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SEPTEMBER 2025

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EDITOR'S LETTER

Sovereign AI: Ambition or Illusion?

Since late 2023, Nvidia CEO Jensen Huang has been polishing a strategic vision: Shouldn't every country develop its own AI systems, using its domestic infrastructure, data, workforce, and business networks? Couldn't nations build AI factories that take in data and churn out intelligence? Huang calls this concept "sovereign AI," and European politicians are warming to the idea.

"Europe has now awakened to the importance of these AI factories," Huang said in his keynote at GTC Paris during VivaTech 2025. "In just two years, we will increase the amount of AI computing capacity in Europe by a factor of 10."

Huang knows how to speak to European audiences, aligning technological ambition with cultural and historical memory. In his keynote at GTC Paris 2025, he struck a chord by recalling Europe's past as a cradle of the Industrial Revolution, framing AI as the electricity of our era, and positioning AI factories as the new engines of intelligence at scale.

Huang also understands how to make sovereignty relatable. During a panel with French President Emmanuel Macron and Mistral AI CEO Arthur Mensch at VivaTech 2025, he likened intelligence to an inalienable national resource.

"A country can outsource a lot of things, but outsourcing all of your intelligence makes no sense," Huang said. "Intelligence is too foundational. … Intelligence comes from the data of your country. The data of your country belongs to your country. It's your people's knowledge. It's your people's culture. It codifies your common sense. Most of the data is not even on the internet. A lot of it is in your libraries or your companies. That data belongs to you. You should find a way to harvest that data, transform that data into AI; you can still use public models, but here in France, you have the benefit of Mistral [AI]."

This was the backdrop to Huang's recent European tour, during which he met with government and industry leaders in Germany, the U.K., and France. Each stop came with announcements designed to embed Nvidia at the heart of Europe's AI ecosystem. In Germany, Nvidia and Deutsche Telekom unveiled plans to build a sovereign AI cloud platform. In the U.K., Huang launched a new Nvidia AI technology center to accelerate work in embodied AI, materials science, and Earth system modeling.

In France, Nvidia, Bpifrance, MGX, and Mistral AI revealed plans for Europe's largest AI campus: a 1.4-GW facility near Paris that will support the entire AI life cycle. Huang described the campus as "transformational infrastructure" for France. Nvidia and Mistral AI also announced a strategic partnership to build an end-to-end cloud platform powered by 18,000 Nvidia Grace Blackwell systems in its first phase, expanding to multiple sites in 2026. This infrastructure will enable European organizations to develop and deploy AI more quickly, leveraging optimized Mistral models and proven AI factory designs to accelerate the rise of agentic applications.

President Macron framed the push to build a European AI infrastructure as "our fight for sovereignty, for strategic autonomy" and hailed the new partnership with Nvidia and Mistral AI as "a historic one."

The vision is bold and the marketing flawless. Nvidia is casting itself not as a foreign supplier but as Europe's indispensable partner in AI sovereignty. For the Santa Clara, California–based company, the opportunity in Europe is too obvious to ignore: The continent has few credible alternatives and little choice but to embrace Nvidia.

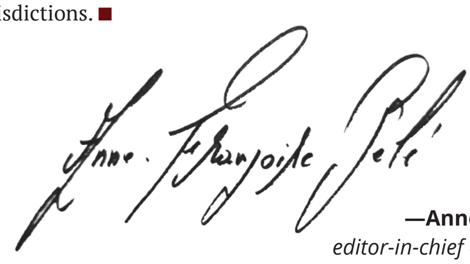
Nvidia's Jensen Huang at GTC Paris 2025
(Source: Anne-Françoise Pelé)

Yet how can a U.S. technology giant convincingly promote and deliver sovereign AI in Europe? And in an era of geopolitical realignment and heightened protectionism, why are European politicians embracing it so readily?

Philippe Notton, CEO and founder of SiPearl, recently voiced a stark warning: "If $100 billion is invested in data centers today, as announced at VivaTech, and there is no oversight or routing of funds, 80% of that money will go to the U.S. Bouygues and Vinci will be happy to construct the buildings. Schneider Electric will be happy to manage power supplies and inverters. STMicroelectronics will be happy to supply power converters. The remaining 80% will be Dell, HP, and Lenovo servers, as well as Intel, AMD, and Nvidia components. What will Europeans have at the end of the day? And in 10 years? Nothing."

In Notton's view, semiconductors account for 80% of the strategic value of a data center or supercomputer. To avoid a future in which Europe operates data centers stamped "Made in the U.S.," he argues, European decision-makers must prioritize investment in homegrown computing technologies.

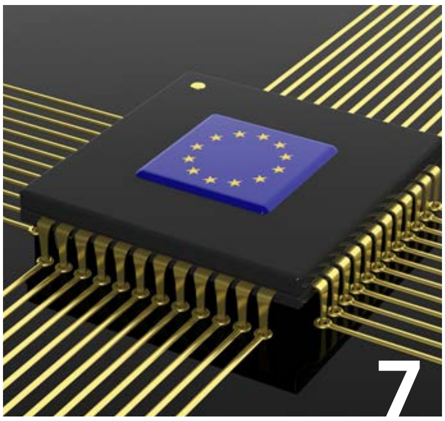
Data sovereignty may begin in the data center, but true sovereignty lies deeper: in mastering our needs, developing our own semiconductors, and ensuring that our data remains anchored in compliant jurisdictions. ■



—Anne-Françoise Pelé,
editor-in-chief of EE Times Europe

VOL 8 | NO 3 | September 2025

EE|Times EUROPE



ONLINE MUST READS

- ***For Leti and ST, the Fastest Way to Edge AI Is Through the Memory Wall***
- ***AI and Semiconductors Dance a Quick Two-Step***
- ***SiPearl Tapes Out Rhea1 Processor, Closes Series A, Preps Series B***

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FRONT COVER ILLUSTRATION: ADOBE STOCK

SEMICONDUCTOR MANUFACTURING

GlobalFoundries Champions ‘Essential Technologies’ Over Moore’s Law

By Pat Brans

Gregg Bartlett tells EE Times Europe why legacy nodes, power GaN, and MRAM still drive real-world innovation—and how imec helps fuel that mission.

At ITF World 2025, GlobalFoundries CTO Gregg Bartlett delivered a provocative message: The semiconductor industry has overhyped Moore’s Law and underinvested in the foundational technologies that underpin the modern world. “Moore’s Law gets too much airtime,” Bartlett said in his keynote. “Nodes like 130 nm and 90 nm may seem outdated, but they’re still essential technologies, and they’ve even evolved.”

In an exclusive interview, Bartlett reinforced the vision he’d offered his keynote audience at the conference, held in May in Antwerp, Belgium. “If I have one goal,” he told EE Times Europe, “it’s to kill terms like ‘legacy’ and ‘more than Moore.’ They’re no longer meaningful. Technologies like GaN and silicon photonics don’t scale along Moore’s trajectory. They require different innovation models—and different partners.”

AN ENDURING PARTNERSHIP WITH IMEC

Since exiting the 7-nm race in 2018, GlobalFoundries has focused its R&D on what Bartlett calls essential technologies: nonvolatile memories, such as MRAM and RRAM; RF and power GaN; and silicon photonics. These technologies enable platforms for edge AI, automotive radar, data center power delivery, and secure mobile transactions. “We’ve actually increased our 130-nm capacity in recent years,” Bartlett said. “It supports 150-V battery management systems, which are mission-critical for electric vehicles.”

Bartlett illustrated how a single platform evolved from crypto-mining ASICs to Wi-Fi, millimeter-wave RF, and embedded MRAM—and is now used in silicon-28-based quantum research. “It’s a Swiss Army knife of essential features,” he said. “That’s the kind of utility you get from mature, flexible technologies.”

At the heart of this transformation is imec, Belgium’s nano-electronics powerhouse. “This is our deepest and most successful research partnership globally,” Bartlett told EE Times Europe. “When we pivoted away from Moore’s Law, they adapted with us. Luc [Van den hove, imec president and CEO] and his team have been phenomenal.”

The collaboration includes joint programs on MRAM, RRAM, power GaN, and silicon photonics. The two organizations also exchange wafers for prototyping. “We supply wafers to imec, and we get wafers from imec. That kind of prototyping loop is incredibly valuable,” Bartlett said.

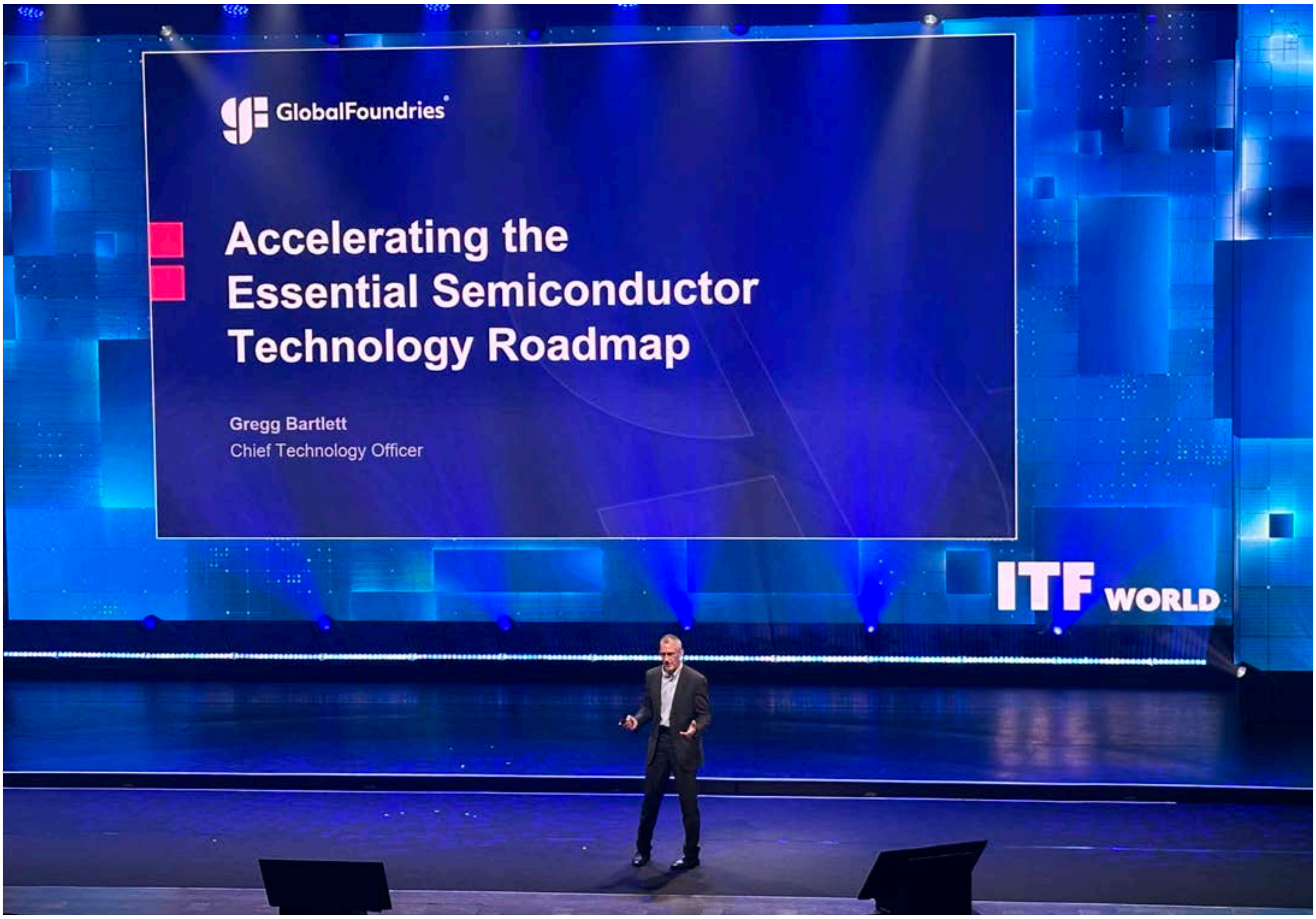
A striking example of the depth of this partnership came when export controls disrupted GlobalFoundries’ GaN supply chain. “Our Chinese vendor suddenly stopped shipping wafers,” Bartlett said. “Imec stepped in and used their own epi reactor to supply us with GaN wafers. That wasn’t part of their business model; they just did it because we asked. That’s part relationship, part culture.”

Bartlett attributed part of this responsiveness to personal continuity. “We joined imec shortly after we spun off from AMD, around 2010,” he said. “And we recently renewed our agreement through 2028. Imec has been a steadfast R&D partner all along. When we pivoted away from Moore’s Law scaling and toward what we now call essential technologies, they adapted their model to align with our shift.”

Bartlett highlighted how imec’s research model is uniquely international and collaborative. “In the U.S., R&D funding is more local and fragmented,” he said. “Imec runs a multi-participant, open ecosystem. That’s much more effective for our work.”

GlobalFoundries supports this model through its in-house Jedi program, placing postdoctoral engineers at imec for several years before rotating them to GF sites in Dresden, Germany; Singapore; or Malta. “These aren’t just tech transfers; they’re relationship builders,” Bartlett said. “The human connections endure.”

“Moore’s Law gets too much airtime,” GlobalFoundries CTO Gregg Barlett told his ITF World audience.
(Source: ITF World/GlobalFoundries)



"The EU is ahead of the U.S. in discussing the next generation of incentives," Bartlett told his keynote audience.
(Source: ITF World/GlobalFoundries)

As Europe pushes for sovereignty in semiconductors, Bartlett sees GlobalFoundries playing a pivotal role. "Our Dresden site will soon be the largest fab in Europe," he said. "We're ready to expand. We just need final approvals."

GlobalFoundries is also committed to imec's new research facilities in Spain and Germany, including the upcoming automotive center in Heilbronn, Germany. "We'll definitely participate there," Bartlett said. "Automotive is a core focus for us. And we're keeping a close eye on imec's new site in Malaga [Spain] to assess where we might contribute."

Bartlett praised Europe's commitment to semiconductor investment, including what might become the European Chips Act 2.0. "The EU is ahead of the U.S. in discussing the next generation of incentives," he said.

NEXT-GEN INTEGRATION AND AI WORKLOADS

Advanced packaging and heterogeneous integration featured heavily in Bartlett's keynote and in his interview comments. "Chiplets aren't just about GPUs," he told EE Times Europe. "Zonal automotive architectures will need 3D integration of low-power logic and high-frequency analog. That's our sweet spot."

Bartlett revealed to EE Times Europe that GlobalFoundries is developing stacked systems combining 22FDX (22-nm fully-depleted silicon-on-insulator) logic with silicon-germanium components for future 140-GHz automotive radar. "We're already working on the building blocks today," he said. "You can't get to those frequencies monolithically."

Bartlett also addressed AI's impact. "For edge AI, we benefit directly from our work with imec on MRAM and resistive RAM," he told EE Times Europe. "Resistive RAM offers a lower-cost solution, while MRAM gives us high reliability for mission-critical inference workloads."

And for data center AI, the story isn't about logic scaling but about efficient power delivery and photonic interconnects. "GaN for power management and silicon photonics for 800-Gbps links—these are where the challenges lie," he said.

Sustainability is integral to GlobalFoundries' strategy, Bartlett said. "One of the principles of our sustainability strategy is our 'Journey to Zero,' which describes our continuous improvement to minimize environmental impacts. For carbon, that would be our long-term goal to achieve net zero. In the short term, we just increased our ambition level to a 42% reduction by 2030."

Here, too, imec plays a key role: "They've established a dedicated sustainability program, focused on rigorous metrics and materials innovation," Bartlett said. "We're deeply engaged."

Bartlett's message was clear: The industry must redefine what it means by advanced. "Silicon photonics, power GaN, embedded memory—these are advanced technologies," he said. "They're not about dimensions. They're about systems, materials, and physics. And they're indispensable."

For GlobalFoundries, essential doesn't mean outdated. It means enduring innovation—and the company is betting that with imec as a partner, this approach will shape the future of electronics. ■

Pat Brans *is a contributing writer for EE Times Europe.*

SEMICONDUCTOR MANUFACTURING

Europe's Semiconductor Plan Caught Between Vision and Reality

By Yu-Han Chang, IDTechEx

A chip is no longer just a component.

From smartphones to generative AI, silicon chips power the technologies that shape modern life. Once seen as industrial components, semiconductors are now recognized as strategic assets, critical to national power and security, economic resilience, and technological sovereignty.

COVID, AI, AND GEOPOLITICS RESHAPE CHIP PRIORITIES

The Covid-era chip shortages exposed the fragility of a highly concentrated semiconductor supply chain, halting automotive production and rippling through other industries. At the same time, the explosive rise of AI has intensified a race among nations to secure access to advanced Si chips. In the U.S., a series of export controls has been enacted to block China's progress in advanced Si chip manufacturing, underscoring semiconductors' geopolitical weight.

Nowhere is this tension more evident than in Taiwan, home to the world's most advanced chipmaker, TSMC. The island's centrality to global production, especially for leading-edge nodes, is now seen as a strategic vulnerability in light of rising cross-strait tensions.

In response, governments have launched industrial strategies backed by unprecedented public and private investment. The U.S., China, Japan, South Korea, and the EU are all competing to build resilient, sovereign semiconductor ecosystems. Europe's answer is the EU Chips Act.

THE EU CHIPS ACT: VISION, STRUCTURE, AND STRATEGY

Announced in February 2022, the EU Chips Act aims to double Europe's share of global chip production from 10% to 20% by 2030. Born out of pandemic-era disruption, the act recognizes semiconductors as essential to Europe's digital sovereignty, economic competitiveness, and long-term innovation.

The EU Chips Act is built around three main pillars:

- Funding for next-generation R&D in areas such as advanced semiconductors and quantum technologies
- Support for first-of-a-kind manufacturing, packaging, and testing facilities
- Coordination on supply chain monitoring and emergency response

This article focuses on the second pillar,

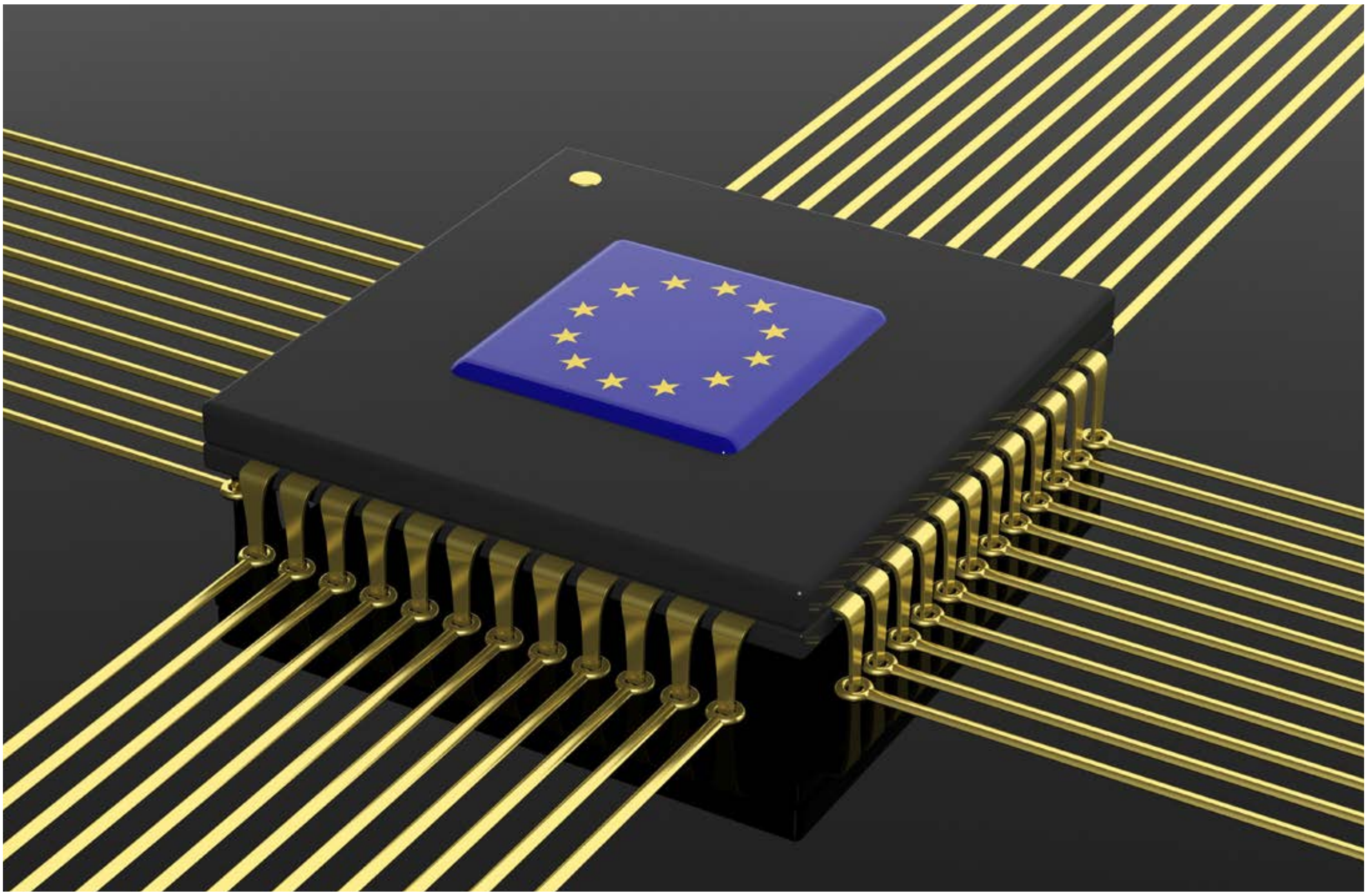


IMAGE: ADOBE STOCK

as it most directly impacts Europe's chip self-sufficiency ambitions.

