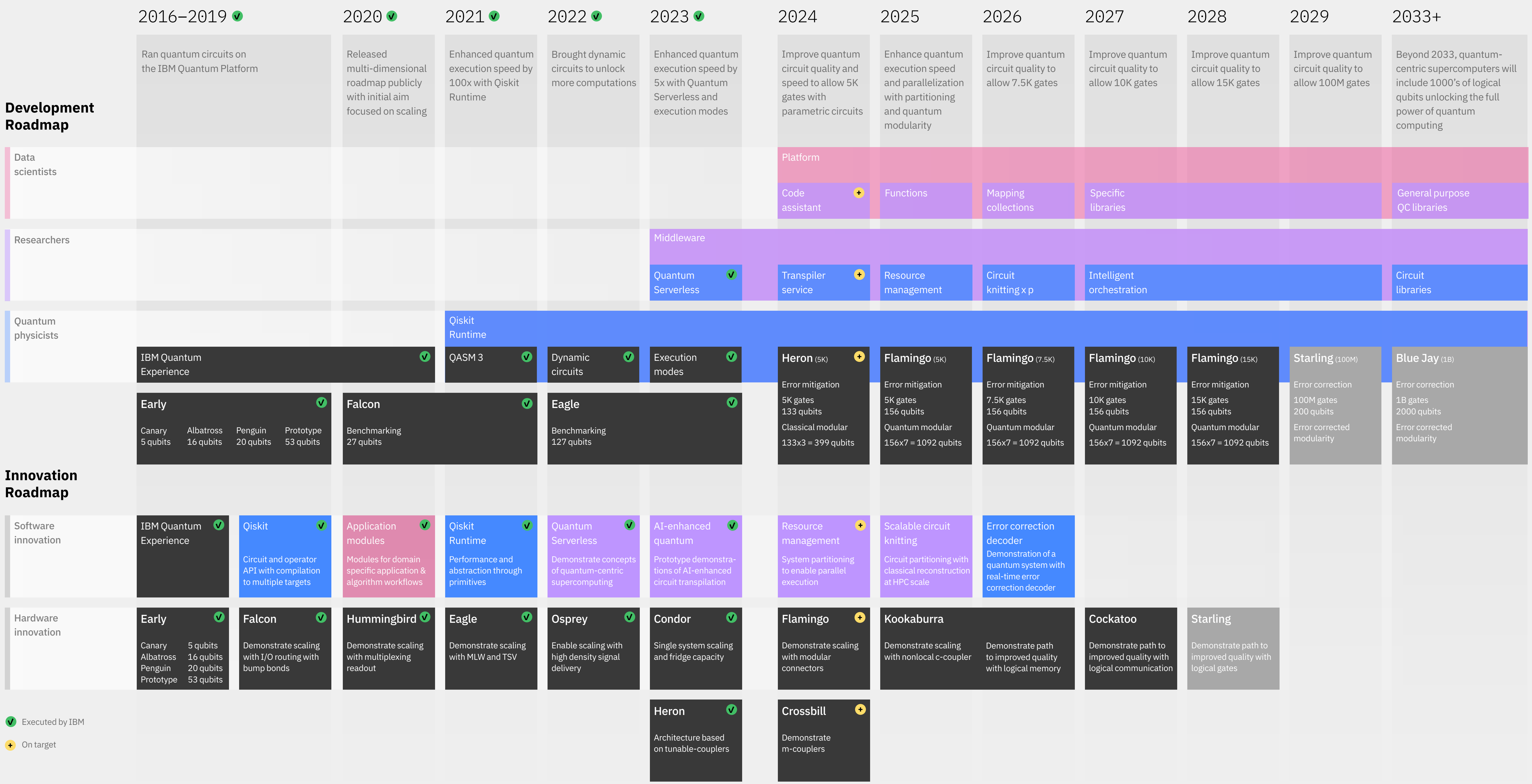
The quantum methods, algorithms, and end-to-end workflows needed to solve many real-world industry problems have been established. Now, the challenge is scaling these approaches to practical sizes on rapidly developing quantum hardware.

