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Steady progress in approaching the quantum advantage

Quantum technology could create value worth trillions of dollars within the next decade. The third annual *Quantum Technology Monitor* synthesizes the latest opportunities in this burgeoning field.

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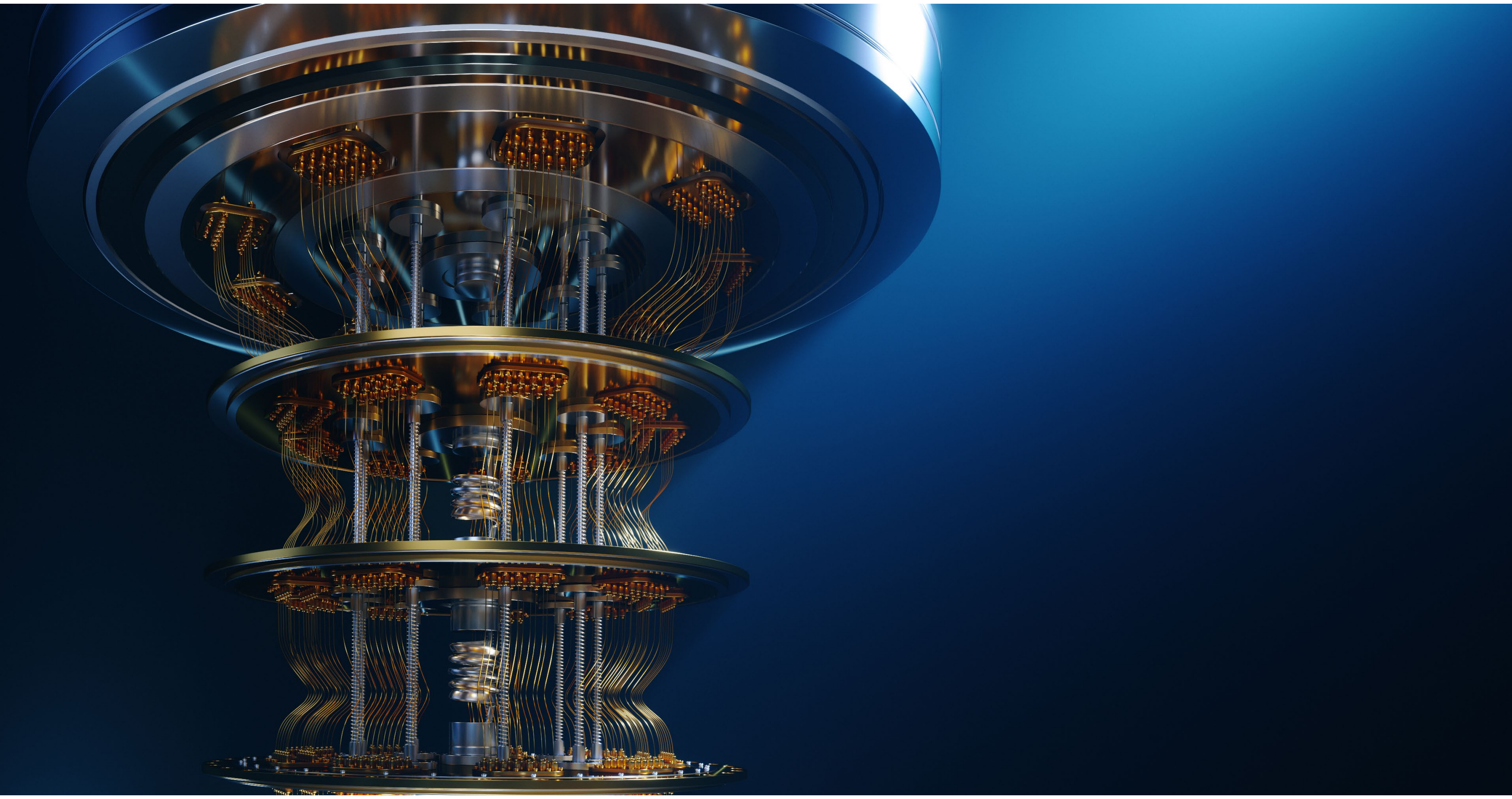

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A year of strong funding coupled with sturdy underlying fundamentals and significant technological advances reflected strong momentum in quantum technology (QT).

Updated McKinsey analysis for the third annual *Quantum Technology Monitor* reveals that four sectors—chemicals, life sciences, finance, and mobility—are likely to see the earliest impact from quantum computing and could gain up to $2 trillion by 2035 (see sidebar "What is quantum technology?").