MEGA PROJECTS UNDER THE EU CHIPS ACT

The European Commission (EC) has approved seven projects thus far, five of them involving more than €1 billion in combined public and private investment. These are detailed by country below.

In Germany:

- The ESMC JV, involving TSMC, Bosch, Infineon, and NXP, plans to invest more than €10 billion in a fab manufacturing 28-/22-nm and 16-/12-nm Si chips, with €5 billion in approved state-aid funding. The facility is expected to reach full capacity by 2029.
- Infineon is also expanding its Dresden operations, investing €4.46 billion in a fab for discrete power devices and analog/mixed-signal ICs, supported by €920 million in approved state funding. Full capacity is targeted for 2031.

In Italy:

- STMicroelectronics (ST) plans to invest €5 billion in a SiC chip fab in Catania with €2 billion in approved state funding. This fab would ramp to full capacity by 2032.
- Silicon Box, a Singaporean company, is setting up a €3.2 billion facility in Novara focused on advanced packaging, including panel-level and 3D integration. It has secured €1.3 billion in state-aid funding and is aiming for full capacity by 2033.

In France:

- ST and GlobalFoundries are jointly investing €7.5 billion in a 300-mm FD-SOI fab in Crolles, near Grenoble, supported by €2.9 billion in state aid. The fab was expected to be operational by 2027, but as of mid-2025, reports indicate the project has been paused, raising uncertainty about its future.

In other billion-euro-level moves:

- Onsemi is planning a $2 billion (~€1.9 billion) expansion in the Czech Republic. The project awaits state aid approval.
- NXP secured a €1 billion EIB loan to support R&D activities in multiple EU countries.

These projects reflect Europe's ambition to reestablish a stronger semiconductor presence. Whether the efforts deliver as planned remains to be seen, as there are many influencing factors outside of Europe's control.

INTEL'S MAGDEBURG RETREAT

Intel's setback in Magdeburg, Germany, reflects the obstacles to realizing Europe's chip strategy. Announced in 2022 as a €17 billion project, with the potential to scale to €30 billion, the deal included up to €9.9 billion in approved state aid. Despite those numbers, the project was officially canceled in mid-2025 because of soaring costs, a lack of committed customers, shifts in strategic priorities under new leadership, and delays from bureaucratic and infrastructural hurdles. The cancellation points to deeper structural issues that are also affecting other approved projects.

Once seen as industrial components, semiconductors are now recognized as strategic assets.

INTERNAL CHALLENGES

Turning the EU Chips Act's goals into working projects has proved challenging. Even after receiving state funding approval, projects often face national-level delays because of legal reviews, budget processes, and fragmented permitting. Those hurdles, combined with inconsistent local coordination, can stretch timelines and weaken investor confidence. Compounding the issue, there is no unified mechanism at the EC level to monitor progress or flag delays.

Securing private co-investment is essential, but doing so has proved difficult. High capital costs, long payback periods, and macroeconomic uncertainty continue to deter investors. One recent example is the suspension of the JV in France between ST and GlobalFoundries, a move reportedly driven by soft customer commitments, weak demand beyond AI applications, and a strategic shift toward more attractive overseas markets. Shortages across all levels of the semiconductor workforce continue to pose serious constraints, and in many regions, the lack of supporting infrastructure such as packaging and testing adds further risk.

EXTERNAL PRESSURES: GLOBAL COMPETITION

While internal obstacles remain unresolved, the external environment is becoming increasingly competitive as global rivals accelerate their semiconductor strategies.

- The U.S. has $52.7 billion (€46.2 billion) in CHIPS Act funding and offers a 25% investment tax credit, leveraging private capital and geopolitical influence to attract major projects from overseas, such as TSMC's Arizona fab and Samsung's Texas facility, with about $32.5 billion in grants awarded by early 2025.
- South Korea's K-Semiconductor Strategy calls for ₩622 trillion (~€440 billion) in mostly private investment through 2047, alongside an expanded government support package of ₩33 trillion (~€21 billion).
- Japan has committed up to ¥10 trillion (~€58.3 billion) in government subsidies and incentives by 2030 under its semiconductor strategy, funding projects such as Rapidus's collaborative program and TSMC's Kumamoto fab.
- China has invested more than $100 billion in semiconductors since 2014 through its state-backed Big Fund, including ¥344 billion (~€42.3 billion) for the latest phase, launched in 2024, to accelerate domestic chip production despite ongoing export restrictions.
- Taiwan, home to TSMC, retains its lead in advanced nodes by keeping cutting-edge production domestic and maintaining a highly skilled local workforce and strong chip ecosystem.

In contrast, the EU's €43 billion Chips Act remains modest at best. Despite Europe's strengths in research and equipment from imec, CEA-Leti, ASML, and others, its position in semiconductor manufacturing is limited, especially in advanced nodes. Apart from Intel's Irish fab, most existing and planned facilities rely on mature technologies, restricting Europe's role in producing chips for AI and HPC.

CLOSING THE GAP: WHAT EUROPE MUST DO

Bridging this gap will take more than political ambition. Without faster permitting, stronger coordination between Brussels and member states, and a credible path to execution, the goal of reaching 20% of global chip production by 2030 is basically out of reach. Real progress will require accelerated approvals, a skilled engineering workforce, de-risked private investment, and a complete value chain, from design to advanced manufacturing and packaging.

Only by addressing these structural gaps can Europe move beyond political signaling and establish a lasting foothold in the global semiconductor landscape. ■

Yu-Han Chang *is a principal technology analyst at IDTechEx.*

SPECIAL REPORT: THE QUANTUM LEAP

Catalyzing Europe's Quantum Leap

By Anne-Françoise Pelé

Quantum technologies have undergone spectacular development in recent years, with McKinsey estimating their potential to create trillions of dollars in value over the next decade. From computing to sensing to communications and cryptography, the world is abuzz with quantum innovations. The question now is whether Europe has the strength to transition from lab to widespread adoption.

On July 2, the EC presented its Quantum Strategy, aimed at making Europe a global leader in quantum by 2030. While Europe leads in quantum talent, academic research, and early-stage entrepreneurship—it is home to about one-third of the world's quantum companies—it still lags in commercialization, private investment, and patent filings.

Backed by more than €1 billion in EU funding and aligned with the Chips Act and the Economic Security Strategy, the Quantum Strategy focuses on dual-use potential, industrial scaling, and strategic autonomy. It introduces new coordination bodies and pilot lines to accelerate the deployment of quantum computing, communication, and sensing technologies in key sectors such as energy, finance, health, and defense.

Open questions remain: What is the state of quantum startup funding? Can hybrid quantum computing systems deliver value now? What is the most efficient path to scaling quantum computers? Is silicon spin qubit the technology to bet on? How to prepare for post-quantum cryptography? What are the real-world applications for quantum sensors? What are the promises of quantum communication systems?

This Special Report will assess the current state of quantum research by examining the latest advancements in quantum computing, sensing, and communication and their implications for Europe's position in the global race.

It relies on a collection of contributions by Tematys, IQM Quantum Computers, Q-Ctrl, Quantum Brillance, and Ulster University in Northern Ireland. It also reflects discussions with Olivier Ezratty, author of "Understanding Quantum Technologies," and key European quantum players such as Bluefors, CEA-Leti, Cloudflare, Delft Circuits, D-Wave, IQM Quantum Computers, the Jürlich Supercomputing Center, the U.S. National Institute of Standards and Technology, the U.K.'s National Quantum Computing Centre, Nu Quantum, Phasecraft, QuiX Quantum, Quobly, SemiQon, and the VTT Technical Research Center of Finland.

To illustrate the continued, gradual rise in the representation of quantum technologies in EE Times' Silicon 100, our annual list of 100 promising electronics and semiconductor startups, we'll zoom in on the developments and evolution of some of the European quantum startups on this year's list. ■

IMAGE: ADOBE STOCK

OPINION | **THE QUANTUM LEAP** | EUROPE'S PLEDGE

The Quantum Race: Finding Europe's Formula 1

By Arturo Elías Llumbet, **Susmita Sridhar**, and **Thierry Robin**, Tematys

Quantum technologies are rapidly reshaping the frontiers of computing, communication, and sensing—areas with implications far beyond the laboratory. As nations and industries race to secure leadership in this highly dynamic field, the outcomes will redefine global competitiveness, cybersecurity, and scientific capability. In this high-stakes landscape, strategic investments and collaborations are no longer optional; they are imperative.

In 2024, nearly half of all global quantum investments flowed into European startups, with Europe standing out for its strong presence of startups in the critical seed and Series A stages, according to Amires. Still, Europe's claim to leadership in the quantum race is increasingly being challenged on several fronts. The continent holds a strong position in quantum research, boasting top-tier universities, accessible foundries, and a robust ecosystem of component suppliers, but it significantly lags the U.S. and China in commercialization.

As nations and industries race to secure quantum leadership, the outcomes will redefine global competitiveness, cybersecurity, and scientific capability.

Europe's missing piece is a powerful class of large system integrators and venture-backed companies capable of pushing technologies to market. "Basically, what Europe is missing are buyers of last resort," as Ward Hendriks, co-founder and CTO of Aluvia Photonics, put it.

This gap results in lower private investment and an administrative burden inherent to public funding that slows product development and limits responsiveness to market needs. "We are shooting ourselves in the foot by making it too complicated," Hendriks said.

While public investment supports R&D, it often lacks the directionality that customer-driven demand provides, making it harder for European innovators to scale up. Furthermore, the European quantum research landscape is fragmented, with many countries and institutions independently working on similar topics. Such fragmentation dilutes funding, focus, and impact.

"Probably, we should spend less time fighting for the piece of cake, but rather make the cake," said Alexander Bachmann, senior director for R&D technology at Toptica Photonics. "I think there is a lot of potential in Europe, but we need to cooperate more than compete."

Industry fragmentation hinders large-scale quantum computing efforts, which require massive, coordinated investment and infrastructure. On the other hand, it might be suited to quantum sensing, a domain that favors smaller, more focused projects and lower capital thresholds.

In any case, addressing Europe's structural challenges—potentially through centralized hubs and collaborative industrial models like Airbus—will be essential for its transition from research excellence to global quantum leadership.

In fact, lessons on the benefits of the collaborative, coordinated approach are evident within the quantum field itself, where quantum computing hybridization with classical computing is already delivering value across several sectors through high-performance computing (HPC) clusters. Consider the Euro-Q-Exa initiative (EuroHPC Joint Undertaking, October 2024), which leverages the existing infrastructure of HPC clusters to help overcome part of the elevated upfront costs of quantum computers. Investing in completely new facilities comes with a high risk, along with the inflated cost set by the market potential of the technology. The hybridization approach is also essential from a practical standpoint, as problem simulations are first run on classical systems to assess requirements before being transferred to quantum processors.

Despite the hybrid approach, if quantum computing is to reach industrial maturity, the scalability challenge must be overcome. Key barriers include fault-tolerant error correction, hardware integration, and cost-effective production. A modular architecture is emerging as the preferred path forward, especially in photonics.

By enabling components to mature independently before being integrated, modular systems minimize the risk and allow for parallel development. Once proven, these modules can be densely integrated to reduce system footprint and manufacturing costs.

"If you are uncertain about the risks at the system level, then the modular approach is a must and a good first approach," said Rolf Evenblij, strategic cooperations manager at QuiX Quantum. "The complexity of the modular approach will not increase anymore, so now the industry is in the position of integrating these modules into more complex systems/subcomponents."

Recent efforts on scaling quantum hardware have focused on spin qubits. This technology offers compelling advantages, including compatibility with established semiconductor manufacturing, high integration density (up to ~1,000 spin qubits in the space of a single transmon), long coherence times (close to 20 µs), and operation at higher temperatures (up to 4 K). These attributes position spin qubits as a promising platform for large-scale quantum systems.

However, the path is far from frictionless. The interconnect bottleneck—where each qubit ideally requires its own control line—limits system scalability, particularly in cryogenic environments. Further challenges include low device uniformity, which complicates shared control schemes, and a lack of robust mapping and compilation tools tailored to spin-qubit-specific architectures. Even for the first 2D crossbar architectures that have been demonstrated, the most advanced mapping methods have focused on

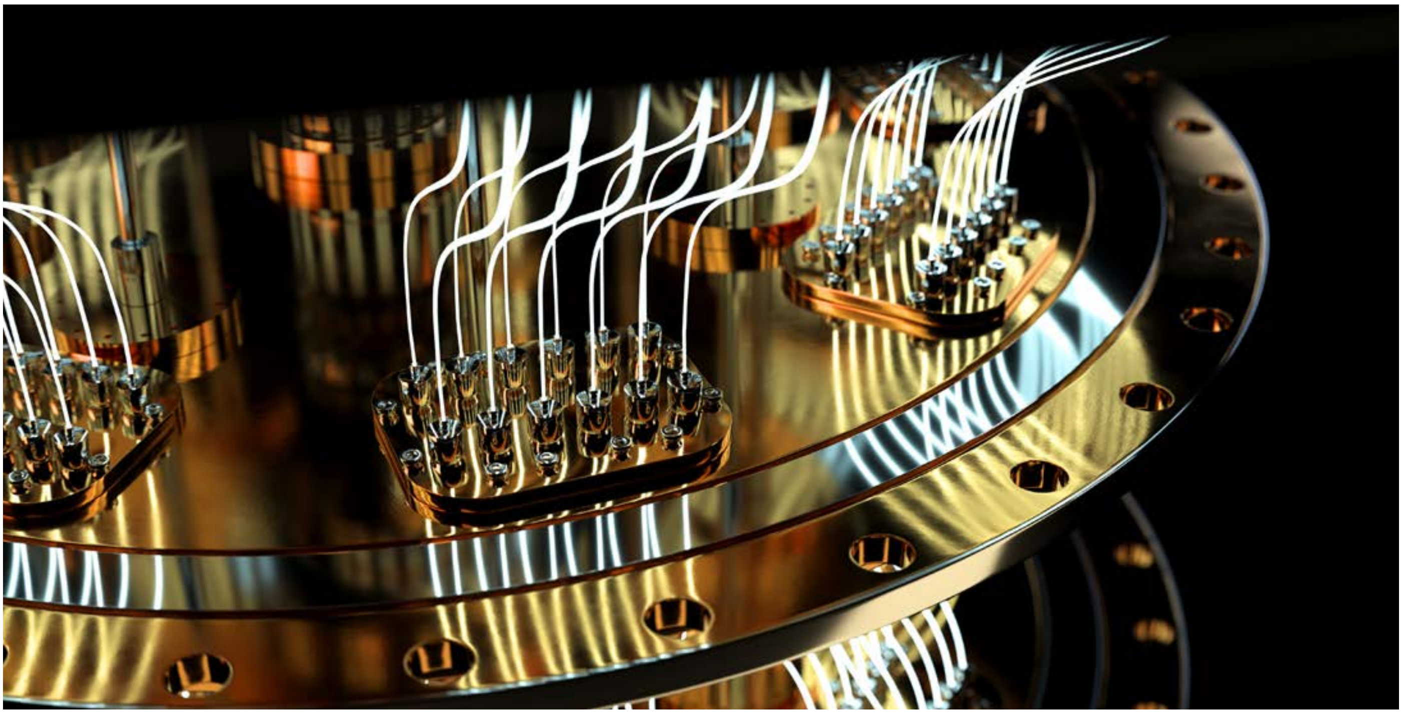


IMAGE: ADOBE STOCK

the more mature ion-trap and superconducting devices (Paraskevopoulos et al., 2023).

Those factors have some in the quantum community questioning whether silicon spin qubits are the technology to bet on. "No, if [it were] up to me," Evenblij said. "Photonics, despite the challenges in losses, proves much more scalable" and promises a clear path to maturity.

For Evenblij and many others, the photonics approach outpaces spin qubit systems in its potential to enable scalability and integration for quantum computing. In quantum photonics, most components operate at room temperature. While today's most sensitive detectors, such as superconducting nanowire single-photon detectors, require cryogenic cooling, there is an ongoing push to develop high-performance, room-temperature detectors, such as germanium-on-silicon single-photon avalanche diodes. Further lowering this deployment barrier, alongside decades of fabrication expertise in photonic integrated circuits (PICs), could be the game-changer in the race toward dominating core hardware manufacturing for next-generation computers.

Indeed, Aluvia Photonics co-founder and CSO Sonia Garcia Blanco asserted that "PICs are the only way to grow a quantum system."

Aluvia's Hendriks agreed, saying, "Without PICs, the quantum computer doesn't exist."

PICs offer exceptional scalability by enabling the dense integration of thousands of optical components onto a single chip, significantly reducing system size and complexity. Their compatibility with CMOS fabrication processes ensures reproducible, cost-efficient manufacturing and facilitates the transition from experimental setups to commercially viable quantum hardware. PICs support miniaturization, allowing large optical tables from laboratories to be condensed into compact, portable platforms suitable for field deployment.

Furthermore, they enhance system robustness by replacing manually aligned free-space optics with lithographically defined waveguides, improving phase stability and coherence by increasing environmental tolerance. Finally, PICs enable hybrid integration of photonic and electronic components, paving the way for compact, energy-efficient quantum systems across computing, communication, and sensing applications.

Europe is betting on PICs for its future quantum systems by investing almost €6 million in the Qu-PIC initiative. This Horizon Europe project is committed to delivering a universal PIC platform that leverages the low-loss performance and broadband operating spectrum (UV to mid-IR) of aluminum oxide.

Qu-PIC seeks to deliver two application demonstrators: a source of Gottesman-Kitaev-Preskill states for quantum processing and an ytterbium-based atomic clock for quantum sensing. What makes the project particularly relevant to Europe's quantum industry, however, is the ambition to secure a full European supply chain of quantum building blocks. This effort, along with delivering an open Process Design Kit (PDK) to accelerate quantum system development, promises to be the first centralized hub and collaborative academic-industrial model pushing Europe toward a global leading position in quantum computing as well as in sensing applications.

Importantly, PICs are not expected to replace other enabling technologies in quantum, because no single platform can meet the diverse requirements of all quantum applications, such as varying power levels, wavelengths, and qubit modalities. Instead, PICs are expected to coexist with and enable other technologies by providing scalable, integrated photonic solutions.

Björn Globisch, head of R&D at Toptica Eagleyard, acknowledged the industry's need to pursue all avenues. "Quantum communication, especially quantum key distribution, is well-suited for PIC implementation," he said, but he added that "in quantum computing, the dominant technology is still uncertain."

The quantum race has reached a thrilling stage—so much so that betting on a winner-takes-all outcome feels riskier than backing the technologies capable of bridging with multiple quantum computing platforms. In the end, one qubit-hardware type may rise above the rest in the race toward industrial scale. But whichever qubit crosses the finish line first, its enabling technology will be right there with it.

If PICs are destined to be the qubit's final companion in this high-stakes journey, we may find out sooner than we think. ■

Arturo Elías Llumbet *is a photonics market analyst and European projects manager,* **Susmita Sridhar** *is a photonics market analyst and the head of European projects, and* **Thierry Robin** *is a partner and co-founder, all at Paris-based photonics and quantum market consultancy Tematys.*

THE QUANTUM LEAP | EUROPE'S PLEDGE

From Foundry to Fridge: Europe's Role in the Global Quantum Supply Chain

By Pat Brans

As companies around the world build variations of quantum computers, Europe's unsung heroes are building the infrastructure that makes it all possible.

Sal Bosman, CEO of Netherlands-based Delft Circuits, didn't set out to build full quantum computers when he co-founded the company in 2016. Instead, he focused on the plumbing—the cables, connectors, and interconnects that make those computers viable.