Perspective

Gaining altitude: The extended IBM quantum roadmap

This extended IBM quantum roadmap shows how IBM aims to make quantum computers more useful in the coming years on the way to quantum-centric supercomputing. The roadmap has two sections to track this complex mission. The Development Roadmap details major releases to quantum computing users, and the Innovation Roadmap details the technology milestones required to deliver them.

The Development Roadmap has three layers. The bottom layer represents hardware, the middle represents software, and the top layer represents applications. For most aerospace organizations, most of the value of quantum computing should come from the top applications layer.



The aerospace application runway: Four use case examples for quantum computing

The years prior to 2029 will provide time for aerospace leaders to identify use cases that could transform product development and other key capabilities. Prioritizing the right use cases—those that can disrupt and transform the industry—is critical to deriving commercial value from quantum computing.

Many potential application areas have been identified that could benefit from the unique properties of quantum computing. Three quantum computing application areas are of particular interest to the aerospace industry. One application area, advanced math and complex data structures, has two important sub-areas. These areas, which have experienced significant development, include:

Advanced math and complex data structures

Linear algebra: Accelerating computational fluid dynamics, finite element analysis, and other systems modeled by large sets of simultaneous linear equations.
Machine learning: Generalizing hard-to-see patterns when datasets are scarce.

Search and optimization

Identifying more optimal solutions in hard-to-search solution spaces.

Simulating nature

Simulating the quantum mechanical universe.

Use case examples follow for each of these application sub-areas to illustrate the range of potential design, engineering, manufacturing, and business impacts that quantum computing may have on aerospace organizations.

Use Case 1

Aircraft simulation with computational fluid dynamics and finite element analysis

Transforming computational fluid dynamics and finite element analysis beyond design confirmation to simulate high-fidelity designs

A major challenge in aircraft development is that most development costs and timelines are determined by decisions made early in the design process—when the least amount of information is available. More will be understood once the design is manufactured and tested, but the design-manufacture-test cycle is an iterative process, and a single iteration can take months or years.

Computational fluid dynamics (CFD) and finite element analysis (FEA) can reduce the number of development iterations. However, with runtimes of days, weeks, or more for single designs, CFD and FEA models must often be reduced and defeatured to shorten runtimes, but that reduces simulation accuracy. As a result, the most accurate, fully featured CFD and FEA models are impractical for design exploration. If they are used, they are typically only applied to design confirmation.

When fully realized, quantum algorithms have the potential to accelerate CFD and FEA computations and may make it possible to accurately simulate multiple, high-fidelity designs against both the performance requirements for the item and its inherent manufacturability. Simulating multiple designs can transform the roles of CFD and FEA from design confirmation to design exploration or provide the ability to run many virtual cycles, reducing overall development costs and timelines.

Moreover, an ability to accurately predict aircraft performance with high-fidelity simulations may produce insights that enable better decision-making earlier in the development program. This can have enormous repercussions in overall program cost and time. A failure that is discovered later in a development program requires design and manufacturing changes to one component, which then impacts other components. This leads to further design and manufacturing changes and increases development time and cost. If too many changes are required, program goals may not be achieved, and the program may be cancelled.

Viewed from this perspective, the disruptive potential of quantum computers on aircraft performance simulation is high, with many ways to apply this capability throughout the aerospace product development process. When quantum computing is available at scale, designers and engineers may finally be able to explore, iterate, create, and qualify a range of new products, unlimited by the constraints of classical computing.

Use Case 2

Topology optimization design

Quantum computing could significantly speed up aerospace design optimization and shorten the design-manufacturing-qualification-learning cycle

Today's aircraft and spacecraft are some of the most complex systems ever made. Working on hypersonic flight, low observability aircraft, remotely piloted systems, and other advanced technologies is very challenging in a classical computing environment. Fully optimizing aerospace design requires exploring huge, multidimensional design spaces for parts such as wings, control surfaces, landing gear, and propulsion systems against a variety of requirements for performance, manufacturability, and supportability.