Private and corporate funding for quantum technology start-ups in pursuit of that value, however, took a notable dip. Investments decreased 27 percent from the previous year, with the biggest drop in quantum sensing start-ups. This decline, however, was smaller than the 38 percent decline in all start-up investment worldwide. Notably, the majority of funding (62 percent) went to companies founded five or more years ago, reflecting a shift in investments toward more-established and promising start-ups, with a focus on scaling them.

In contrast to the private sector, public investments increased more than 50 percent over 2022, making up almost a third of all investments in quantum technology. A range of countries, led by Germany, the United Kingdom, and South Korea, have announced significant new funding for QT development, bringing the global public funding total to date to about $42 billion.

Underscoring this momentum was continued strong growth in QT foundations. There was a wave of new or enhanced offerings (for example, start-ups that made their quantum computing accessible through the cloud) and significant technological advancements—especially in quantum error correction and mitigation—as well as a small increase in patents filed. In addition, we found a notable increase in quantum technology

What is quantum technology?

Quantum technology encompasses three subfields:

- Quantum computing (QC) is a new computing paradigm leveraging the laws of quantum mechanics to provide significant performance improvement for certain applications and to enable new territories of computing compared to existing classical computing.
- Quantum sensing (QS) includes a new generation of sensors, based on quantum systems, that provide measurements of various quantities (for example, electromagnetic fields, gravity, or time) and that are orders of magnitude more sensitive than classical sensors.
- Quantum communication (QComm) is the secure transfer of quantum information across distances, and it could ensure security of communication even in the face of unlimited (quantum) computing power.[1]

[1] Quantum cryptography draws on the exchange of a secret key to encrypt messages based on the quantum mechanical phenomenon of entanglement. Unlike any classical cryptographic protocol, it is in principle not possible to "eavesdrop" on messages exchanged with quantum cryptography without detection. However, early implementations have been shown to have some weaknesses due to, for example, physical implementations of the protocols.

programs offered by universities, with the European Union taking the lead in the number of graduates in QT-related fields.

In this article, we'll go into these and other findings in greater detail (for more on the research, see sidebar "About the *Quantum Technology Monitor* research").

Private investment dropped while public investment surged, with a focus on scaling established start-ups

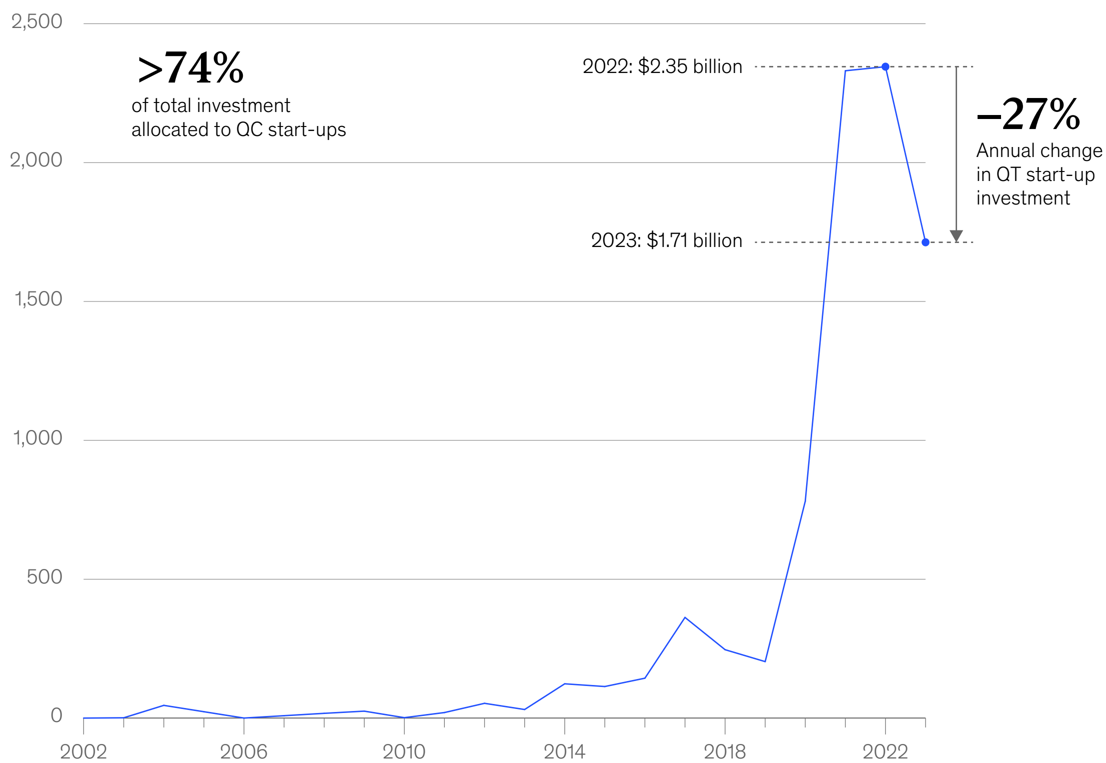
In 2023, $1.71 billion was invested in QT start-ups, which represents a 27 percent decrease from the all-time high of $2.35 billion in 2022 (Exhibit 1). Nonetheless, the decrease is smaller when compared to the 38 percent decrease for all start-ups globally. The slowdown in the number of new QT start-ups founded continues (13 in 2023 versus 23 in 2022). Deal sizes have decreased as well, with the average deal size being $40 million in 2023 compared to $105 million in 2022 and $107 million in 2021. In line with this development, deal counts dropped to 171 in 2023 from 206 in 2022.