"My mother once told me, 'Look where others don't go. That's where opportunity lives,'" Bosman revealed to EE Times Europe. Her advice fueled Bosman's instinct to pursue components rather than compete in the crowded race to build entire quantum systems, and today he argues that the critical-niche strategy is the right one for Europe. "We should approach quantum from a supply chain perspective," he said.

Delft Circuits' Sal Bosman

Olivier Ezratty, author of "Understanding Quantum Technologies," shares Bosman's philosophy. Europe excels in the infrastructure and tooling needed to support quantum computing, he noted. As companies in the U.S. and China race to deliver full-stack systems, Europe has taken a quieter but no less vital route: Its companies supply the cables, cryogenics, instrumentation, and packaging that quantum machines can't operate without.

"Europe has strength in the middle of the stack," Ezratty told EE Times Europe. "We're not building many complete systems, but we're indispensable."

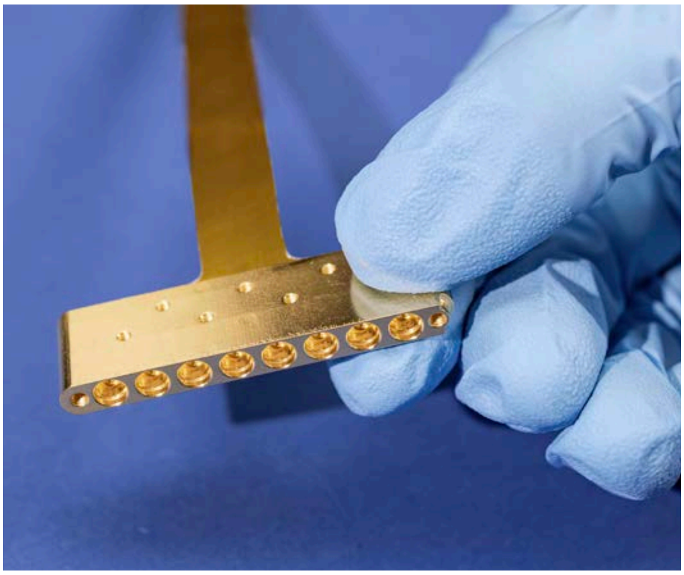
Two companies that have leveraged niche strategies to build global businesses are Bosman's own Delft Circuits, for quantum interconnects, and Helsinki-based Bluefors, for cryogenics.

Author Olivier Erzatty

DELFT CIRCUITS: INTERCONNECTS THAT SCALE

Bosman stressed that innovation in interconnects is essential if quantum systems are to scale. A cryogenic fridge may contain tens of thousands of connections, each one a potential point of failure. His company's solution is to reduce complexity at the hardware level, removing joints and improving modularity.

Delft Circuits specializes in making quantum-ready cabling that minimizes heat flow and reduces the number of joints in the cryogenic environment. "In quantum, the analog world rules," Bosman said. "You can't just digitize and clean it up later; you need a clean signal throughout. Everything matters—noise, impedance, geometry." The company's signature product, Cri/oFlex, addresses this challenge by combining flexible cabling with robust connectors designed to survive sub-kelvin temperatures.



Delft's eight-microwave–channel Cri/oFlex flex cable with high-density SMP connectors is available in normal and superconducting versions, including integrated components such as attenuators and filters. (Source: Delft Circuits)

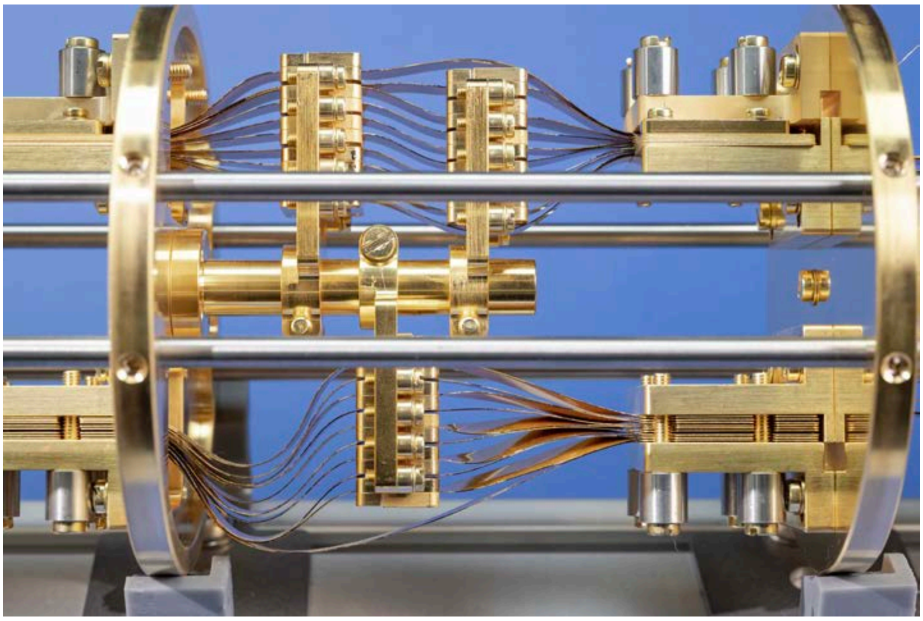
As Bosman explained, recent advances in quantum error correction and quantum processor designs have dramatically increased the number of interconnects required per qubit. "We used to need one or two lines per qubit; now, with tunable couplers and better error correction schemes, we're talking four I/O channels per qubit," he said. The payoff for higher qubit interconnectivity is less overhead for error correction. IBM, for instance, once required hundreds of physical qubits to create a single logical qubit; now, the target is closer to 50.

The wiring demands are still phenomenal. Bosman pointed out that a 1,000-qubit system would require management of more than 50,000 mechanical connection points, each one a possible source of failure or heat leakage.

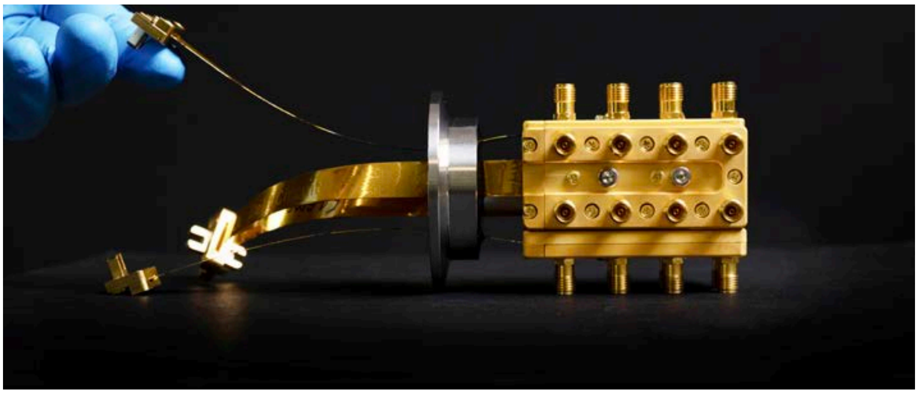
The shift toward error-corrected, fault-tolerant quantum computing brings with it new challenges in packaging and interconnects. "Instead of local connections between neighboring qubits, error correction schemes require much more global interconnectivity," Bosman said. "That means more cables, more precision, and more thermal constraints." Delft Circuits' technology aims to address these demands with fewer joints, better thermal isolation, and scalable architecture.

The company delivers its interconnects in the form of pre-assembled, monolithic modules that customers can install quickly and reliably. "What we sell is an I/O module—a loader that you just slide into the fridge," Bosman said. Unlike conventional coaxial

From Foundry to Fridge: Europe's Role in the Global Quantum Supply Chain



I/O module showing the thermal anchoring and fridge mount at 4 K of 160 microwave channels, consisting of 20 Cri/oFlex circuits of eight channels each (Source: Delft Circuits)



These vacuum ports are available as standard on typical dilution refrigerators and are usually used for readout lines or other important peripherals. The main ports where the I/O modules are entered are typically used for control I/O lines. (Source: Delft Circuits)

wiring, which can require 20 mechanical interruptions per channel, Cri/oFlex minimizes contact points, reducing both complexity and failure rates. The company says the design allows for rapid integration and easier maintenance, which is essential as systems scale to thousands of qubits.

Bosman also stressed the importance of interoperability. "If we're going to scale quantum, we need the pieces to talk to each other—mechanically, thermally, and electrically. That's where investment should go—into interoperability."

BLUEFORS: CRYOGENICS AT INDUSTRIAL SCALE

While Delft Circuits brings innovation to interconnects, Bluefors is solving another piece of the puzzle: cooling. CTO David Gunnarsson described to EE Times Europe how the company's systems support nearly every qubit modality, from superconducting to photonic and spin qubits. "Cryogenics is essential across the board," Gunnarsson said. "And when you scale, quality control becomes your biggest challenge."

In a recent project for Japan's National Institute of Advanced Industrial Science and Technology, Bluefors delivered a system with more than 100,000 wiring joints. "If your failure rate is one part per million, there's a good chance you'll have failures with 100,000 parts," Gunnarsson said. "So we had to build in inspection, measurement, and redundancy at every level." Bluefors incorporated the takeaways into its global strategy, including operations at Bluefors Labs, in Delft and Chicago, which provide shared access to cryogenic testbeds.

Gunnarsson said Bluefors differentiates itself not only through technical performance but also in customer support. The company offers service-level agreements and local spare parts depots in Europe, North America, and Japan. "These aren't lab tools anymore," he said. "They're industrial assets. They need 24/7 uptime and predictable maintenance."

Bluefors has also responded to space constraints in academic and industrial labs by launching a compact cryogenic system with a two-rack footprint. "We wanted something that could fit in a standard lab," Gunnarsson said. "No vacuum shaft, just power and cooling water. It's plug-and-play yet still supports hundreds of qubits."

Relationship building has a role alongside product engineering, Gunnarsson said. "We work closely with our customers in development cycles. Whether [the partner is] a university building a custom fridge for a single experiment or a startup looking to scale qubit count, our role is to adapt and support."

That includes operating shared infrastructure at innovation hubs. "These are places where academic, startup, and even corporate R&D teams can test, validate, and troubleshoot without needing their own systems," Gunnarsson said. "It helps accelerate learning curves and feeds into our product development."

Asked about the cultural shift as quantum transitions from labs to fabs, Gunnarsson was candid: "There's a different mindset now. You don't just sell a fridge and wish the team luck. You stay with them—train them, service them, optimize with them. That's industrialization."

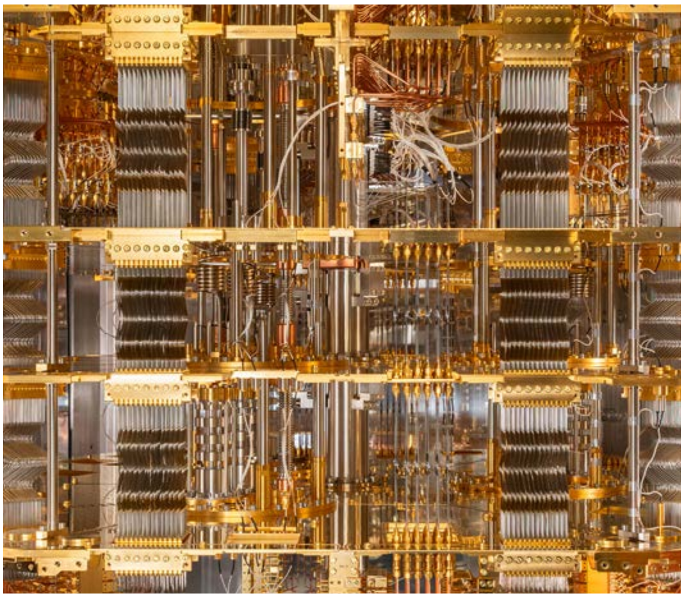
Gunnarsson cited workforce and tooling requirements as future bottlenecks. "We're already hiring for cryogenic techs, software, systems engineers—many of these roles didn't exist five years ago in this context. And we're tooling up for manufacturing like a mid-sized semiconductor company."

Bluefors's David Gunnarsson

Europe's edge lies in this blend of deep science and industrial rigor, the Bluefors CTO believes. "We can still do quantum science at the highest level, but we're also learning how to deliver at scale, with quality," he said. "That's not easy. But that's how you become essential."

The Bluefors KIDE cooling platform was installed in May 2025 at an AIST center in Tsukuba, Japan. The system is equipped with measurement infrastructure to support 1,000 superconducting qubits.
(Source: Japan's National Institute of Advanced Industrial Science and Technology)

This illustration of the freestanding Ultra-Compact LD System from Bluefors shows an arrangement that can be easily adopted into an HPC center. (Source: Bluefors)



Inside view of the KIDE cooling platform (Source: Bluefors)

EUROPE'S STRATEGIC ROLE

Delft Circuits and Bluefors are not the only European companies whose technology and services have become essential to the worldwide quantum supply chain. There are many more—including high-profile players CEA-Leti, STMicroelectronics, and Infineon Technologies, for semiconductor manufacturing and advanced packaging, as well as Zurich Instruments and Qblox, both for control electronics; Toptica Photonics, for lasers; Riverlane, for quantum error correction hardware and software; and QphoX and Welinq, for quantum computer interconnect technologies.

According to author Ezratty, Europe's quantum role is unlikely to shrink anytime soon. With so many companies focused on specialized subsystems, the continent has become indispensable to labs and quantum startups worldwide. "They may buy their qubits from the U.S., but they buy a critical part of their infrastructure from Europe," Ezratty said.

This growing reliance on European infrastructure companies reflects both a technological advantage and an industrial mindset rooted in precision and specialization. Unlike the U.S. model of vertically integrated tech giants, Europe tends to build collaborative networks of SMEs, each contributing a piece of the stack. "We don't have the quantum computers of IBM," Ezratty said. "But we're the toolbox IBM uses."

From pilot lines for quantum chips to shared cryogenic testbeds and standardization initiatives, the continent is quietly shaping the tools and processes that everyone else will need. As quantum technologies inch closer to commercial viability, the question is no longer whether Europe will participate but how it will lead.

For Bosman, Ezratty, and Gunnarsson, the answer lies in greater interoperability, smarter investment, and continued industrialization. Europe may never dominate the quantum endgame, but if it plays to its strengths, it will secure its critical role. ■

OPINION | **THE QUANTUM LEAP** | EUROPE'S PLEDGE

Room-Temperature Quantum Can Revitalize Europe's Semiconductor Industry

By Mark Mattingley-Scott, Quantum Brilliance

Europe's quantum community is witnessing the transformative potential of quantum technologies to revolutionize not just computing but the entire European semiconductor ecosystem.

While the semiconductor industry continues to struggle with geopolitical tensions, supply chain vulnerabilities, and a relentless push toward smaller manufacturing process nodes, a quantum revolution is quietly reshaping what is possible in the future.

QUANTUM AT ROOM TEMPERATURE

Casual observers of quantum computing assume that all systems require temperatures colder than that of outer space to maintain qubit stability and minimize errors. However, there are other approaches, such as room-temperature systems based on diamond nitrogen-vacancy centers, that can operate under ambient conditions without the need for complex and energy-intensive cryogenic hardware.

When quantum processors can perform computations at the edge or in data centers without infrastructure requirements, or when quantum sensors are able to operate in industrial environments and monitor magnetic fields with unparalleled precision, we are looking at a paradigm shift with practical and deployable quantum devices that could completely redefine Europe's position in the global semiconductor value chain.

The quantum transition could revive segments of the European semiconductor industry that have struggled to remain competitive with Asian manufacturing scale.

THE EUROPEAN ADVANTAGE IN QUANTUM MANUFACTURING

Europe's semiconductor industry transition to the quantum era directly plays to its existing strengths. Manufacturing room-temperature qubits requires atomic-level precision in nitrogen implantation and subsequent processing. Those requirements align perfectly with Europe's expertise in advanced materials and process engineering.

The quantum transition could also revitalize segments of the European semiconductor industry that have struggled to remain competitive with Asian manufacturing scale.

With established research institutions and industries in place, the quantum manufacturing supply chain presents a unique opportunity for the European Union. Unlike traditional semiconductor manufacturing, which has become increasingly concentrated in Asia, quantum device fabrication requires specialized knowledge in quantum materials, precision optics, and novel packaging techniques. Europe already leads in many of the relevant areas, from diamond synthesis to quantum control systems.

SENSING REVOLUTION: QUANTUM ADVANTAGE IN INDUSTRIAL APPLICATIONS

The immediate commercial opportunity lies not in quantum supremacy for computational problems but in quantum sensing applications that provide tangible value in industrial settings. Room-temperature quantum sensors can detect magnetic fields with sensitivities approaching fundamental quantum limits, offering near-term useful applications in mobility, medical devices, and industrial monitoring.

In automotive applications, for instance, quantum magnetometers could revolutionize navigation systems, providing GPS-independent positioning with unprecedented accuracy. For medical devices, quantum sensors could enable new classes of noninvasive diagnostics, detecting cellular-level magnetic signatures that classical sensors cannot resolve. Industrial applications range from detecting microscopic defects in manufacturing to monitoring the integrity of critical infrastructure.

Unlike the exotic environmental conditions of most gate-based quantum computers, quantum sensors can operate in factory environments, vehicles, and portable devices. Such practicality transforms quantum technology from a research curiosity into a viable commercial product category that European companies can address with existing manufacturing capabilities.

RETHINKING THE COMPUTING PARADIGM

While quantum sensing offers immediate commercial opportunities, the computing applications of room-temperature quantum devices present longer-term strategic implications. Rather than compete directly with classical computers for general-purpose computing, room-temperature quantum processors excel at specific optimization problems and quantum machine-learning applications.

Contrary to a commonly held view, achieving quantum utility doesn't require millions of qubits. For many commercially relevant problems, such as portfolio optimization, supply chain management, and ML feature mapping, quantum processors with small numbers of high-quality qubits can provide meaningful advantages. Room-temperature systems, while currently limited in qubit count compared with cryogenic systems, can achieve the coherence times and gate fidelities necessary for these applications.

This creates a compelling value proposition for European industrial companies. Rather than wait for fault-tolerant quantum

IMAGE: QUANTUM BRILLIANCE

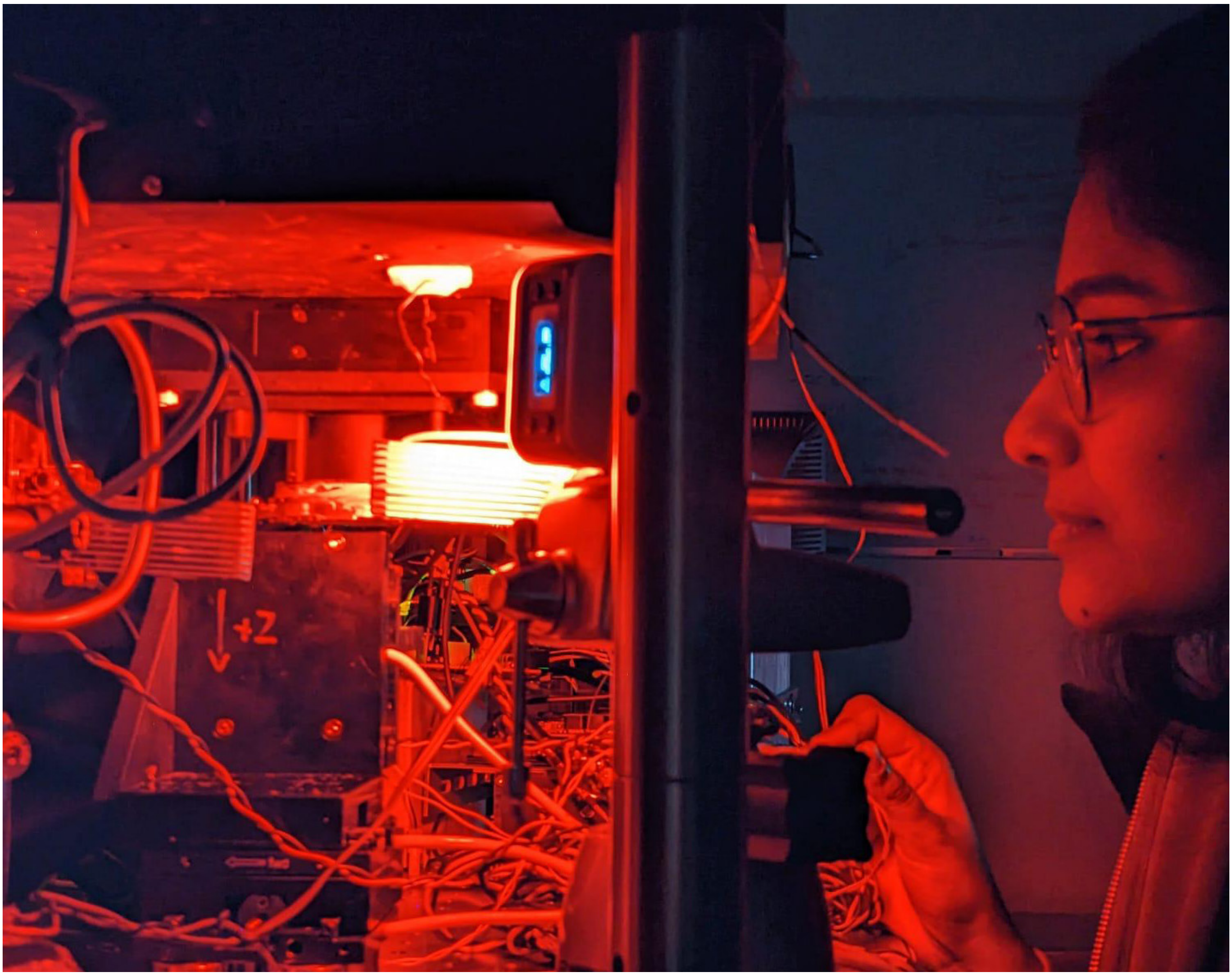


IMAGE: QUANTUM BRILLIANCE

computers that may be decades away, they can begin integrating quantum processing capabilities into existing workflows today.