Topological optimization greatly expands the traditional design space. Freed from traditional design approaches, these designs often do not look like typical human-engineered constructs or machines—instead, they often resemble the structures of living organisms. Because these design spaces are large, identifying optimal designs is challenging. Classical computing algorithms can have difficulty in scaling to large problem sizes and can get stuck in suboptimal solutions.

Quantum algorithms have the potential to search vast design spaces more widely and quickly to discover more optimal solutions. Together, quantum-powered simulation and optimization could shorten aerospace product development schedules and help create more efficient, higher-performance aircraft and spacecraft designs.

One of the highest-impact benefits may include the ability to build more lightweight structures, which can offer performance benefits including fuel efficiency, faster lift-off, reduced wear, and greater sustainability. Even a 10% reduction in the weight of a fuel tank or wing structure would be a significant gain.

In a recent demonstration of topology optimization on an IBM quantum computer, a manufacturer demonstrated a scalable quantum approach to optimize thermal conductivity by calculating the conductivities of different structures simultaneously and then extracting the optimal structure.[12] This approach has the potential to scale more favorably than brute-force classical approaches of individually calculating the conductivities of each structure.

Since every design must be tested for optimality, this use case is tightly coupled with evaluation methods such as CFD or FEA simulations. Topological design itself is expected to have an evolutionary impact on the aerospace industry. However, when connected with quantum-powered CFD and FEA, the total impact could be enormous.

Use Case 3

Accelerated materials development

Accelerating the development of new materials by predicting performance under real-world conditions

Often, the biggest jumps in the cost-performance curves of new products come with the introduction of new materials such as carbon fiber composites. When the Boeing 787 and Airbus A350 aircraft were rolled out, their extensive use of these materials marked a revolutionary material advancement in aviation. But it came with a very high price tag. The 787 took nine years to get to market at a final cost of $5.5 billion. The A350 was delayed by over two years, and the cost grew from $5.3 billion to nearly $10 billion.[13]

What if other aerospace materials with advanced capabilities and higher cost-performance curves could be investigated, tested, and developed more rapidly, at lower cost? This would be a game-changer, especially in the current aerospace development environment where qualification is challenging and limited datasets for new materials inhibit the exploration and exploitation of new materials.

One vision is that quantum computers transform materials development from a largely empirical to a computational discipline. On these systems, exploration is conducted computationally, and the role of experiment is moved from exploration to confirmation. This shift could greatly accelerate materials development.

Typically, new material development is conducted by costly and time-intensive trial-and-error empirical methods. Development can take decades. Unlike many other fields, computation is difficult to apply to materials development because many aspects of materials are determined by their quantum nature. On classical computers, material simulations of quantum-determined properties often scale exponentially with simulation size, and those simulations quickly become intractable. However, the capabilities of quantum computers map naturally to the quantum simulation of materials. The result: material simulations scale at a much more manageable polynomial rate with simulation size.

Quantum simulation methods for new materials could predict responses to environmental conditions, such as UV light exposure, temperature variations, and chemical exposure, enabling faster identification of materials that are more likely to pass qualification at earlier development stages. In addition, other quantum algorithms could assist the design and development of advanced materials with specific properties, such as lightweight and high-strength composites or durable materials for high-performance engines. This could lead to developing new materials for structures, propulsion systems, and energy storage, ultimately helping to improve performance and efficiency.

When quantum computers are ready to tackle materials optimization problems at scale, it could have revolutionary and disruptive implications for the aerospace industry, not only in terms of step changes in aircraft or spacecraft performance, but also in cost savings and accelerated development schedules.

Use Case 4

Machine learning for manufacturability and quality control

Confirming part compliance with more accuracy and smaller datasets to enable more rapid scaling

Ensuring that manufactured parts meet quality standards is crucial in any industry, but aerospace organizations must meet higher quality standards than most other fields. Deficient aircraft parts can lead to regulatory and safety issues, making manufacturability and quality control top priorities.

While aerospace specifications are extremely exacting, manufactured components can deviate from design intent. That's why evaluation and integration of complex manufacturing data is required to confirm that parts coming off the line comply with the original design. Alternatively, revealing the "quality tradespace" to assess observed deviations against cost, schedule, or performance facilitates a richer insight into the impacts of accepting certain levels of risk.