There are several factors causing the decrease in private investment into QT, including a significant shift in focus toward generative AI as well as lingering perceptions of QT being a long-term technology whose potential in various sectors is still being understood and evaluated.

Exhibit 1

Total investments in quantum technology start-ups decreased by 27 percent year-over-year in 2023.

Annual raised start-up investment,[1] $ million



[1]Based on public investment data recorded in PitchBook; actual investment is likely higher.
Source: PitchBook

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About the *Quantum Technology Monitor* research

Our research covers the three main areas of quantum technologies: quantum computing, quantum sensing, and quantum communication. The analysis is based on inputs from various data sources, including publicly available data sources and expert interviews. Because not all deal values are publicly disclosed, this research does not provide a definitive or exhaustive list of start-up and funding activities. Minor data deviations may exist as databases are updated.

Public funding for quantum technologies, on the other hand, jumped more than 50 percent over 2022. While China and the United States have previously dominated QT public investment, new announcements from Australia, Canada, Germany, India, Japan, the Netherlands, South Korea, and the United Kingdom reflected a growing realization among a broader range of governments of the importance of QT; South Korea and the United Kingdom, in particular, made significant increases to their funding levels (Exhibit 2).

Most of these national initiatives aim to establish technological leadership and sovereignty and spur private investments for quantum technology development. For example, the aim of the United Kingdom's National Quantum Strategy, which includes $3.1 billion in public funding over ten years, is not only to allow the United Kingdom to be a leading quantum-enabled economy but also to generate $1.3 billion in private investment in quantum technologies.

Where did the funding go? The vast majority of investments have been in US companies (more than two times the amount compared to the next country), followed by companies in Canada and the United Kingdom. The majority of venture capital funding went to scaling up established start-ups, with more than 75 percent of the total investment value going to series B or later funding rounds. This suggests the establishment of more-mature technological platforms for quantum computing and signals investors' potential risk aversion to early-stage start-ups and unproven technologies or approaches—which also partially explains the 43 percent drop in new start-ups compared to 2022.