STRATEGIC IMPLICATIONS FOR EUROPEAN SEMICONDUCTOR POLICY

The quantum transition presents both opportunities and challenges for European semiconductor policy. On the one hand, quantum technologies offer a path to technological leadership in a field where European research institutions and companies are already globally competitive. On the other hand, the quantum supply chain poses new dependencies and security implications to consider.

The European Chips Act focuses primarily on traditional semiconductor manufacturing, but quantum technologies will require a different strategic approach. To take full advantage of the opportunity, additional targeted investments in quantum materials research, manufacturing process development, and the creation of quantum-ready industrial ecosystems will be needed.

Security considerations are particularly important in the utilization and application of quantum technologies. Room-temperature quantum devices, while less powerful than cryogenic systems for certain applications, are far more deployable in distributed sensing networks and edge computing applications. While this creates new opportunities for European companies, it also requires careful consideration of export controls and technology transfer policies.

THE PATH FORWARD: QUANTUM-READY INDUSTRIAL ECOSYSTEMS

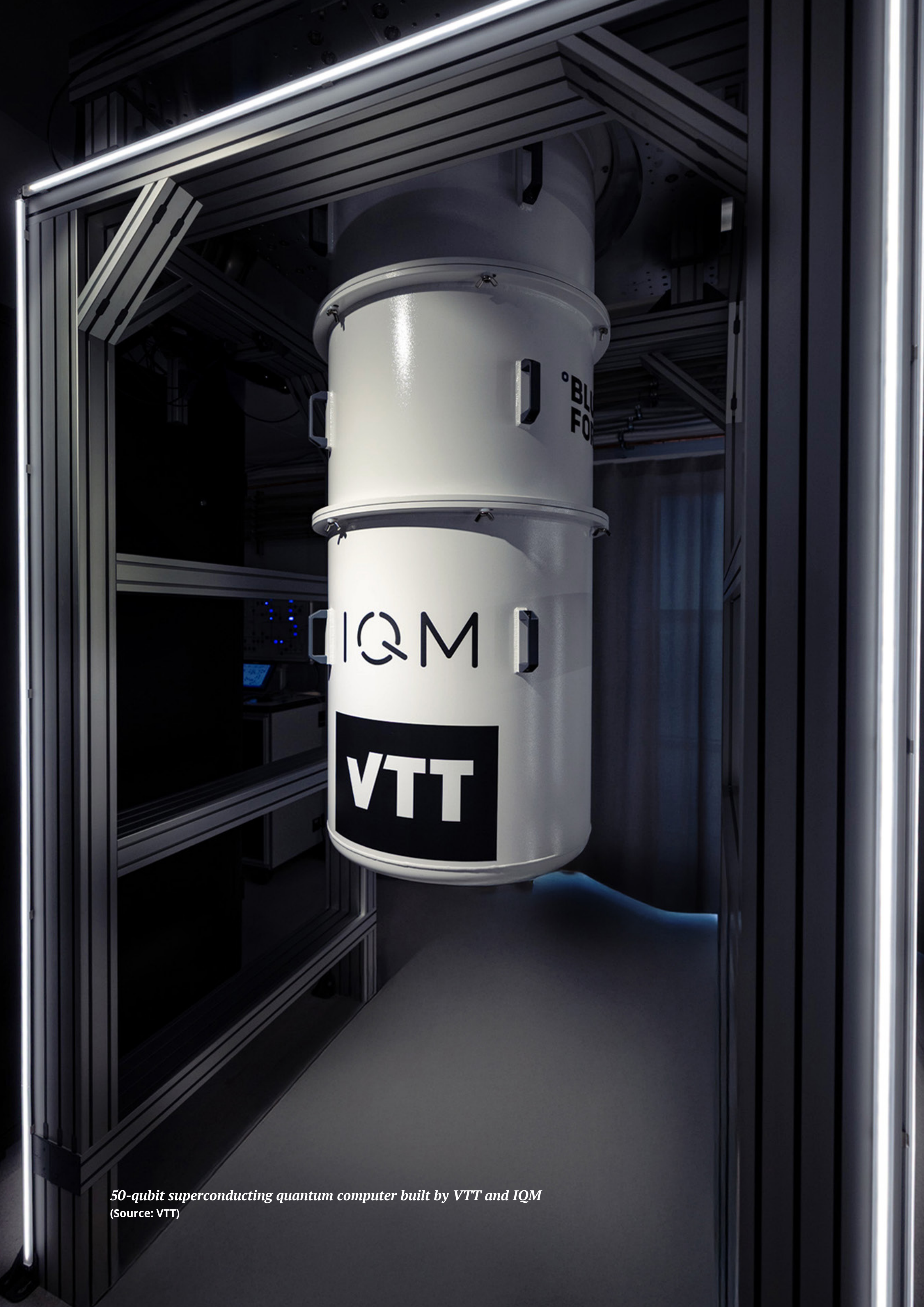
The magnitude of this opportunity extends beyond device manufacturing alone and will need to include quantum software development, system integration, and application development. European companies can create quantum-ready industrial platforms that combine room-temperature quantum devices with classical computing systems, enabling industrial customers to realize quantum advantages without requiring deep quantum expertise.

This ecosystem approach could position Europe as the global leader in practical and near-term quantum technologies and applications, while other regions focus on more exotic quantum computing approaches. By concentrating on applications that provide immediate commercial value, European companies can build sustainable quantum technology businesses that, in turn, can fund continued research and development.

The companies that recognize this transition early and invest in quantum-ready capabilities will be best positioned to capture the value of the quantum economy. For Europe's semiconductor industry, this represents not just a technological opportunity but a strategic imperative to maintain competitiveness in an increasingly quantum-enabled world.

The quantum age is only beginning, and Europe should take full advantage of the technology's optimum, near-term modalities for the region's long-term benefit. ■

Mark Mattingley-Scott *is chief revenue officer at Quantum Brilliance.*



50-qubit superconducting quantum computer built by VTT and IQM
(Source: VTT)

THE QUANTUM LEAP | EUROPE'S PLEDGE

Can Finland Build Europe's Leading Quantum Computing Ecosystem?

By Pat Brans

With a national strategy grounded in collaboration, superconducting expertise, and startup momentum, Finland is emerging as one of Europe's most ambitious quantum hubs.

In late 2023, VTT Technical Research Center of Finland and IQM Quantum Computers unveiled Europe's first 50-qubit superconducting quantum computer—a milestone that not only underscored Finland's engineering chops but also spotlighted a national strategy sharply focused on long-term competitiveness in quantum computing. With a 300-qubit system on the horizon and a dense web of partnerships across government, academia, and industry, Finland may offer Europe's most coherent model for quantum development.

STARTING WITH A FOCUS ON SUPERCONDUCTING QUBITS

As a small country with limited resources, Finland made a calculated bet: Rather than chase every quantum modality, it would first concentrate on superconducting quantum computing. That decision was rooted in more than just technological preference; it was born from decades of investment in low-temperature physics and device fabrication.

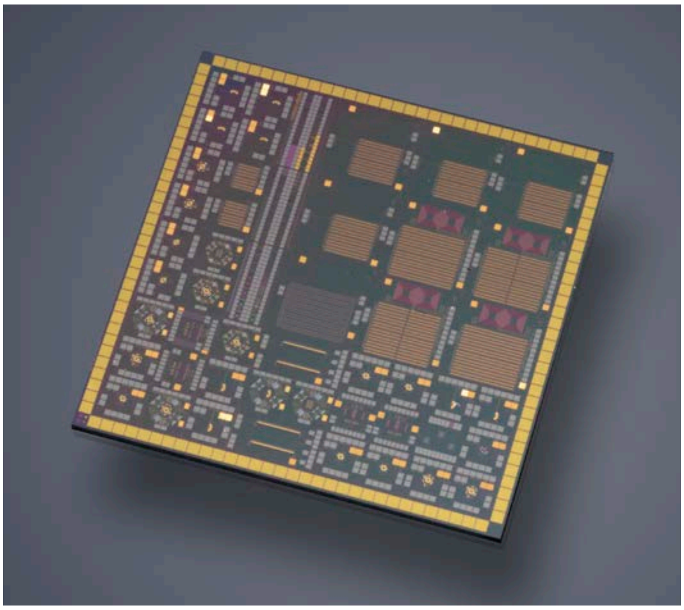
VTT's Pekka Pursula

"VTT has been building superconducting devices for over 30 years," Pekka Pursula, director of Microelectronics and Quantum Research at VTT, told EE Times Europe. "It started in the 1990s with SQUIDs [superconducting quantum interference devices] and Josephson junctions for medical imaging. So superconducting qubits were the natural choice."

SQUIDs are highly sensitive magnetometers used to measure extremely subtle magnetic fields; Josephson junctions exploit quantum tunneling to allow super currents to pass through insulating barriers. Those two key technologies in superconducting electronics laid the foundation for Finland's expertise in quantum hardware.

As a result, Finland now has a tightly integrated ecosystem that can supply much of the quantum stack—from Bluefors's cryogenic systems to IQM's quantum computers and VTT's fabrication and research capabilities. Efforts expanded to other qubit modalities. Photonics and silicon spin qubits are now supported through shared infrastructure and spinouts such as SemiQon. (See article on page 30.)

But the crown jewel of Finland's quantum ambitions is homegrown quantum computer manufacturer IQM, which bases its machines on superconducting qubits and has benefited from a strong partnership with VTT. Jan Goetz, co-CEO of the company, sees the collaboration not as a one-off R&D project but as a launchpad for industrialization.



The superconducting fabrication line at VTT enables complex quantum chips with thousands of Josephson junctions. (Source: VTT)

"Most deep-tech companies start with science, but we started with product," Goetz told EE Times Europe. "The 50-qubit machine has a user manual and a spec sheet, and we're installing copies in Munich and Italy. We're not just building once; we're scaling."

That product mindset is baked into IQM's roadmap. Each year brings a new chip generation, including a 150-qubit system in 2026. "We use Finland as the prototype site and then replicate to other countries," Goetz said. "It's similar to how supercomputers are upgraded."

IQM's Jan Goetz

The 150 qubits will be built on a single chiplet, which the following year will be replicated to form a 300-qubit system. "We'll scale by combining chiplets—side by side, and eventually stacked," Goetz said. "It's still superconducting technology, just packaged using semiconductor techniques."

By building and exporting systems from Finland, IQM ensures that the country remains central to operations even as its footprint expands globally. "There's a Finnish legal entity as our headquarters, and fully owned subsidiaries in countries like Germany, Spain, and the U.S.," Goetz added. "But the hardware is developed and manufactured in Finland."

DRAWING FROM A CULTURE OF INNOVATION AND COOPERATION

In Finland, government agencies, startups, research institutions, and universities tend to row in the same direction—a quality not always found in larger ecosystems. "Other countries try similar models, but alignment often breaks down because everyone is pursuing their own agenda," Goetz said. "In Finland, the roadmap is shared. That's a huge advantage."

IMAGE: ANTON SUCKSDORFF

SemiQon's Antti Vasara

This alignment extends to funding mechanisms. VTT's partnership with IQM was structured through public procurement, but with an unusual twist: The requirement wasn't just to build a machine but to build domestic capacity.

"We didn't want a black box," said Antti Vasara, former CEO of VTT and now chairman at SemiQon. "The procurement emphasized co-development. We chose IQM because they were willing to collaborate deeply."

That model helped develop local skills, inspired researchers, and laid the foundation for repeatable public-private innovation. "Ambitious goals energize people," Vasara told EE Times Europe. "At VTT and IQM, people realized they were building something historic."

With work toward a 300-qubit project now underway, the focus has shifted to architectural innovation. "Scaling from 50 to 300 by brute force is possible, but beyond that, fundamental changes are needed," Pursula said. VTT targets foundational technologies: cryogenic CMOS to reduce cabling, long-distance qubit couplers, and hardware that supports advanced error correction protocols.

"We're looking at the latest research on quantum error correction—for example, new error correction schemes from IBM and Microsoft that require qubits to interact beyond nearest neighbors," Pursula said. "That calls for more than just an incremental challenge; it requires a fundamental change in design."

Hardware advances are closely tied to integration with Finland's flagship Lumi supercomputer. "Right now, quantum computer calls are slow compared with traditional Lumi workflows," said Pursula. "But the goal is much faster turnaround for hybrid quantum-classical loops. That's where quantum will show early advantage, especially in materials modeling."

Finland's work on hybrid computing doesn't stop at software. VTT is developing electro-optical readout mechanisms to replace RF cabling and is working on solid-state on-chip coolers that could shrink today's refrigerator-sized cryostats down to tabletop units.

Finland is also designing its ecosystem to foster application development and startup formation. The 50-qubit system is available free to Finnish companies and researchers, provided they submit a proposal and publish results. "We want serious users who will contribute to the ecosystem," Pursula said. "It's about engagement, not just access."

That engagement is bearing fruit. Startups such as Quanscient, which uses quantum computing as part of a multi-physics simulation platform, have emerged from this model. And VTT recently spun out Arctic Instruments to develop cryogenic traveling wave parametric amplifiers. To connect all the dots, two national institutes (BusinessQ and InstituteQ) were formed to link universities, companies, and research labs in structured collaboration.

Even cultural factors play a role. Vasara pointed to Finland's long tradition of "building things ourselves," noting that the country installed its first telephone system just one year after the U.S. invented it. "We're a do-it-yourself society," he said.

QPU placeholder (Source: IQM)

That DIY culture has led to unique choices. When VTT realized there were no quantum computers available to run its algorithms in 2019, the company didn't wait—it built one. That same ethos applied in the 1950s, when Finland built its first classical computer from scratch using 400 vacuum tubes.

As geopolitical tensions grow, Finland's approach feeds into Europe's broader quest for technological sovereignty. "The QPU [quantum processing unit] is made in Finland; the cryogenics are from Bluefors; IQM supplies the control electronics—it's a European stack," Pursula said. Some dependencies remain—such as imported semiconductors and Helium-3—but Finland has demonstrated that Europe can build complete quantum systems without relying entirely on U.S. vendors.

Goetz underscored the importance of values. "European values are about collaboration, transparency, and building things that work," he said. "There's less hype than in the U.S., but we deliver." He also asserted that Finland's early focus on superconducting quantum computing makes it a natural leader in that domain. "We're already ahead in hybrid integration [with Lumi], and we're contributing to programs like the EU's AI Factories initiative. Even the U.S. is watching what we're doing here."

Four 5-qbit QPUs (Source: IQM)

Finland's model is not without its challenges. Talent remains a bottleneck, and the ecosystem is relatively small in absolute terms. But its coherent strategy, coupled with public-private alignment and a bias for execution, makes it a compelling case study in how a small country can lead in deep tech.

While Goetz cautioned against declaring any country a winner just yet—"Google has more than 100 qubits, and we're developing 150"—he emphasized that the goal isn't to beat others but to make progress together.

"The important thing is that we all move in the same direction," he said. ■

OPINION | THE QUANTUM LEAP | EUROPE'S PLEDGE

Europe's Quantum Strategy: Urgency Beyond the Blueprint

By Juha Vartiainen, IQM Quantum Computers

Recently, the European Commission (EC) rolled out its quantum strategy, with a welcome and necessary blueprint that speaks of ambition, sovereignty, and a clear intent to position Europe as a global leader in the quantum age by 2030.

The strategy focuses on five key areas: research and innovation, infrastructure, the quantum ecosystem, space and dual-use technologies, and skills development. But beyond the blueprint, the real test lies in its execution to truly harness the potential of quantum technologies.

The convergence of the strategy, the Quantum Act,[1] which the strategy has slated for proposal in 2026, and the multiannual financial framework negotiations presents a complex challenge. But it also poses a rare opportunity to rethink our approach and push the boundaries of what's possible—a mindset deeply ingrained in the quantum sector.

The voice of industry must be heard loud and clear, articulating its most urgent needs to enable a seamless transition over to the next phase. With the commercial quantum era on the horizon, the EU has a vital role to play in providing the necessary support and instruments needed to drive progress.

Fortunately, the EU already has a broad set of tools at its disposal. Now is the time to deploy them effectively.

The key to accelerating any innovation lies in creating a supportive ecosystem that mitigates risks and rewards investments. By implementing EU-guided tax incentives, such as harmonized tax credits like those proposed by DigitalEurope, we can provide a vital stimulus to businesses investing in quantum technology.

This can be achieved through tax deductions or refunds, making it more attractive for companies to invest in quantum research and development. Additionally, introducing first-loss guarantees can help de-risk private investments, reducing the exposure of investors to potential losses. When paired with programs such as the Scaleup Europe Fund, these measures can create a powerful synergy that stimulates innovation.

In the near future, Europe's quantum ecosystem will be ready for large-scale industry adoption, but a catalyst is needed to ignite widespread uptake. Public–private partnerships offer a powerful mechanism to create and shape early markets, but their success depends on thoughtful design and effective execution.

Large-scale industry adoption remains elusive. To bridge this gap, we can leverage initiatives such as the EU's AI Gigafactory network, which builds on the AI Factories initiative, harnessing Europe's cutting-edge EuroHPC supercomputing network. Such initiatives can work as platforms to foster collaborations between European companies and private sector players, driving industry-wide adoption and fueling growth through EU-backed incentives.

The proposed EU Grand Challenge[2] mechanism is designed to accelerate quantum innovation by supporting individual startups and scaleups in developing their groundbreaking technologies. Through a competitive and collaborative process, this initiative would bring together startups, researchers, and industry users to tackle the most pressing challenges in the field. By fostering collaboration and knowledge sharing, the Grand Challenge mechanism could serve as a powerful catalyst for quantum breakthroughs and significantly accelerate progress in quantum technologies.

To complement this effort, we propose introducing more dynamic funding models, such as fast-track funding calls with accelerated decision-making timelines—e.g., 90 days or less—to empower scaleup-ready firms to translate their research rapidly into industrial applications, driving economic growth and competitiveness.

The key to successful quantum computer deployments lies not only in technological advancements but also in deep understanding of end user needs. By placing users at the center of public procurement processes, we can ensure that quantum technologies are aligned with real-world applications and industry demands. The upcoming EU Quantum Computing and Simulation Roadmap,[3] scheduled for release in 2026, presents an opportunity to shape the future of quantum technology. This roadmap aims to establish clear benchmarks and a monitoring process to track the progress and maturity of various quantum platforms. By incorporating user requirements directly into the roadmap's monitoring and evaluation framework, we can ensure that the development of quantum technologies is relevant and widely adopted from the start.

Quantum chips are the backbone of Europe's future competitiveness and technological autonomy. To maintain our lead, we must move beyond lab experiments and scale up to industrial foundry-level production. This requires a clear roadmap, targeted funding, and strategic investments—particularly in defense-related applications. Aligning the proposed Quantum Chips Industrialization Roadmap,[4] which aims to support full industrialization planning and its implementation, with the upcoming Chips Act 2.0 is essential to prevent funding gaps and secure Europe's leadership in quantum technologies.

Finally, the EU's technology strategy should draw lessons from both past successes and earlier challenges. In this context, cloud-delivered quantum services must not be overlooked. As the landscape evolves, there is a unique window of opportunity for growth and innovation. Rather than introduce new regulations at this stage, the EC should focus on targeted support, enabling European providers to develop quantum-based cloud services and empowering the first wave of end users to drive early demand.