Quantum computing offers the potential to enhance machine learning (ML) and optimize pattern recognition algorithms used to inspect aerospace components. On some datasets, quantum ML models have demonstrated improved accuracy with less data when compared to classical ML counterparts.[14] As a result, quantum ML is a good fit for applications where accuracy is important and/or data is hard to obtain.

Anomaly detection fits within this description. Anomalies are by nature rare, so gathering large datasets is challenging. Nevertheless, accurately detecting anomalies in manufacturing offers huge cost benefits. Automated, state-of-the-art computer vision inspection systems typically yield false positive rates that often exceed 10% to 15%, an unacceptably high rate of good parts being labeled bad.[15]

Quantum computing has high potential for advancements in anomaly detection, virtual metrology, and predictive maintenance for aerospace systems. Although not foreseen as disruptive as other use cases, the magnitude of value derived from quantum-powered ML for manufacturability and quality control could have bottom-line significance to the aerospace industry.

Action guide

01

Recognize the disruptive potential of quantum computing.

Continuing advances in quantum computing have the potential to disrupt the aerospace industry and solve problems that have long been considered impractical by using classical computing systems alone.

02

Start working with quantum computers now.

First movers could have a competitive advantage; early followers may have long waits for quantum computing resources and miss opportunities to innovate and create intellectual property assets. The learning curve is steep—it can take three to four years to master quantum and turn mastery into applications. By starting now, readiness can be achieved within the expected window of the first applications and shortly before the arrival of more powerful quantum algorithms enabled by quantum error correction.

03

Identify key opportunities and threats.

Quantum computing offers potential for a wide variety of applications, and it is important to focus on the critical aerospace quantum use cases for your organization. Identifying the disruptive potential of a paradigm shifting technology like quantum computing is challenging, and it requires reconsidering old assumptions and revisiting established workflows.

04

Build in-house expertise to monitor quantum and inform decision making.

Quantum computing is progressing rapidly, and developments require regular monitoring. To stay current, each organization needs subject-matter experts who understand your organization's technology strategy, quantum hardware and algorithms, key aerospace quantum use cases, and the current state-of-the-art classical computing methods for those use cases. Quantum talent is hard to find, and internal upskilling is a more viable approach to developing quantum teams. Integration speed will highly depend on expanding the quantum talent pool of each organization.[16]

05

Join a quantum computing ecosystem to support quantum readiness.

The quantum computing stack is often too much for single organizations to master. Joining an ecosystem where hardware, software, algorithms, and application development can be shared is preferable. The application space is wide, and many challenges can be shared without conflicts of interest. Now is the time to find partners in industry, academia, and government that support your quantum computing strategy.

Methodology

In May 2024, representatives from across the aerospace industry participated in a two-day workshop sponsored by the US Air Force Research Laboratory. Workshop participants included industry thought leaders from: Boeing, Collins Aerospace, Dassault Systèmes, GE Aerospace, Lockheed Martin, National Institute for Aviation Research, Northrup Grumman, Ohio Aerospace Institute, Parker Aerospace, Raytheon Technologies, Spirit AeroSystems, and Wichita State University.

During the workshop, the participants collaborated, explored, and developed strong quantum use cases for aerospace. After discussing over 25 candidate use cases that could drive value, the participants identified and prioritized the four leading use cases explored in this paper.

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DRIVE is a consortium which facilitates the US Air Force's commitment to the transformation of digital practices across its acquisition, operations, and sustainment enterprises. Called DRIVE—Digital Research, Innovation, Validation and Experimentation—the consortium is executed in collaboration with the Air Force Research Laboratory (AFRL) and the AFMC Digital Transformation Office to establish an ecosystem for mitigating transformation risks in US Air Force programs and activities.

The goal is to foster collaboration between US Air Force organizations, original equipment manufacturers (OEMs), technology providers, academia, and other government agencies managing the development and demonstration of processes, tools, and architectures supporting transformed acquisition and sustainment, and identifying critical business, policy, and cultural constraints.

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