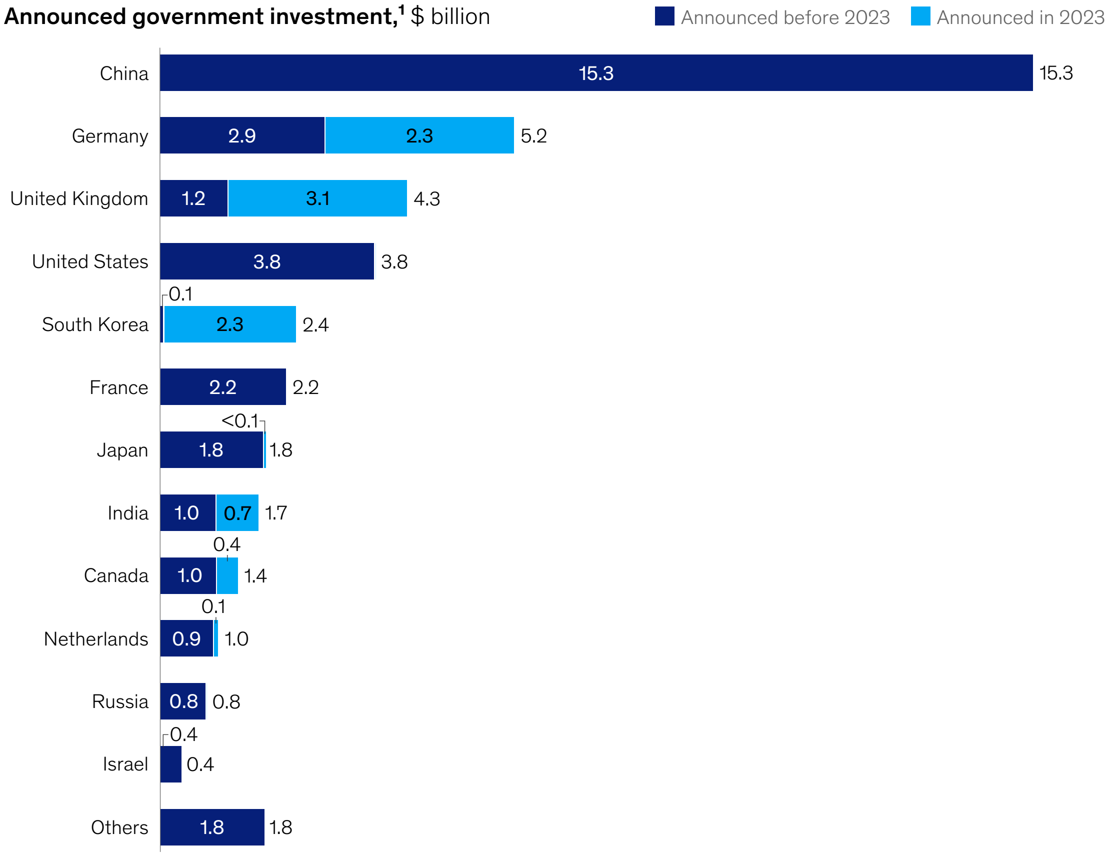
With quantum talent growing, countries need to focus on broad collaborations to build strong capabilities

Talent development took a notable step forward in 2023, reflecting a positive focus on building QT's foundations. There were 367,000 people who graduated in 2023 with QT-relevant degrees. Meanwhile, the number of universities with QT programs increased 8.3 percent, to 195, while those offering master's degrees in QT increased by 10.0 percent, to 55. The European Union and the United Kingdom have the highest number and density, respectively, of graduates in QT-relevant fields. This surge helps explain why scientists from EU institutions contributed most often to quantum-relevant publications.

Building off of this talent and these investments to generate value is still a challenge because of limited access to state-of-the-art hardware and infrastructure, limited awareness and adoption of quantum technologies, and a lack of interdisciplinary coordination (such as between academia and industry) required to bring technologies to market. Collaboration between industry, academia, and government is

Exhibit 2

Global public investments in quantum technology reached $42 billion in 2023.



[1]Total historic announced investment; timelines for investment vary by country.

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essential to accelerating development of quantum technology to industrialize technology, manage intellectual property, and overcome talent gaps.

To address this issue, "innovation clusters" are emerging worldwide. These clusters are coordinated networks of partnerships between researchers, industry leaders, and government entities that contribute to the technological advancement of quantum technologies and drive regional value creation (Exhibit 3).

Most clusters share the following elements:

— *Academic hubs.* Large academic institutions provide vibrant research ecosystems and talent, as well as access to the latest scientific breakthroughs.

— *Government support.* Government support for innovation clusters comes in the form of public funding to support technology development at institutions and start-ups, as well as funding infrastructure for national research centers such as national labs, dedicated facilities, and capabilities for quantum technology development.

— *Entrepreneurship.* Start-ups are typically spun off from academic groups but retain ties to academic groups and take advantage of infrastructure within research institutions.

Exhibit 3

Building innovation ecosystems and clusters requires a range of support actions from stakeholders.