The strategy seeks to prioritize and focus Europe's efforts, ensuring that we are pursuing the right goals, at the right scale, and with a forward-looking mindset. This demands intentional choices, even when outcomes remain uncertain.

Europe's active participation in the global race for quantum advantage not only is feasible but is essential to the continent's future prosperity. Even more essential is a sense of urgency. ■

Juha Vartiainen *is a co-founder of IQM Quantum Computers and is the company's chief global affairs officer.*

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[3]Quantum Europe Strategy, 2025, p.7
[4]Quantum Europe Strategy, 2025, p.12

THE QUANTUM LEAP | EUROPE'S PLEDGE

Quantum Computing: Can £670 Million Put the U.K. on Top?

By Rebecca Pool

With tech rivals racing ahead and talent in high demand, the U.K. government's quantum investment is designed to bolster homegrown innovation and safeguard sovereignty.

In a move to secure the U.K.'s future at the forefront of quantum innovation, the government pledged £670 million (~€772 million) in June to supercharge the technology, which promises to revolutionize industry sectors from medicine discovery to clean energy. Described by the Department for Science, Innovation and Technology as "one of the largest and longest-term national commitments to quantum computing anywhere globally," more than £500 million (~€576 million) of the new funding will back near-term innovation—that is, within the next five years. Meanwhile, the National Quantum Computing Centre (NQCC), the U.K.'s national lab for quantum computing, is set to receive funds over 10 years, providing much-needed long-term certainty for development.

National Quantum Computing Centre's Michael Cuthbert

"This is hugely welcome, as well as a signpost to the market that we have this shared vision that quantum computing will take 10 years or more to come to fruition in terms of the scale we are seeking," NQCC director Michael Cuthbert said.

The latest funds follow a decade's worth of investment from the U.K. government with its National Quantum Technologies Programme, a £1 billion (~€1.15 billion) collaboration among industry, academia, and government. "This hasn't been a short-term endeavor, and certainly across government and [various] political parties, there's this view that [quantum] is a critical technology for which U.K. should be a leader," Cuthbert said.

But what do the latest funds mean for U.K. quantum computing sovereignty? Undoubtedly, the landmark investment will help to reduce reliance on overseas quantum technology providers.

Phasecraft's Ashley Montanaro

Ashley Montanaro, chief executive of U.K.-based quantum software developer Phasecraft, is among the industry leaders who have emphasized the need for funding to ensure a quantum computing lead.

"The U.K. has a fantastically good reputation in this field, but maintaining that is difficult," Montanaro said. "Successive U.K. governments have had this long-term commitment … and this level of commitment is necessary for the U.K. to keep calling itself a leader in quantum."

Ed Wood, vice president of product for Nu Quantum, agrees on the importance of public funding for the burgeoning industry. Last year, the company, a University of Cambridge Cavendish Laboratory spinout developing scalable quantum networks, released a qubit-photon interface for coupling qubits with photonic networks. In June of this year, Nu Quantum unveiled a quantum networking unit (QNU) for entanglement distribution across quantum data centers. The QNU has a technology-readiness level of 5 and can entangle a cluster of four quantum processors via four ports, but the aim is to network hundreds of processors eventually.

Nu Quantum's Ed Wood

"When the company started out, we really benefited from early [government] grants, feasibility studies, and procurement deals … that allowed us to really mature our technology," Wood said. "So we now really welcome this money. It's timely, and for companies like us, it will give us the opportunity to continue to adopt a lead position in quantum networking."

The Nu Quantum roadmap "is around scale—more connections, connecting more quantum computers," he added. "Assuming [the latest funds] are applied intelligently, this will allow companies like us to really shine on the world stage."

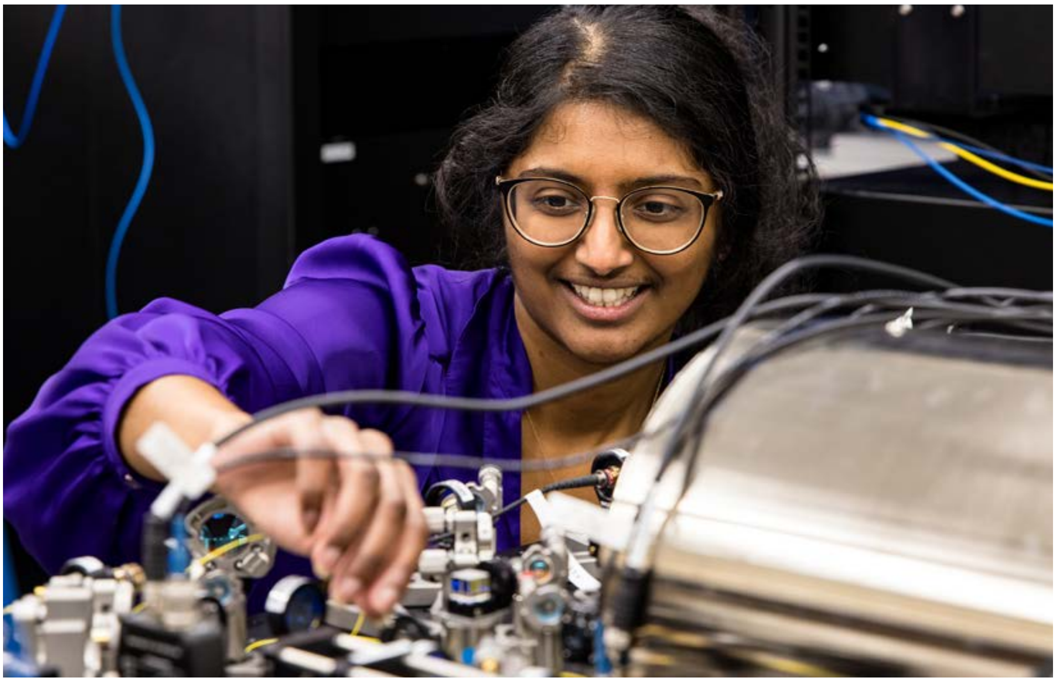
REACHING FAULT TOLERANCE

Cuthbert reckoned that large-scale, commercially available quantum computing by 2030 looks "increasingly like a reality" for U.K. companies, given recent quantum progress and the latest funding. According to the NQCC director, the U.K. has some 45 quantum startups, about half of which are working on computing. "We're seeing growing clarity on roadmaps as to when quantum computing will transition from technology under development to deployable technology with commercial value," he said.

Indeed, last year, Quantinuum—formed through the merger of Honeywell Quantum Solutions and Cambridge Quantum—published its roadmap toward fault-tolerant quantum computing, targeting hundreds of logical qubits by 2029. Meanwhile, Oxford Quantum Circuits just released its roadmap, aiming to reach 200 logical qubits by 2028 and 50,000 logical qubits by 2034. IBM has defined a large-scale fault-tolerant system as one that can execute more than 100 million quantum operations across hundreds of logical qubits.

On top of converging roadmaps, Cuthbert cited the numerous U.K. companies taking part in U.S. Defense Advanced Research Projects Agency (Darpa) programs. Darpa's U.S. Quantum Benchmarking

NQCC, the U.K.'s national lab for quantum computing, is set to receive funds over 10 years, providing much-needed long-term certainty for development.
(Source: National Quantum Computing Centre)



In the lab at the NQCC: The National Quantum Computing Centre houses 12 quantum computers that are not restricted to government ownership or use; anyone with a valid use case can access the systems. (Source: National Quantum Computing Centre)

Initiative, for example, has selected world-leading quantum players to assess the feasibility of building a useful quantum computer by 2033. U.K.-related participants include Quantinuum, Oxford Ionics (recently acquired by IonQ), Diraq, Rigetti U.K., Orca Computing, and others.

"We've also had a number of Series A, Series B, Series C funding rounds—ever larger-scale investments—coming into U.K. companies," Cuthbert said. "This and many announcements genuinely flag a thriving quantum ecosystem in the U.K. … I don't think we do enough to shout about the progress we're making."

BEYOND THE STACK

The transition from development to deployment demands not only scalable hardware but also robust algorithms—and Phasecraft's Montanaro believes the U.K. can really shine in providing the latter. "I run a software company, so it's no surprise to hear me say that software algorithms and application layers of quantum computing are essential yet perhaps have been overlooked historically," he said. "But over time, the improvement in computational costs you can get from algorithms far outstrip improvements in hardware."

For quantum technologies, "we see this clear parallel with classical computing in that the U.K. has not tended to be a leader in hardware but can be in the software," he added. "I think this is the area the U.K. really needs to capitalize on."

Other U.K. quantum software developers include Riverlane, which provides both quantum error correction hardware and software; Quantinuum, headquartered in both the U.K. and U.S. and developing both hardware and software; and algorithm software developer Qoro Quantum. But can U.K. software development rival overseas efforts?

As Montanaro pointed out, "You have to look at the whole effort that's going into quantum software in the U.S., for example, where there's a huge academic base working on this, as well as significantly funded efforts within some large quantum computing companies. If the U.K. wants to lead here, it's possible, but it's going to be tricky."

A clear indication of overseas quantum strength came late last year when Google unveiled its Willow chip, which demonstrated an exponential reduction in error rate, driving down errors while scaling up qubit numbers. "This [chip] shows there is a genuine pathway toward fault tolerance, [within] a reasonable time scale," Montanaro said.

The Phasecraft chief executive said he had yet to see a "U.K. breakthrough with this level of excitement" but hopes U.K.-based efforts will yield software breakthroughs of similar significance. "This is what we're working toward," he said.

Of course, this is where the latest government funds—provided to accelerate the application of quantum technologies—should help. Still, Montanaro cautioned, "It's really important that the [latest funds] are delivered in year one and not year nine … and they need to be deployed wisely.

"If these funds are used to enable companies such as ourselves to have certainty and an engaged customer base, that could be a really good way to accelerate the industry in the next couple of years," he added. "We need to see the funds getting implemented on a timescale of months and not a timescale of years."

KEEPING TALENT

The new funds were announced in the wake of a cross-Atlantic acquisition deal, with U.S.-based trapped-ion quantum computer developer IonQ acquiring Oxford Ionics earlier in June for a mighty $1.075 billion (~€0.93 billion). Oxford Ionics currently holds the world record for quantum fidelity, a measure of quantum operation accuracy, and as Cuthbert noted, the deal is a "huge endorsement" of the U.K. startup's quantum progress and technology.

"This had a very, very significant price tag … and is amongst a number of recent announcements that genuinely flag our thriving quantum ecosystem," he said.

As the quantum computing industry matures, expect further consolidation, mergers, and acquisitions involving homegrown technology developed by startups. And while the £670 million government backing signals the U.K.'s intent to protect its domestic quantum market and lead in the field, concerns around talent acquisition by overseas players are clear.

"Oxford Ionics is not the only company in the U.K. making quantum hardware—we're not yet at a stage where we need to maintain everything in terms of our hardware platform—and we also have a fantastic relationship with the U.S., where many of the world's top hardware companies are based," Montanaro said. "But in terms of building up a U.K. quantum industry, it will be unfortunate for the U.K. if we see a trend of quantum companies being snapped up and effectively moving offshore."

The threat of key technology and talent moving overseas will likely remain real for some time. However, the U.K. government's investment over the next decade can only help to push U.K. quantum computing from a promising frontier into a commercially viable reality on the world stage. ■

Rebecca Pool *is a contributing writer for EE Times Europe.*

THE QUANTUM LEAP | HYBRID COMPUTING

Hybrid Quantum-Classical: Europe's First Exascale Computer Connects to D-Wave

By Pat Brans

The Jülich Unified Infrastructure for Quantum Computing is located at the Jülich Supercomputing Center within Forschungszentrum Jülich. (Source: Forschungszentrum Jülich/Michael Bresser)

Jupiter host JSC and D-Wave hope to raise the stakes in hybrid computing.

Europe has taken another step forward in quantum-classical integration. The Jülich Supercomputing Center (JSC), home to the newly ranked No. 4 system on the TOP500 list, has installed a D-Wave Advantage 5000+ system onsite and is working to couple it tightly with Jupiter, Europe's first exascale computer. The initiative reflects Germany's determination to explore real-world applications in quantum optimization, chemistry, and materials science.

The hybrid arrangement isn't a new idea; the concept dates back to the origins of quantum algorithms. Shor's algorithm, introduced in the 1990s for factoring large integers, assumed a hybrid architecture, with quantum computation performing key steps and classical computation handling others. For the foreseeable future, virtually all quantum algorithms will be hybrid, a model that reflects the limitations and strengths of each type of processor—quantum systems handle the complex tasks on which they demonstrate supremacy, while classical systems manage control, preprocessing, and interpretation.

Some organizations rely on cloud-based services to perform the quantum operations. JSC chose to buy its own system and run it in-house.

BUILDING QUANTUM-CLASSICAL SYNERGY ON-PREMISES

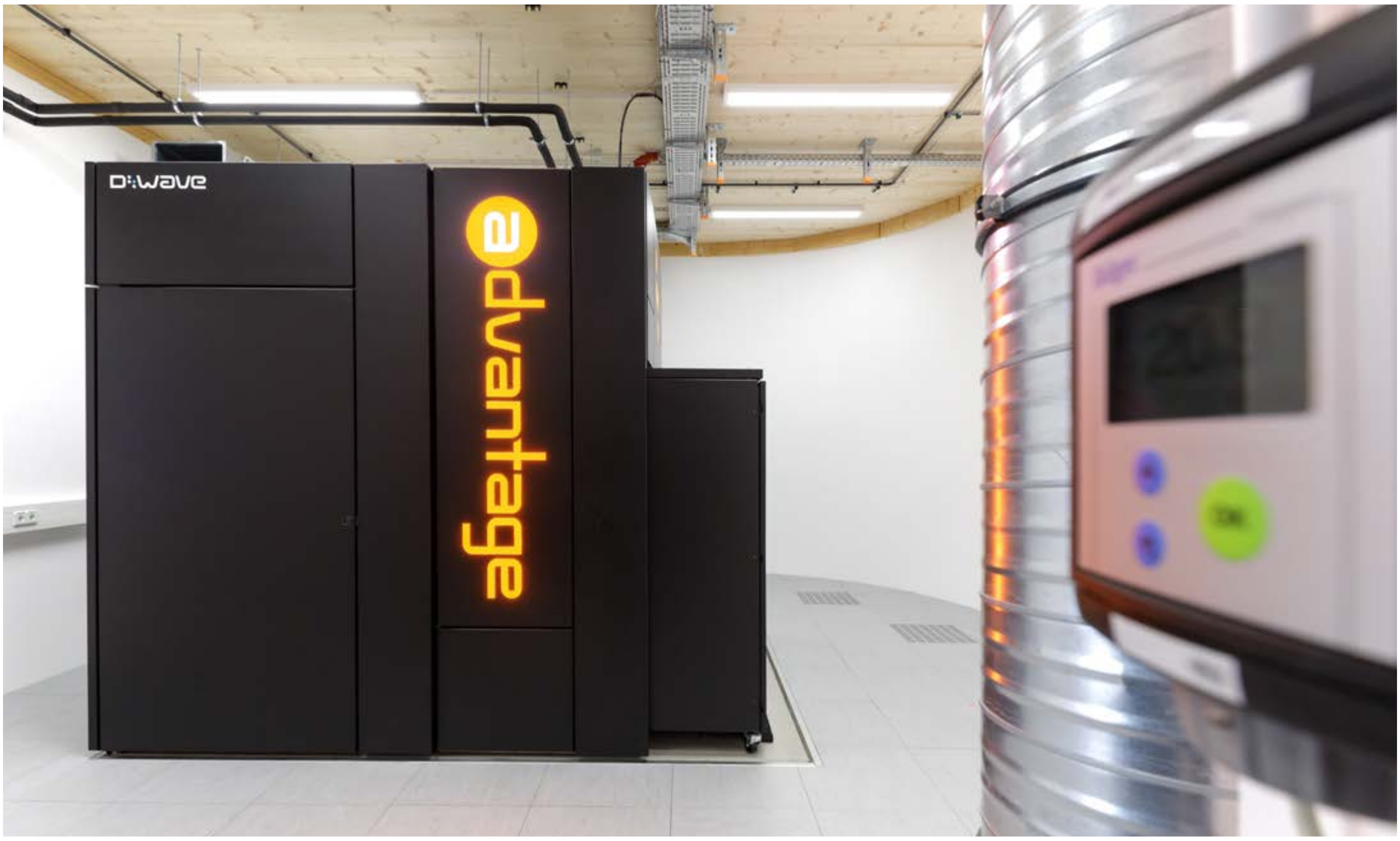
According to Kristel Michielsen, co-lead of JSC and head of its quantum information processing division, the decision to host a quantum annealer on-premises rather than rely solely on cloud-based access reflects both technical and strategic priorities. "We wanted a machine that is mature, ready for users, and able to support prototyping of real applications," she said. Unlike many gate-based quantum systems still operating in fragile lab settings, the D-Wave annealer is robust and commercially deployable.

Jülich Supercomputing Center's Kristel Michielsen

Borrowing from metallurgy, where "annealing" refers to a process of heating and then slowly cooling a material to remove defects and reduce energy states, quantum annealing involves purpose-built machines that seek the lowest energy configuration of a complex system—effectively finding optimal or near-optimal solutions to such problems as scheduling, routing, and machine learning. Unlike gate-based quantum computers, which operate using logical gates to perform arbitrary computations, a quantum annealer encodes a problem into a network of qubits, which then evolve toward a minimum-energy state that represents the best solution.

The maturity of D-Wave's systems was a key factor for selecting one to integrate with the complex workflows of high-performance computing (HPC). JSC has experience managing sophisticated HPC infrastructure, from air cooling to hot water cooling, and now sees quantum hardware as the next evolutionary step. By installing the machine locally, JSC's infrastructure team gains critical experience in maintaining and operating quantum systems—skills that will be essential as quantum accelerators become more mainstream.

D-Wave, for its part, views the deployment as a strategic inflection



D-Wave Advantage System in the Jülich Unified Infrastructure for Quantum Computing building at the Jülich Supercomputing Center
(Source: Forschungszentrum Jülich/Ralf Uwe Limbach)

point. "JSC's purchase enables us to work together to deeply understand the requirements for HPC integration and develop system configuration changes that best support that," Trevor Lanting, chief development officer at D-Wave, said. He emphasized that on-premises access opens new research opportunities, enabling direct control over system parameters and collaboration on workflow orchestration.

The integration of the quantum machine into Jupiter is still in development. While details are being worked out in collaboration with D-Wave, the vision is clear: a tightly coupled system with minimal latency and efficient workload orchestration. Rather than use cloud-based APIs, the JSC team aims to create direct, high-speed connections between the classical and quantum computers.

D-Wave's Trevor Lanting

The approach requires adapting existing job schedulers, such as the Simple Linux Utility for Resource Management, to accommodate quantum workflows. Michielsen described a modular architecture in which the quantum annealer is treated like a specialized booster module, similarly to how GPUs are integrated today. In this model, quantum jobs are scheduled within classical HPC workflows, with quantum tasks spun off at key moments and results reintegrated seamlessly.