Support actions by ecosystem stakeholder

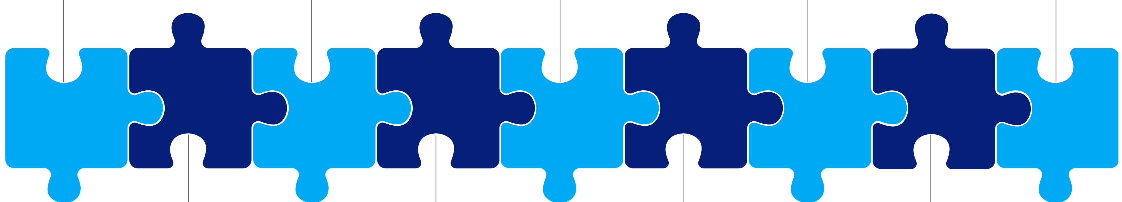
Government
- Develop national quantum strategy
- Identify priority innovation areas for investment
- Address policy challenges
- Foster effective local ecosystems

Research institutions
- Develop beyond-the-state-of-the-art quantum technologies
- Partner with relevant players to collaborate on full-stack quantum solutions

Corporate end users
- Develop quantum adoption road maps
- Co-develop technology
- Build quantum workforce
- Utilize quantum as a service

Start-up accelerator programs
- Operate as exclusively quantum-focused programs to grow quantum start-ups
- Offer coaching and necessary platform for start-ups to take ideas into implementation

Infrastructure
- State-of-the-art equipment
- Capital investments
- Talent
- Physical space
- Training and education



Quantum companies
- Experiment with proofs of concept
- Build strategic road map to integrate into business
- Build internal quantum workforce
- Start-ups:
  - Obtain funding
  - Receive mentorship from network

Academia (education and research)
- Train and educate the next generation of talent in quantum and related areas
- Produce cutting-edge research
- Design study programs for quantum

Investors
- Access expertise in technology to inform investment avenues
- Prioritize high-potential technologies
- Access cluster's start-up network for investment

Administrative organization
- Interface with cluster members for strategic partnerships in research, knowledge and technology transfer, and workforce and ecosystem development
- Manage a portfolio of industry partners to spur the creation and growth of ventures

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Start-ups also benefit significantly from mentorship (for example, through accelerators and tech transfer organizations) to develop and commercialize innovations.

— *Industry partnerships.* Local companies or large corporate entities that are interested in applying quantum technologies provide funding or dedicated infrastructure to researchers.

Developing and scaling such regional innovation ecosystems (including research consortiums) will be a determining factor for achieving wide adoption and commercialization of quantum technology.

Technology breakthroughs, particularly in fault-tolerant quantum computing, reflect meaningful progress

The past year marked continued advances for all quantum technologies, with a range of enhanced and new QT offerings coming to the market. One advance was the transition from the NISQ[1] era to the

[1] NISQ stands for noisy intermediate-scale quantum, an era in quantum computing characterized by use of quantum processors containing up to 1,000 qubits, which were prone to noise and error.

FTQC[2] era. Other key breakthroughs included the following:

- *Quantum computing.* Quantum error-correction proposals and demonstrations by large companies show promise of steps toward large-scale, fault-tolerant quantum computing. Record qubit fidelity of 99.5 percent (by QuEra, MIT, and Harvard) and, most recently, 99.9 percent (by Microsoft and Quantinuum) were achieved by combining new error-correction schemes and groundbreaking architectures for logical qubits. Shifting the focus from hardware alone to software and architecture-based schemes for error mitigation and correction promises to significantly reduce the hardware overhead (for example, physical qubit counts for each logical qubit) and accelerate timelines for the advent of universal fault-tolerant quantum computers.

- *Quantum sensing.* Researchers are developing improved techniques to control ensembles of solid-state spins for a range of sensing applications. Researchers at MIT, for example, developed a novel technique that could significantly improve the sensitivity of quantum sensing devices. Quantum sensing technology's capabilities in monitoring, imaging, navigation, and identification will have a significant impact, both on their own and as enablers of processes. Our analysis shows that private sectors such as oil and gas, automotive and assembly, aerospace and defense, medtech, and media and entertainment, as well as the public sector, could experience disruptive impact from quantum sensing after 2030.

- *Quantum communication.* Researchers are improving the performance of quantum key distribution, demonstrating longer transmission distances and increased data rates using innovative techniques. China and Russia both successfully tested the longest established quantum communication, which was over a distance of 3,800 kilometers. Researchers are also developing platforms for quantum memories using trapped ions, rare earth ions, and atomic vapors, and they are using trapped ions to demonstrate quantum repeaters, which operate at telecom wavelengths.

For the full set of insights and data, download the entire *Quantum Technology Monitor*.

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[2] FTQC stands for fault-tolerant quantum computing, an era in quantum computing in which computation involves low logical error rates.