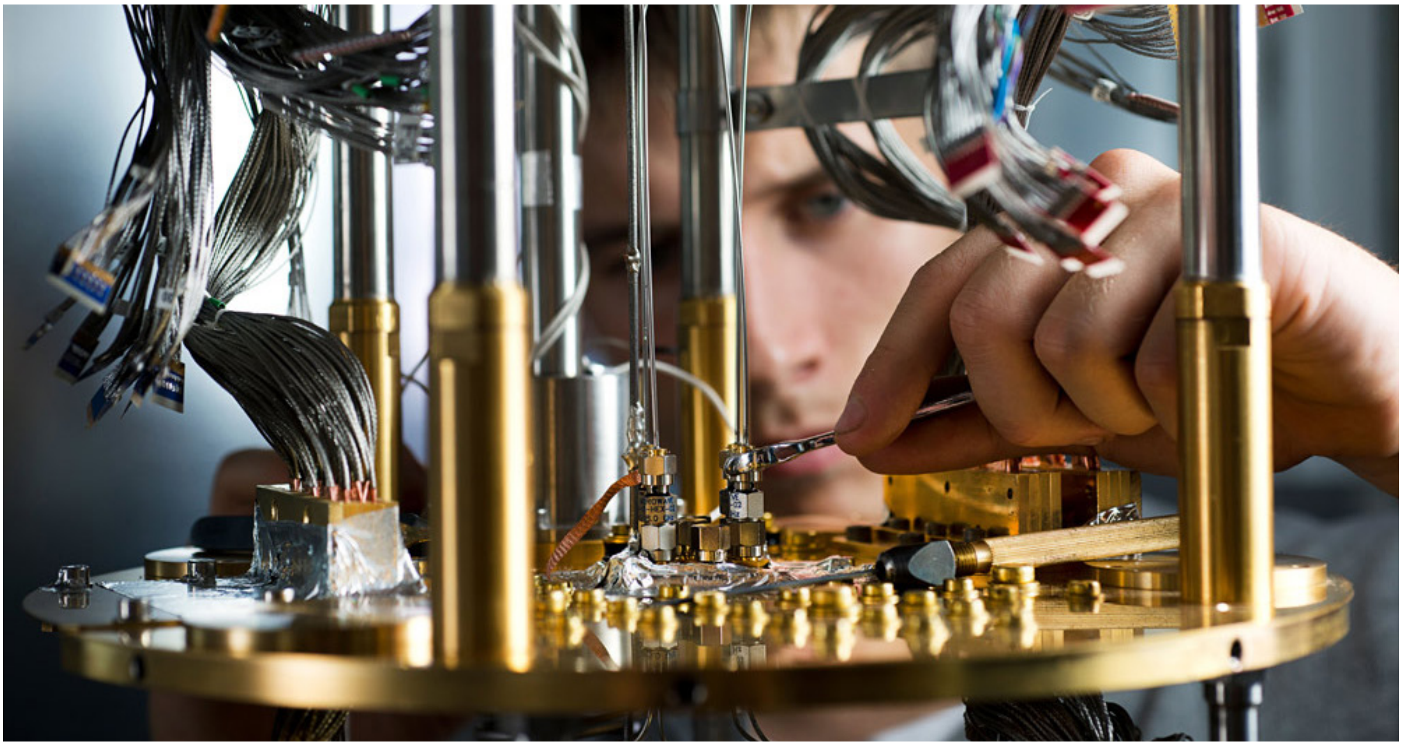
D-Wave is supporting these efforts. "Hybrid workflows will increasingly mirror today's HPC model, where CPUs, GPUs, and now QPUs each play a role," Lanting said. In his view, quantum processors will complement classical accelerators, particularly in domains such as AI and materials science, where computational bottlenecks persist. D-Wave's ongoing hardware development—most recently with the Advantage2 system, which brings improved connectivity, coherence, and noise reduction—aims to extend the reach of quantum solutions in exactly these areas.

ACHIEVING PRACTICAL ADVANTAGE WITH GOOD USE CASES AND ENERGY EFFICIENCY

JSC sees two main classes of hybrid use cases. The first is D-Wave's native hybrid solvers, which divide optimization problems between quantum and classical systems. The second is more deeply integrated workflows, in which a classical simulation—for example, in climate modeling or materials science—calls on the quantum annealer for a specific optimization task before continuing. This model allows researchers to explore quantum acceleration in practical contexts without rearchitecting their entire pipelines.

The center is cautious but optimistic about performance gains. As Michielsen explained, benchmarking quantum advantage is a tricky business. Classical algorithms have been refined for decades, making it hard for a new technology to match them on speed or precision. But there are other forms of advantage. "It does not always have to go faster," she said. "If you can get a reasonable result on a quantum system using less power or fewer resources, that is also a benefit."

Lanting echoed the point, citing peer-reviewed research in which D-Wave's systems performed simulations at a fraction of the energy cost of traditional supercomputers. "For some problems, our systems have delivered results orders of magnitude faster and using dramatically less power—sometimes less than a dollar's worth of electricity for workloads that would otherwise consume the world's annual energy



Closeup view of D-Wave's dilution refrigerator (Source: D-Wave)

supply," he noted. The promise of energy-efficient computing is especially relevant for Europe, where sustainability is becoming a defining feature of tech policy.

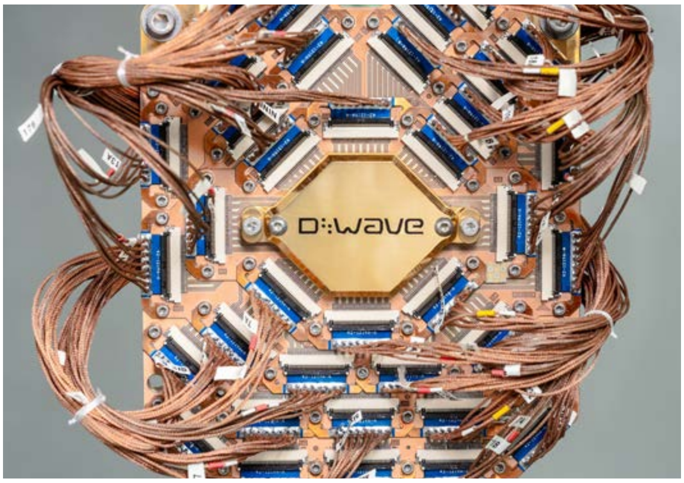
That pragmatic attitude also guides the center's application strategy. While quantum computing holds promise in fields such as drug discovery and battery design, Michielsen urges caution. Much of the existing literature demonstrating quantum benefit is based on solving trivial problems with very few qubits. "Maybe the potential is there, but bringing theory into practice involves many challenges," she said.

According to JSC's Kristel Michielsen, the decision to host a quantum annealer on-premises rather than rely on cloud-based access reflects technical and strategic priorities.

JSC is exploring use cases in protein folding and quantum machine learning, particularly image classification.

Germany's leadership in materials science and chemistry provides fertile ground for quantum exploration, but JSC's goal is not to hype quantum computing; it's to make the technology usable. That includes designing access mechanisms to integrate quantum systems into existing HPC user workflows. Academic users already access JSC's quantum systems through peer-reviewed proposals, with rolling submissions and fast-track reviews. Industry access is growing, too, especially with European regulations that favor on-soil hosting.

Michielsen noted that the D-Wave system is already undergoing its first upgrade—from Advantage to Advantage2—without disrupting the operational environment. That upgradability is another reason JSC opted for D-Wave: As the computers improve, they can be swapped in with minimal disruption. Future upgrades may require more extensive integration efforts, but JSC's experience and partnership-first philosophy prepare it well.



Quantum processing unit used in D-Wave's Advantage2 (Source: D-Wave)

JSC has long championed hybrid HPC-quantum systems. In fact, Michielsen believes the center was among the first to articulate this vision in Europe. Today, similar strategies are emerging across the continent, aided by European funding for quantum pilot lines and system integration.

The cultural challenge, Michielsen said, is often greater than the technical one. Users accustomed to CPUs and GPUs must adopt new tools, new workflows, and new ways of thinking. JSC addresses this by embedding quantum within existing HPC service models, providing training, support, and realistic expectations. Sometimes that means redirecting users to conventional HPC before they leap to quantum.

Ultimately, JSC said it hopes to demonstrate real, reproducible advantage within two years of the system going live. The D-Wave machine is expected to be fully operational in 2026, and early hybrid prototypes could appear as soon as 2027.

But Michielsen was clear: There will be no shortcuts. Demonstrating value takes time. ■

THE QUANTUM LEAP | SILICON SPIN QUBITS

Silicon Spin Qubits: Scaling Toward the Million-Qubit Era

By Pat Brans

As quantum computing heads toward industrial readiness, a new class of qubits is emerging with potential for large-scale deployment: silicon spin qubits.

Quantum supremacy—the point at which quantum computers solve problems infeasible for classical ones—may be achievable with hundreds or thousands of qubits. But large-scale applications such as quantum chemistry, capital allocation, and advanced machine learning require qubit counts in the millions. Moreover, error correction schemes require hundreds of physical qubits for every logical qubit.

CEA-Leti and Quobly are collaboratively applying their deep semiconductor know-how, a shared lab, and a bold roadmap to the problem, betting that silicon—the material that scaled classical computing—will do the same for quantum computing. “All leading technologies now offer strong quantum performance for small systems,” Maud Vinet, CEO of Quobly, told EE Times Europe. “What sets us apart is scalability.”

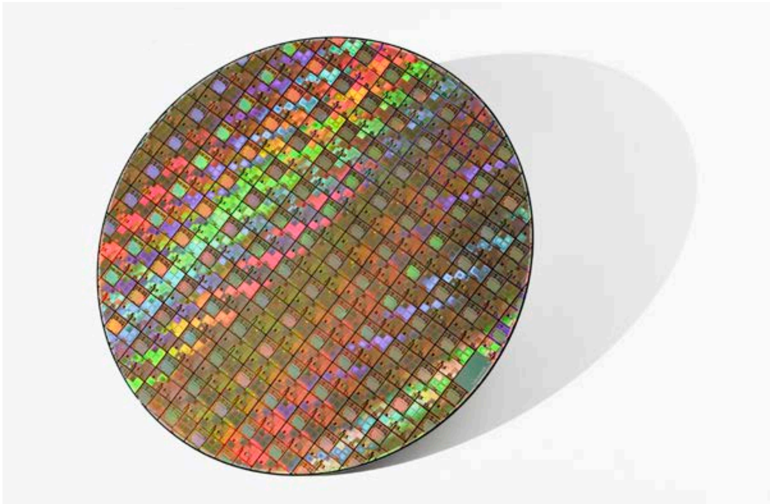
Quobly’s Maud Vinet

Quantum computing modalities—such as superconducting qubits, trapped ions, photonics, and silicon spin qubits—can be compared based on several metrics: qubit fidelity, coherence time, gate speed, scalability, fabrication complexity, and compatibility with existing technologies. Each modality comes with tradeoffs: For instance, superconducting qubits offer fast gates but are quite large and require complex cryogenics, while trapped ions have relatively high fidelity but are difficult to scale.

Silicon spin qubits are emerging as a promising middle ground that balances speed, scalability, and manufacturability. The nanometer-scale devices store quantum information in the spin state of electrons within silicon quantum dots, offering fast gate operations. All operations are performed within microseconds, providing the ability to run billions of operations very quickly. Moreover, millions of silicon spin qubits can be squeezed onto a single chip. (See article on page 30.)

CEA-Leti’s Olivier Faynot

“CMOS technology has enabled very high transistor densities in classical computing, and we believe this same foundation can be leveraged to scale up quantum systems,” Olivier Faynot, EVP and head of the silicon components division at CEA-Leti, told EE Times Europe. Existing CMOS processes offer a path to fabricate chips with silicon spin qubits en masse—once the technical hurdles are resolved.



Quobly silicon wafer for quantum chips
(Source: Emmanuel Nguyen Ngoc, Quobly)

CMOS, SUPERCONDUCTING INTERCONNECTS

According to Faynot, two big challenges stand in the way of scaling silicon spin qubits into the millions. The first is in developing cryogenic CMOS electronics that can function effectively at near-zero temperatures. The second centers on engineering advanced packaging using superconducting 3D interposers to isolate qubits from thermal noise.

Silicon spin qubits must operate at temperatures of about 1 K to maintain coherence and preserve quantum states. To manipulate and extract information from the qubits, highly specialized electronics are required. Control circuits initiate operations on specific qubits by applying voltage or magnetic pulses, while readout circuits measure their quantum states—usually by detecting spin-dependent currents or changes in resonance frequencies. These functions must be performed with minimal power dissipation to avoid disturbing the delicate cryogenic environment.

“We’re tackling these challenges with ultra-low-power cryogenic CMOS and superconducting interconnects,” he said. “Our cryo-CMOS work has already been published and demonstrates extremely low power consumption, [which is] critical for maintaining qubit coherence.”

The approach is based on a microsecond-scale readout circuit with a 10× reduction in power usage. As reported in both a Quobly press release and an IEEE panel chaired by Vinet, the quantum integrated circuit uses cryo-CMOS transistors and multiplexing techniques to address the wiring bottleneck at cryogenic temperatures. “Current

Quobly cryostat with photonic cryo-compatible backend
(Source: Emmanuel Nguyen Ngoc, Quobly)

prototypes rely on lots of wiring, which isn't scalable," Vinet said. "Cryo-CMOS is essential for reducing wiring and minimizing latency—especially for quantum error correction."

Leti is also exploring ultra-low–temperature packaging and 3D integration methods such as hybrid bonding. These are critical for maintaining superconductivity and reducing thermal flux in multilayer quantum chips.

Superconductors are used with silicon qubits for thermal insulation and to enable the magnetic fields required for fast operations without heating the environment. "Each layer must maintain superconducting characteristics to avoid even millikelvin fluctuations," Faynot said. "Our goal is to isolate the cryogenic part of the system and handle readout and control with minimal thermal impact."

The near-term goal for Quobly is to deliver the Q100T processor, a 100-qubit chip that integrates cryogenic control electronics. The effort is supported by a €21 million funding grant from Bpifrance—France's public investment bank—within the framework of France 2030, announced earlier this year. The Q100T is a steppingstone to a fully error-corrected, scalable quantum system. "By 2027, we expect to demonstrate quantum error correction," Vinet said.

To support long-term ambitions, Quobly is also investing in development tools. A recent announcement highlighted the release of a silicon qubit emulator that enables early-stage software development and testing of quantum algorithms. The tool aims to lower the barrier for researchers and developers building on Quobly's hardware, and it signals the company's commitment to full-stack integration. "We're forming partnerships with cloud service providers to integrate our systems into existing infrastructures," Vinet said.

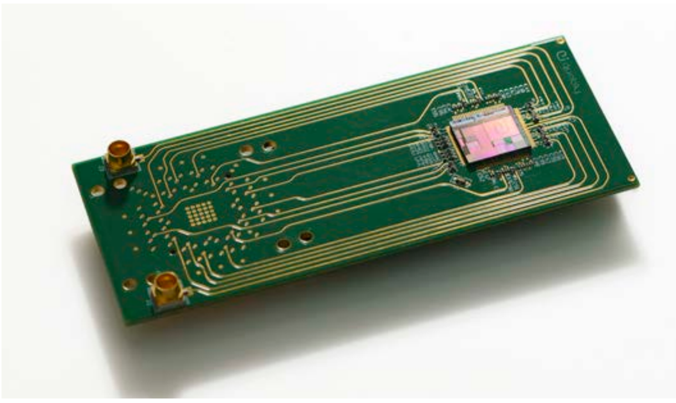
GRENOBLE STAKES ITS CLAIM IN THE GLOBAL QUANTUM RACE

Based in Grenoble, France, Quobly is surrounded by an ecosystem of semiconductor and academic players. "We're close to CEA-Leti, STMicroelectronics, CNRS [the French National Center for Scientific Research], Inria [the French Institute for Research in Computer Science and Automation], and Université Grenoble Alpes," Vinet said. This proximity enables rapid iteration and knowledge sharing. CEA-Leti and other academic partners focus on R&D—addressing the fundamental physics, developing cryogenic circuits, and demonstrating feasibility. Quobly drives execution, turning lab results into manufacturable technologies.

At the heart of the project is a shared lab between CEA-Leti and Quobly. The two teams meet weekly, share technical resources, and operate with tight milestone alignment. "Our collaboration works because of our proximity and complementarity," Vinet said.

Quobly has also signed a partnership with STMicroelectronics, which will play a critical role in industrializing Quobly's technology. "Our agreement with ST is unique in the quantum industry," Vinet said. "It gives us access to industrial-quality processes."

The strategic alignments are not just technical; they help position France as one of the most ambitious players in the quantum race. Germany and the Netherlands are also advancing silicon-based quantum research (via Fraunhofer and QuTech, respectively), but France's integrated ecosystem of national labs, startups, and industrial partners is unique in its cohesion and scale. In the U.S., companies such as Intel and HRL Laboratories are also investing in silicon spin qubits but with less direct access to a national lab/manufacturing collaboration like the one Quobly has through its partnerships with Leti and ST.



Quobly photonic cryo-compatible backend with quantum chip
(Source: Emmanuel Nguyen Ngoc, Quobly)

With a 100-qubit chip on the horizon, a rich European innovation ecosystem, and a vision that scales to millions of qubits, CEA-Leti and Quobly hope to position silicon spin qubits as the missing link between quantum promise and commercial reality. ■

THE QUANTUM LEAP | SILICON SPIN QUBITS

SemiQon Builds Momentum for Silicon Spin Qubits in Europe

By Pat Brans

As quantum computing progresses rapidly, its future may depend less on exotic physics and more on silicon.

As researchers and startups weigh competing quantum computing approaches, a growing number are betting on silicon spin qubits, which offer the advantage of compatibility with the same CMOS technology that powers today's smartphones and supercomputers.

One of the most ambitious players in this space is SemiQon, a Finnish startup spun out of VTT Technical Research Center. Rather than build full-stack quantum computers, SemiQon focuses on supplying the qubit chips and cryogenic control electronics that will power scalable quantum systems. CEO and co-founder Himadri Majumdar believes that Europe—long sidelined in classical chipmaking—has a chance to lead in quantum if it gets behind technologies such as cryo-CMOS and silicon spin qubits.

SemiQon's Himadri Majumdar

"Silicon qubits can be operated at around 1 kelvin, enabling better scalability," Majumdar told EE Times Europe. "They're also extremely small—about 100,000× smaller in area than typical superconducting transmon qubits—which becomes critical when you want to put hundreds of thousands or even millions of qubits on a chip. Most importantly, silicon is the only manufacturing technology that has proven yield for chips with billions of components. That growth potential is essential for large-scale quantum."

While silicon qubits can in theory be fabricated in standard fabs, the specialized doping, patterning, and isolation requirements are not entirely compatible with classical CMOS lines. In practice, adapting these lines for quantum-grade silicon remains nontrivial and capital-intensive. Scalability beyond a few thousand qubits is still only theoretical.

SemiQon is not the only company in Europe pursuing silicon spin qubits. In France, Quobly is developing its own approach in partnership with CEA-Leti. Their near-term goal is to deliver a full quantum computer: a 100-qubit system based on spin qubits in CMOS-compatible processes (see article on page 28).

"There are different ways of building silicon spin qubits," Majumdar said. "You have the CMOS approach, the FD-SOI [fully depleted silicon-on-insulator] approach, silicon germanium, pure germanium, and donor-based qubits. SemiQon and Quobly are similar in some respects, but while Quobly relies on room-temperature CMOS transistors adapted for cryogenic use, we have developed a transistor specifically optimized for cryogenic conditions."

That design difference may prove significant. Majumdar believes energy efficiency, thermal stability, and interconnect architecture will determine which technology wins in the long run. "With cryo-CMOS and spin qubits co-integrated, our architecture supports low-power operation, enabling fidelity and control even as systems scale to thousands or millions of qubits," he said.

COVERING ALL THE BASES WITH RESEARCH INSTITUTES

One way SemiQon accelerates development is by running its own processes in the VTT Micronova pilot line using its own staff—without relying on VTT technicians. "This allows us to own our process design kits and maintain full control over the recipes we develop," Majumdar said. "It also means we can iterate and run experiments 4× to 5× faster than companies that depend on external foundries."

Quantum computing is a priority for VTT, Erja Turunen, executive vice president of digital technologies at the research institute, told EE Times Europe. "We see quantum computing as a powerful tool in areas like chemistry, materials science, and pharmaceuticals."

But while both partners are full speed ahead on quantum, neither is seeking an exclusive arrangement. Even when homegrown startups are involved, VTT deliberately avoids picking winners. "As a research organization, we support multiple qubit technologies—superconducting, silicon-based, and photonics," Turunen said.

Broad engagement lets VTT play an enabling role in Finland's—and Europe's—quantum roadmap. For example, the institute recently launched a 50-qubit superconducting system with IQM Quantum Computers and aims to support additional modalities through infrastructure such as Micronova and Kvanttinova, two pilot-line foundries backed by EU Chips Act funding. "It's not our role to say which approach will win out," Turunen said. "There are still many open questions, and we want to ensure that all of them are given robust scientific and technological support."

VTT Technology Research Center's Erja Turunen

SemiQon is also playing the field, having recently entered into formal collaboration with imec, one of Europe's leading advanced semiconductor R&D institutes, to accelerate industrial readiness. While VTT remains its primary manufacturing host, SemiQon sees imec as a complementary partner for aligning cryogenic chip design with cutting-edge CMOS platforms.

"We want to avoid owning a fab, and we want to be interoperable," Majumdar said. "Working with imec ensures we're not locked into any single approach."

Cryogenic measurements in the SemiQon lab (Source: SemiQon)

SemiQon Builds Momentum for Silicon Spin Qubits in Europe

COMMERCIALIZING CRYO-CMOS

In contrast to full-stack quantum computing companies, SemiQon's ambition lies in being a core component supplier—providing chips and cryogenic electronics rather than complete quantum systems. "We're not building quantum computers," Majumdar said. "We're building quantum processors and cryogenic electronics. Others can take those and build full systems. That's our business model." (See article on page 13.)

Central to that strategy is cryo-CMOS, which enables quantum and classical electronics to coexist on the same chip under cryogenic conditions. Traditional CMOS transistors are not optimized for sub-kelvin temperatures, and that inefficiency can lead to thermal noise that disrupts qubit operations.

SemiQon has addressed this by engineering custom transistor architectures that it says maintain high fidelity, low power consumption, and thermal stability in cryogenic environments. The approach allows tighter integration of control logic with quantum dots on the same chip, reducing latency and improving scalability. Importantly, cryo-CMOS enables the monolithic integration of classical and quantum components, eliminating the bulky control hardware that currently fills racks in most quantum computing setups.

"Cryo-CMOS is where we shine," Majumdar said. "We've developed record-low-power cryogenic transistors. Combined with our quantum dot qubits, this makes scalable, energy-efficient processors possible."

The company has already begun shipping R&D kits to universities and corporate labs, and it participates in the European Quantum Pilot Line, where it provides hardware and testing capabilities. By 2026, SemiQon aims to transition from innovation to commercialization.

THE PATH TO SCALABILITY

According to Majumdar, two breakthroughs will ultimately determine the viability of silicon spin qubits at scale. The first is efficient two-dimensional qubit arrays. While it's relatively straightforward to build one-dimensional chains of qubits, scalable quantum error correction requires connecting distant qubits across a two-dimensional plane. "That's a huge challenge," Majumdar said. "You need architectures that allow communication between far-apart qubits while maintaining fidelity."

The second necessary breakthrough is in high-performance interconnects. Control and readout systems require fine-grained communication between qubits and classical electronics. SemiQon's monolithic integration approach, bringing cryo-CMOS and quantum dots onto the same chip, aims to make that communication fast, dense, and power-efficient. "Without interconnects," he added, "you cannot scale to a million qubits."

Wafer probe station in the SemiQon lab (Source: SemiQon)

SemiQon 4-qbit module (Source: SemiQon)

SemiQon is currently developing a 12-qubit 1D array and is working toward a 100-qubit 2D array using multiplexed readout. "We plan to reach 1,000 qubits on a single chip by 2030," Majumdar said. "After that, we aim to double the qubit count each year, reaching 100,000 by 2035 and 1 million by 2040."

Could Moore's Law hold for silicon spin qubits? It will depend not only on qubit fidelity and gate speed but also on manufacturability, integration with classical electronics, and resilience across global supply chains. But if the trend does hold—and if SemiQon's approach to silicon spin qubits becomes the dominant modality for large-scale quantum processors—perhaps that exponential scaling will come to be known as Majumdar's Law.

Majumdar believes Europe is uniquely positioned to lead in silicon quantum because of its legacy in low-power CMOS, rich academic ecosystems, and public investment in pre-commercial pilot lines. "We've lost our edge in traditional CMOS to Taiwan and the U.S., but we can reclaim leadership by investing in futuristic technologies like cryogenic CMOS," he said.

In Majumdar's view, silicon spin qubits offer the clearest path to quantum systems that don't just work but scale. "We envision a future where the room full of racks used to control quantum processors can shrink to a handful of silicon chips," he said. "That's the same transformation classical computing went through—and that's what we're driving for in quantum." ■

THE QUANTUM LEAP | PHOTONIC QUANTUM COMPUTING

QuiX Quantum Aims for Universal Photonic Quantum Computer in 2026

By Anne-Françoise Pelé

Dutch quantum photonics startup QuiX Quantum has defined a clear R&D roadmap toward the demonstration of quantum computers that will be, first, universal; second, error-corrected; and third, fault-tolerant. The company's recent, €15 million Series A funding round should help it move from theory to practice.

Rendering of QuiX Quantum's first-generation universal photonic quantum computer (Source: QuiX Quantum)

PHOTONS AND SILICON NITRIDE

QuiX Quantum's approach centers on photonic quantum computing, in which photonic qubits use photons as carriers of quantum information. Photonic quantum systems offer advantages in communication and scalability, as photons can travel long distances with minimal loss. In recent years, it has become feasible to address the key technical challenges in photonic quantum computing, namely the generation and entanglement of photonic states. The company also maintains that error correction may be easier to implement in photonic systems than in other quantum computing modalities.

QuiX Quantum's Stefan Hengesbach

Another distinctive advantage of photonic quantum computers is that their core components operate at room temperature, which reduces operating costs and makes the computers easier to maintain. "QuiX Quantum's quantum computers are designed for use in data centers without retrofitting complex liquid helium cooling infrastructure," Stefan Hengesbach, CEO of QuiX Quantum, told EE Times Europe. "Since our qubits are encoded in photons, which move at the speed of light through standard telecom fibers, photonic computers are highly scalable and have the highest clock speeds" among the various types of quantum computers.

QuiX Quantum's processor chips are based on silicon nitride (SiN), a material distinguished by its low light losses and broad spectral coverage. "Photonic quantum computers are very insensitive to noise and work at room temperature," Hengesbach said. "However, the main error in these systems is photon loss. … There is a [photon loss] threshold for the overall transmission that is required for photonic quantum computers, and SiN chips can work below that threshold, enabling quantum computations."

FROM BOSON SAMPLER TO UNIVERSALITY

Founded in 2019 as a spinoff from the University of Twente (Enschede, Netherlands), QuiX Quantum generates revenue from the sale of processors and quantum computers. In 2022, it became the first company to sell both 8- and 64-qubit photonic quantum computers to the German Aerospace Center. Two years later, it started offering cloud access to its quantum systems, creating a platform for hybrid computing and bringing near-term quantum computing to real-world applications in sectors such as infrastructure, defense, healthcare, and IT.

The company has also developed a non-universal quantum computer with a current-running boson sampler. At the computer's core is the company's quantum photonic processor in the form of a reprogrammable interferometer.

"The boson sampler is a computer that is structured like a giant chessboard of intersections," Hengesbach said. "All inputs can interact with all others. The advantage is that we can view the result post-selectively and simply discard individual measurements. The disadvantage is that the device is not deterministic and grows quadratically in size. For example, if we had 100 inputs for qubits, we would also have to build around 100 × 100 intersections so that all inputs could interfere directly with each other."

But Hengesbach added that "the universal measurement-based quantum computer overcomes both limitations. It requires far fewer intersections but also needs photon sources that provide sufficient photons in each work cycle. The leap from the boson sampler to the universal quantum computer is a gigantic technological advancement."

QuiX Quantum has transitioned from building processors exclusively to positioning itself as a system provider. "Reaching universality is more important than the number of qumodes, which are equivalent to the processor entry and exit ports," Hengesbach said. While the company has expanded its processors from 20 to 32 and 50 qumodes, its next objective is to deliver an 8-qubit universal quantum computer and showcase the performance of its own single-photon sources.

The company's recent, €15 million Series A funding round should help it move its roadmap for a universal quantum computer from theory to practice.

"Qumode" was QuiX Quantum's initial term for its information carriers, but the company has since adopted the more widely recognized "qubit" for ease of comparison across the industry. A qumode represents a single quantized light path within the processor. To perform useful operations, qumodes must be coupled, allowing light to "jump" from one path to another, Hengesbach said. This coupling capability is central both to QuiX Quantum's special-purpose quantum computers and to the processors the company supplies as standalone components.

QuiX Quantum creates its system qubits using methods such as dual-rail encoding, in which a photon passes through a 50:50 beam splitter and exists in a superposition of two waveguides. The company also employs more advanced approaches, including squeezed states, to create qubits.

"The computational advantage does not come only by increasing the number of qumodes," Hengesbach said. "Creating a useful device also requires universality and error correction."

Both are part of ongoing development enabled by the Series A funding. With that €15 million, QuiX Quantum plans to deliver its first-generation universal photonic quantum computer by 2026. The system will feature a universal gate set capable of executing any quantum operation, a step the company sees as pivotal in advancing toward large-scale, fault-tolerant machines.

When asked how a universal quantum computer might prove useful in practical applications, Hengesbach said that its universality allows it to run "any known quantum algorithm, including Shor's and Deutsch's." He noted that the first algorithms expected to outperform classical computers could do so with "just hundreds of logical qubits," a threshold he considers achievable in the foreseeable future. In his view, pharmaceutical and chemical engineering use cases could be addressed with relatively few logical qubits, while defense and intelligence would require a medium number to provide value. Manufacturing, he noted, varies considerably: Tasks such as Grover's search or database queries would demand large qubit counts, whereas modeling new metals and composites could be achieved with comparatively few.

"We are in a flagship project of the German Quantum Computing Initiative, QCI, which has already ordered universal computers," Hengesbach said. "Further developing these prototypes into turnkey-ready industry solutions is the core mission of QuiX. It is expected that early adopters of quantum computers could address 90% of the expected added value by 2040, and it is QuiX's mission to provide the hardware to those early adopters."

SCALING AND ERROR CORRECTION

The 2026 system will implement a universal gate set, enabling it to run any known quantum algorithm. An 8-qubit model will debut first, with a 64-qubit version planned no earlier than 2027. The second-generation system will aim to integrate error correction.

Hengesbach explained that error correction in quantum computing relies on the ability to entangle qubits into primitive states or logical qubits, creating a redundancy of information so that "if a photon is lost, sufficient information about the state function is still present."

Introducing error correction mechanisms requires three conditions. First, the overall system error rate must be low enough that adding physical qubits to the logical qubit increases the probability of successful calculation. Second, the computer must be able to reliably generate sufficient photons in each clock cycle to produce a logical qubit. Third, once those prior requirements are met, the system can be scaled by connecting multiple identical computers, a process that works best when the hardware is compact and operates at high clock speeds. Hengesbach indicated that hardware improvements to reduce transmission losses, careful system design, and a reliable supply chain are all part of QuiX's effort to meet these conditions.

"Once we have a modular hardware solution for generating a logical qubit, it can be connected to a neighboring device via fiber optic cable to expand the quantum computer," Hengesbach said. "For technical and economic reasons, it makes sense for photonic systems to first produce this logical qubit without significant losses below the threshold for error correction.

"Incidentally, the faster these systems are, the more compact they become," he added. "Thanks to their modularity, qubits can then be easily added. In contrast to other modalities, it makes sense in photonics to first significantly increase quality and then scale up."

FIVE-YEAR VISION

The Series A financing round was co-led by Invest-NL and the EIC Fund, with PhotonVentures, Oost NL, and Forward.one also participating. It follows two earlier seed rounds, totaling €9 million, and thus brings the company's total venture funding to €24 million.

In July 2024, QuiX Quantum was selected for the European Innovation Council Accelerator program, an initiative of the EC that supports companies developing market-shaping technologies. The grant, to be disbursed over two years, will contribute to advancing the company's current development roadmap.

Looking ahead, Hengesbach sees highly modular photonic quantum computers installed in data centers worldwide within five years. "They will be compact, energy-efficient, and easy to maintain," he said.

For now, the company's immediate focus is on delivering the 2026 universal system and progressing toward error-corrected, fault-tolerant architectures. "Overall, we are on track with our planning," Hengesbach said. "The focus is on developing a quantum computer that can scale toward a large number of physical qubits to get to 100+ logical qubits in the future." ■

THE QUANTUM LEAP | POST-QUANTUM CRYPTOGRAPHY

Inside NIST's PQC Overhaul, a Year Later

By Pat Brans

NIST published its first PQC standards last summer. Early adopters like Cloudflare are already deploying them at internet scale.

For the past decade, the U.S. National Institute of Standards and Technology (NIST) has led a global effort to develop cryptographic standards that can withstand the looming threat of quantum computing. At the center of that effort is Dustin Moody, supervisory mathematician at NIST.

"The standards are out," Moody told EE Times. "We hope people start migrating. There's guidance available, and the ecosystem is evolving fast. This is a major global shift in cybersecurity."

NIST's Justin Moody

THE STANDARDIZATION PROCESS AND ITS EXTENT

The NIST post-quantum cryptography (PQC) standardization effort began in 2016 as an open competition, drawing algorithm submissions from global cryptographers. The agency ultimately selected three algorithms and published them as standards on Aug. 13, 2024.

It is now finalizing two more: the lattice-based Falcon and code-based HQC. Each algorithm targets one of two core cryptographic functions of asymmetric keys: key establishment and digital signatures.

"We wanted at least two options in each category," Moody said. "That way, if one is broken, systems can fall back to another. That's critical for national security—and for global infrastructure."

To understand which parts of the security stack are most at risk from quantum attacks, it's important to distinguish between the two main categories of cryptography:

- Symmetric key cryptography uses the same secret key to encrypt and decrypt data. Both parties need to know this key, which means they must share it securely, often by using asymmetric cryptography during the setup phase.
- Asymmetric key cryptography, on the other hand, uses a mathematically linked key pair: one public and one private. The public key can be shared freely, while the private key is kept secret. Depending on the purpose, one key encrypts and the other decrypts; this enables secure key exchange over an untrusted channel and underpins digital signatures.

NIST's PQC standards address only the threat that quantum computers pose to asymmetric algorithms, which are vulnerable to Shor's algorithm. It does not address symmetric algorithms, which can be secured against quantum attacks by simply increasing the key size (for example, using AES-256 instead of AES-128) to restore equivalent security strength.

With these distinctions in mind, organizations can make more informed migration plans, deciding where PQC must be prioritized and where simpler adjustments, such as key-length increases, will suffice. This understanding also helps prevent over- or underestimating the work needed to achieve quantum-safe status.

A CASE OF EARLY DEPLOYMENT AT SCALE

Bas Westerbaan, PQC research lead at Cloudflare Research, knows firsthand how much work is involved: His role is to protect Cloudflare's infrastructure against quantum attacks. "We own our full stack, so we started experimenting back in 2019," he told EE Times. "That was necessary because changing cryptography is hard; it takes years to do it right."

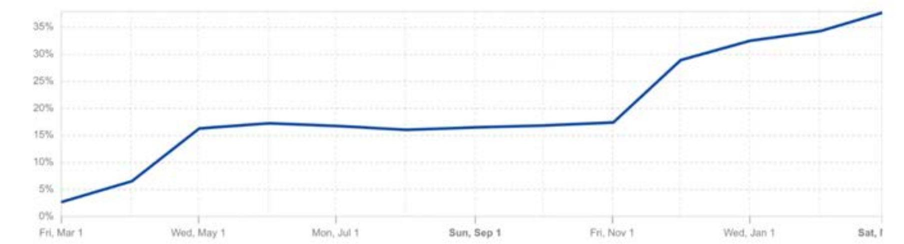
According to Westerbaan, security and privacy are foundational to Cloudflare, and the company saw PQC as a natural extension of its role in secure internet protocols. "We were one of the first to offer free SSL [Secure Sockets Layer] certificates and encrypted DNS [Domain Name System]. We knew that once NIST began its PQC project, regulation would follow. So we started early."

That head start paid off. Today, 38% of all human-generated requests to Cloudflare endpoints use ML-KEM 768, the post-quantum algorithm formerly known as Kyber and now standardized by NIST. This was made possible

IMAGE: J. STOUGHTON/NIST

The NIST Gaithersburg campus in the spring

Inside NIST's PQC Overhaul, a Year Later



Post-quantum encrypted share of human HTTPS request traffic seen by Cloudflare per Cloudflare Radar from March 1, 2024 to March 1, 2025. (Captured on March 13, 2025.)

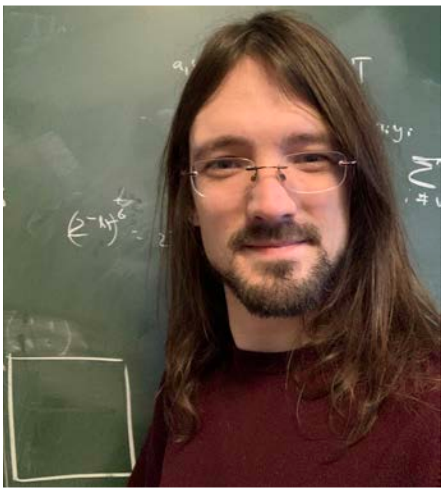
(Source: Cloudflare)

by years of careful ramping up, testing, and working with browsers such as Chrome to address protocol ossification—a situation where cybersecurity engineers don't use some of the options in a protocol and eventually hardcode assumptions that render the protocol inflexible.

"We saw that even small changes, like slightly larger key sizes, could break things," Westerbaan said. "That's why we ramped up slowly. After all, if it breaks even 0.1% of connections, we can't deploy it globally. Over time, we got to where we needed to be."

These technical hurdles are only part of the story; the human and procedural aspects can be even more challenging. "Most organizations don't know where their cryptography lives," Westerbaan said. "And even fewer have a plan to upgrade it."

Because Cloudflare controls the full stack, its engineers know where everything is, which makes it easier to make the transition. Moreover, according to Westerbaan, the company built the industry's first post-quantum zero-trust platform: "With Zero Trust, we can deploy clients or tunnel connections that are post-quantum without having to upgrade every internal service. It gives us a way to accelerate PQC adoption across our product portfolio."



Cloudflare's Bas Westerbaan

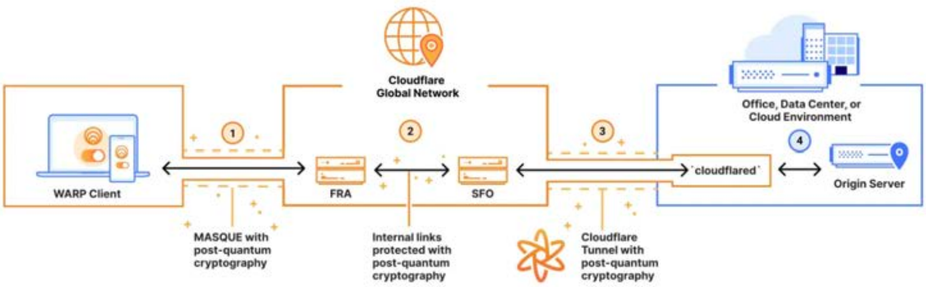
While Cloudflare has rolled out post-quantum key agreements to most products and geographies, certificates, which rely on digital signatures, remain a tougher nut to crack. "Certificates involve many parties—CAs [certificate authorities], browsers, HSMs [hardware security modules]—and they aren't well-automated," Westerbaan said. "Worse, the current post-quantum signature algorithms are very large. If we use ML-DSA everywhere, we could be adding 15 KB to a connection that otherwise transfers just 8 KB."

Moody said. "If your key was established using vulnerable classical methods, that data could eventually be exposed."

Some organizations are not waiting. Thanks to early adoption and rigorous testing, Cloudflare has already integrated post-quantum key agreements into the majority of its infrastructure. "Post-quantum encryption is already becoming the default," Westerbaan said. "I expect that within a year, most TLS connections on the internet will be quantum-secure." Nevertheless, full migration across hardware, embedded systems, and critical infrastructure will take much longer.

While NIST leads the charge, Moody noted that international standards bodies such as ISO, ETSI, and IETF are incorporating NIST's selections, and countries including the U.K., France, and Japan are actively aligning. China and Russia, on the other hand, are developing separate paths.

Westerbaan supports the international alignment: "So far, Europe has followed NIST standards for non-classified data. That's crucial. Fragmentation would be a disaster; if two systems can't agree on an algorithm,



Quantum-safe Zero Trust with Cloudflare's Warp client-to-tunnel configuration

(Source: Cloudflare)

Cloudflare is now exploring ways to reduce the number of required signatures in protocols such as Transport Layer Security (TLS), working closely with Chrome and other ecosystem players in the process. "If it's not efficient, people won't turn it on," Westerbaan said. "And we risk regressing on internet security."

WHAT HAPPENS BETWEEN NOW AND Q-DAY?

Even with today's rapid progress, the ultimate test will come when quantum computers reach the point of breaking classical cryptography. That's the scenario that experts call Q-Day. While nobody knows when that day will come, organizations already need to protect against "store now, decrypt later" attacks, where adversaries collect encrypted data today in hopes of decrypting it with quantum computers in the future. "Foreign adversaries are actively collecting encrypted data today,"

they can't communicate." He also warned of the risk of too much algorithmic diversity: "The more combinations you have to take into account, the more room for implementation errors."

Organizations can take some simple steps to start their PQC journey, Westerbaan said. "Keep your software up to date; you might already be using PQC without knowing it. Automate certificate renewal. And try things early, so you have time to fix issues before it's urgent."

The real challenge, he said, is organizational: "Get the right people on board. Understand your vendors. Create awareness. Most companies are focused on next quarter. You need to think five years out."

The time to prepare is now. Early adopters have shown that global deployment is not only possible but already happening. ■

This article originally ran on EE Times.

OPINION | **THE QUANTUM LEAP** | POST-QUANTUM CRYPTOGRAPHY

'Harvest Now, Decrypt Later' Attacks in the Post-Quantum and AI Era

By Kevin Curran, IEEE, Ulster University

AI and quantum computing offer transformative opportunities but pose an urgent cybersecurity threat that demands an immediate, coordinated response.

Quantum computing has enormous potential to revolutionize entire industries—from healthcare and financial services to national security—but it also introduces a host of complex challenges, particularly when it comes to cybersecurity. Bad actors are already well aware that quantum computing could soon render some traditional encryption methods (e.g., RSA, ECC) obsolete. Indeed, in "harvest now, decrypt later" attacks, sensitive data is quietly being stolen now for cracking when quantum technology matures.

And the threat goes beyond encryption. The growing prominence of AI, the ever-expanding IoT, and the merging of information technology (IT) and operational technology (OT) are broadening the attack surface. What's more, a fragmented global response to standards and the deepening cybersecurity skills shortage has left many businesses dangerously unprepared. The quantum threat isn't coming; it's already here.

RECENT QUANTUM COMPUTE DEVELOPMENTS AND THE FUTURE OF THE TECHNOLOGY

Over the past couple of years, quantum computing has made significant strides. IBM introduced the Quantum Heron processor with 133 qubits, improving performance, and launched the scalable Quantum System Two. Google's Willow chip significantly reduces errors as it scales up and can perform a specialized computation in under five minutes, a feat that would take classical supercomputers an impractical amount of time.
Microsoft's Majorana 1 chip uses topological qubits called topoconductors for rapid scaling, and Amazon's Ocelot chip focuses on error correction with cat qubits, aiming for fault-tolerant systems.

Meanwhile, Fujitsu, and Riken have developed a 256-qubit superconducting computer, while D-Wave's 4,400+-qubit Advantage2 processor solves problems 25,000× faster than its predecessor. Quantinuum's 56-qubit trapped-ion system reached 99.9% gate fidelity. Advances in logical qubits, hybrid digital/analog simulation, quantum networking via the Quantum Internet Alliance's QNodeOS, and photonic systems have improved scalability and stability. Practical milestones include quantum utility demonstrations, certified randomness for quantum-secure applications, and wireless quantum algorithm transmission.

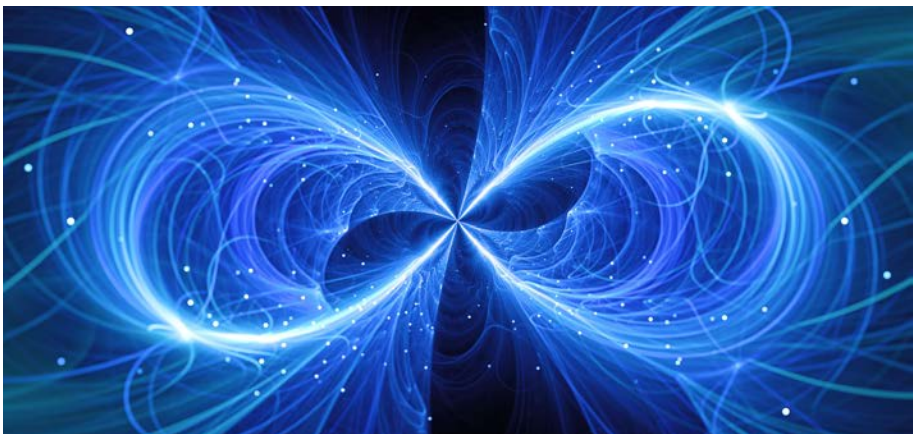


IMAGE: SHUTTERSTOCK

Despite all the advances, however, challenges including error-prone qubits, scalability limitations, and high costs for quantum infrastructure, coupled with skepticism about overhyped claims, continue to hinder progress.

Quantum computing's future is promising but challenging, with practical applications likely 15 to 20 years away. Yet recent advancements suggest progress is being made toward fault-tolerant systems, potentially enabling niche uses in cryptography, materials science, and optimization within a decade.

Quantum computers are set to complement classical systems and will excel in specific tasks, but their cryptographic impact is set to force a global shift to post-quantum encryption.

Recent advancements suggest progress is being made toward fault-tolerant systems, potentially enabling uses in cryptography and materials science within a decade.

THE CYBERSECURITY IMPLICATIONS OF THE POST-QUANTUM AND AI ERA

AI and quantum computing can mutually enhance each other. AI improves quantum computing by optimizing qubit control, reducing errors, and aiding algorithm design, as seen in efforts involving IBM and Google systems. Quantum computing boosts AI by accelerating optimization tasks, solving linear systems faster, and enabling quantum machine learning to uncover patterns in complex data, benefiting such fields as drug discovery and logistics. Practical examples include AI-driven quantum error correction, quantum-AI drug simulations, and optimized logistics with D-Wave systems. However, this synergy is early-stage, limited by noisy quantum hardware and complexity.

In the next five years, organizations will face cybersecurity threats from AI-powered attacks, including automated vulnerability detection and adaptive malware, necessitating advanced AI defenses despite risks including data exposure. Quantum computing may also soon break traditional encryption, enabling attackers to unlock the encrypted data captured through "harvest now, decrypt later"

IMAGE: SHUTTERSTOCK

attacks, requiring a shift to quantum-resistant cryptography amid complex migrations.

The growing IoT and cloud attack surface, with billions of devices and misconfiguration risks, will also increase vulnerabilities, especially in critical infrastructure, as IT and OT converge. Geopolitical tensions will fuel state-sponsored attacks and gray-zone warfare targeting infrastructure and leveraging commercial surveillance, demanding better international cooperation, while smaller organizations will remain at risk.

AI, enhanced by quantum computing's potential to accelerate data processing, can strengthen cybersecurity in critical infrastructure by detecting threats in real time and minimizing disruptions. However, it cannot be trusted with full autonomy. Risks include adversarial attacks that deceive AI; errors in contextual judgment that lead to misinterpretations; and opacity in decision-making, which could cause errors or legal issues, such as shutting down essential services. AI also struggles with novel threats and can be weaponized if compromised.

Hybrid systems with human oversight are more reliable, leveraging AI's speed while ensuring accountability. The push for autonomy is often overhyped by vendors, and in high-stakes environments, human-in-the-loop safeguards are essential to counter sophisticated threats, including state-sponsored attacks.

Consumers should be alert to cybersecurity and secure communications because their personal data is increasingly at risk of theft that could lead to identity fraud or financial loss, especially as digital services grow and as traditional encryption faces quantum threats. Many will be surprised to learn their data is already widely sold on the dark web, as "harvest now, decrypt later" attacks are already threatening future privacy, and that AI deepfakes are being used to impersonate them in scams. The biggest privacy risks include extensive data collection by tech companies, insecure IoT devices leaking personal information, AI-driven social engineering attacks such as phishing, and the future vulnerability of encryption to quantum computing. While these threats are significant, consumers should focus on basic cyber hygiene and be wary of alarmist narratives pushing unnecessary solutions or surveillance.

Both AI and quantum computing offer transformative opportunities but pose immediate cybersecurity challenges. For their part, business leaders should urgently be looking to future-proof their infrastructure, safeguard data, and stay ahead of AI and post-quantum threats, including "harvest now, decrypt later" attacks. ■

Kevin Curran *is an IEEE senior member, a professor of cybersecurity at Ulster University, and an independent cybersecurity expert.*

OPINION | THE QUANTUM LEAP | QUANTUM SENSING

Quantum Sensing Powers a Vital GPS Backup to Protect European Commerce and Security

By Niall Moroney, Q-Ctrl

Modern life runs on GPS. From logistics to aviation, from transport to telecoms, we rely on satellite signals for positioning, navigation, and timing (PNT), but that reliance has become a critical vulnerability.

From all directions, Europe's connectivity to the rest of the world—through aviation, commercial shipping, and defense—is threatened by mounting attacks on GPS.

Pilots, drivers, and ship captains are increasingly affected by GPS denial, with civilian planes, vehicles, and vessels becoming both targets and unintended victims of low-cost jamming and spoofing technology. As this hardware proliferates from consumer- to military-grade, the threat continues to grow.

A 2024 report found that over 1,000 civilian flights per day are disrupted by GPS jamming, which directly impacts their navigation systems while flying. Another analysis, by OpsGroup, an organization of pilots, controllers, and flight dispatchers, found that between the first half of 2024 and the second half, GPS spoofing went up 500%, from 300 incidents per day to 1,500.

This nefarious activity spans the globe, with conflict regions including Israel and Ukraine heavily affected. Closer to home, critical infrastructure (such as airports) is being targeted. In April 2024, Finnair planes flying into Estonia had to divert and return to Helsinki; Finnair subsequently paused flights via that route for a month due to deliberate GPS disruptions. These have persisted to this day in the airspace around Kaliningrad, Russia, covering Poland and the Baltics. Similarly, the airspace around Turkey and Cyprus has been increasingly affected by the same problem, posing a major challenge for the skyways between Europe and Asia that typically traverse this region.

Looking at real-time maps of GPS-jamming incidents in commercial aviation, it looks like a new electromagnetic iron curtain is descending over Eastern Europe, from Kaliningrad to northern Iraq.

The maritime sector is equally affected. Rising tensions in the Middle East have driven a surge in maritime GPS attacks in recent months. Shipping corridors such as the Red Sea and Strait of Hormuz are particularly vulnerable, with hundreds of reported incidents in the region that cause not only critical logistical issues but dangerous disruptions to collision-avoidance software, putting vessels and crews at risk.

CRITICAL WEAKNESS IN A VITAL SYSTEM

GPS relies on the transmission of radio signals from satellites; terrestrial or airborne receivers pick up multiple signals to triangulate position. Most GPS signals are unencrypted and easily overpowered by low-cost, ground-based transmitters employed by nefarious actors. GPS-jamming attacks use these ground-based devices, which intentionally transmit interference to drown out GPS signals to maintain defense and economic advantage. This causes ships, planes, drones, and other vehicles to lose position and timing information. Spoofing uses counterfeit signals to mislead GPS receivers into calculating false positions and timing information.

The impact of these attacks extends far beyond transportation and supply chains. Power grids, financial markets, cloud infrastructure, and telecoms all rely on GPS for timing. A 2019 study estimated that a 30-day GPS outage in the U.S. could cost up to $45 billion, and Europe would face similar consequences.

Considerable investment is currently going into the development of anti-jamming and -spoofing detection technology, but greater resilience is needed.

Governments and commercial operators alike now recognize the need for a robust backup to GPS for circumstances in which it is unavailable or untrusted. Those backups must function in real-world navigation settings and must be unjammable, unspoofable, and, for defense applications, undetectable. There are many options available, but few meet these challenging requirements.

The EU published a report in March 2024 calling for alternatives to Global Navigation Satellite Systems (GNSS) to provide PNT services. The report recommended a "system of systems" approach with market-driven solutions that use a mixture of GNSS alternatives across PNT infrastructure.

QUANTUM SENSING OFFERS A PATH FORWARD

A new class of so-called "alt-nav" solutions is emerging on the back of a brewing technological revolution: the development of quantum technology. Quantum sensors provide new detection modalities with the critical performance—sensitivity and stability—relevant to integration in navigation systems. These devices provide a set of eyes to "see" the critical features and signatures needed to navigate without reliance on external RF beacons.

Governments see the potential and are leaning in:

- The U.S. Defense Advanced Research Projects Agency recently launched a Robust Quantum Sensors program with the goal of advancing quantum sensing technology for defense platforms and use cases.
- The Australian Army's Quantum Technology Roadmap lays out the Defense Department's plans to gain and retain an early advantage by identifying high-value applications of the technology.
- The U.K. has recently completed a U.K. National Quantum Technology Hub in Sensing and Timing project with new programs focused on the commercialization of quantum sensors.
- NATO has identified new forms of quantum sensing as critical technologies in its DIANA accelerator.

The underpinning challenge has always been how to take exceptionally sensitive scientific instruments out of the lab and into real operating environments.

WHY QUANTUM NAVIGATION WORKS

Navigation systems built around quantum sensors offer unique advantages over current GPS and GNSS backup technologies.

A common backup is an inertial navigation system, which calculates position based on velocity, orientation, and motion, but it tends to drift over time without regular manual calibration, resulting in potentially dangerous positioning errors. Similarly, visual

navigation systems can offer drift-free navigation but work only when there's good visibility, and they can be jammed with laser attacks. Radar and LiDAR solutions are excellent in positioning accuracy but actively broadcast signals that give away a vehicle's position to an adversary.

Quantum navigation solutions overcome all of these shortcomings through several complementary strategies:

- Quantum inertial navigation replaces drift-prone accelerometers and gyroscopes with quantum alternatives exhibiting better stability.
- Magnetic navigation uses real-time sensing of Earth's local magnetic field and compares it with known magnetic maps to provide a position fix.
- Gravimetric navigation similarly measures subtle variations in Earth's gravity, mapping invisible "hills and valleys" to determine location with high precision relative to a map.

There are a few competing technologies, but most practical implementations have relied on devices using trapped atoms at their core.

Inertial and gravitational sensors use the wave-like nature of laser-cooled atoms to perform sensitive interferometric measurements of free-falling atoms. Magnetic sensors leverage the intrinsic spin degree of freedom in atoms to serve as a tiny compass needle, aligned and tracked using lasers as it responds to magnetic fields. Because in all modalities the signals come from fundamental atomic behavior, they offer exceptional stability and accuracy and do not require (re)calibration. This unique combination of sensitivity and stability makes quantum navigation systems potentially powerful alternatives when GPS is unavailable or cannot be trusted.

Field-ready quantum navigation systems must meet a set of stringent requirements to be useful in real-world settings. The systems must be small enough to deploy on many platforms and able to mitigate the impact of noise from the environment and the vehicle. The device must be able to accommodate changes in payload, altitude, sensor location, operating location, and vehicle dynamics.

Until recently, quantum navigation systems could not withstand these operational conditions, frequently failing when moved from the lab to the real world. Quantum navigation systems supported by specialized software can overcome these conditions by de-noising the environment and automatically fixing errors in the hardware as they occur. This software also allows quantum sensors to run continuously and reliably without the need for manual intervention and tuning. Recent real-world demonstrations have shown that quantum navigation outperforms conventional alternatives in relevant operating environments and has become viable in the near term.

ACTING NOW TO SECURE RESILIENT NAVIGATION

Both the aviation and maritime sectors face growing threats from GPS interference, and both have urgent needs for resilient navigation solutions. Both sectors are expressing strong demand for quantum navigation solutions, and key players from startups to large defense primes are engaging to deliver. Together, these sectors could lead to the global adoption of robust PNT systems.

There's no single fix. Combining multiple "alt-nav" systems with complementary strengths gives operators a chance to build true resilience. And integrating "dissimilar" solutions provides added safety by reducing common failure pathways.

Quantum navigation is essential to this mix. It delivers unjammable and unspoofable navigation, with no reliance on satellites and no need for clear weather conditions. Paired with other navigation solutions, quantum navigation gives airlines, militaries, and shipping companies the tools they need to operate securely in GPS-denied environments. ■

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THE QUANTUM LEAP SILICON 100

The Quantum Race: Exploring Alternative Qubit Modalities

By Maurizio Di Paolo Emilio

What makes quantum mechanics so important? We can’t discern the true nature of reality with our eyes at the macroscopic level. But at its most basic level, everything is made up of tiny particles that follow the rules of quantum mechanics.

Brilliant scientists from the 20th century came up with this groundbreaking discipline. Werner Heisenberg laid the groundwork, and Niels Bohr, the “godfather” of quantum theory, pushed it forward. But some didn’t like this odd new reality. Albert Einstein strongly disagreed with its probabilistic nature and famously said, “God does not play dice.” But Bohr, who was enthralled with the facts of the quantum realm, had a famous answer for his friend: “Hey, Albert, look, God really plays dice!” He was right to think that the quantum realm is probabilistic: In the end, this means that probability rules us all.

QUANTUM LANDSCAPE AND QUBITS

There are a lot of investments and quick technological changes in the field of quantum computing, as highlighted in EE Times’ 25th revision of its Silicon 100 ebook.

Quantum computers use the concepts of quantum mechanics, such as superposition and entanglement, to solve problems that normal classical machines can’t. Quantum computing is no longer just a dream: It’s making quick progress and solving real-world problems, with the ability to solve even more in the near future. This year is the International Year of Quantum Science and Technology—100 years after the development of modern quantum mechanics by physicists such as Heisenberg, Max Born, and Erwin Schrödinger.

Quantum computing is possible thanks to the way quantum bits (qubits) work. Unlike regular bits, qubits can be in a superposition of 0 and 1, which implies they can accomplish many things at once. When qubits are entangled, the state of one can change the state of another instantaneously, even if they are far apart. Also, quantum interference enables you to eliminate the wrong answers and boost the right ones as you do math. These qualities help quantum computers explore enormous solution regions at the same time when combined with the right quantum approach. This makes problem-solving a much faster process.

Qubits are particularly significant for quantum computing because they let you execute complex algorithms, simulate quantum systems efficiently, and scale up exponentially (2^n states). They also make quantum communication safe.

There are different ways to use qubits in real life. Each approach has pros and cons with respect to coherence time, gate fidelity, scalability, and ease of integration. Coherence time, error rate, gate fidelity, and connection are all ways to quantify the quality of qubits, and all have an impact on how well a quantum computer works and how well it can be scaled up. In the noisy, intermediate-scale quantum age we’re living in now, qubits are already being used to solve problems in banking, cybersecurity, artificial intelligence, logistics, and medicine.

IMAGE: ADOBE STOCK

KEY CONCEPTS

The structure of the qubit has two states of spin that point in opposite directions. We can control these states, which are called +1 and −1 or $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, using quantum mechanics. Superconducting loop couplers are one type of element that can be used to make a multi-qubit processor. It is important to have a switch structure made up of Josephson junctions that can control the operation of the qubits by sending pulses of magnetic information to the right places on the chip and storing the information in a local magnetic memory element for each device.

The Josephson effect occurs when two superconductors are separated by an insulating junction, which is called the Josephson junction. This happens because there is a tunnel effect between pairs of electrons in each of the superconductors. The tunneling effect doesn't occur if the isolation is too wide, because the chances of it happening are low.

Most Josephson junctions are quantum processing units (QPUs). The QPU doesn't have big memory regions (cache), as it works more like a biological brain than a standard silicon processor with a von Neumann design. You can think of qubits as neurons and couplers as synapses that control how information moves between these neurons. The number of qubits that must be large enough to ensure high efficiency is a good way to sum up what is needed for successful quantum implementation. This also means that it could be possible to do a lot of things using qubits in a short amount of time.

To make qubits—the building blocks of quantum computers—you have to initialize, manipulate, and measure quantum particles such as photons, electrons, or ions. Initialization puts the qubit in a starting state, which is generally done by cooling it down to cut down on noise. Lasers or microwaves as quantum gates will do calculations while maintaining quantum coherence. Measurement swiftly verifies the qubit's final state to get the answer.

There are, however, a number of issues that must be resolved before qubits can be created. Decoherence (when qubits lose their quantum state) and scalability (creating enormous arrays of qubits) are two main concerns.

Building massive quantum systems that can manage faults and making quantum hardware simpler to access for research and education are two important goals for the future of qubit-based computing. In the following sections, we examine various types of qubits, including superconducting, trapped-ion, and photonic.

SUPERCONDUCTING QUBITS

These qubits use superconductors, which are commonly made of aluminum or niobium and are kept below their transition temperature so they can transmit current without resistance. A qubit is like an artificial atom that can be in quantum superpositions and connect with other qubits to do hard math. Josephson junctions are often used to make them because they provide the nonlinear inductance that quantum behavior needs.

One of the best things about superconducting qubits is that they can be created with the same tools and procedures that are used to make semiconductors today, meaning that a lot of them can be made. They can also be deliberately engineered to focus on certain quantum properties, and they benefit from decades of work in superconducting electronics and cryogenics. Big companies such as IBM, Google, and Rigetti use superconducting qubits in their quantum processors. These qubits have been proven to switch swiftly.

Also, SpinQ uses its superconducting QPU in its SpinQ superconducting quantum computer aimed at commercial applications. IQM Finland, which trades as IQM Quantum Computers, builds superconducting quantum computers and processors and has its own manufacturing facility in Espoo. IQM has delivered multiple customer quantum computers based on 54-qubit chips. The company is expected to deliver two IQM Radiance quantum computers to Finland's VTT Technical Research Center: a 150-qubit computer in 2026 and a 300-qubit computer in 2027.

But superconducting qubits have several technical problems. They are quite sensitive to noise in the environment; therefore, they need a lot of shielding and dilution coolers that cool the system down to millikelvin levels. The coherence durations of qubits are still constrained, which limits the depth of computing. Inconsistent fabrication causes qubits to be different from each other, and a lot of quantum error correction is needed to keep them accurate. Even with these problems, superconducting qubits are still one of the best ways to gain a quantum edge for the near future.

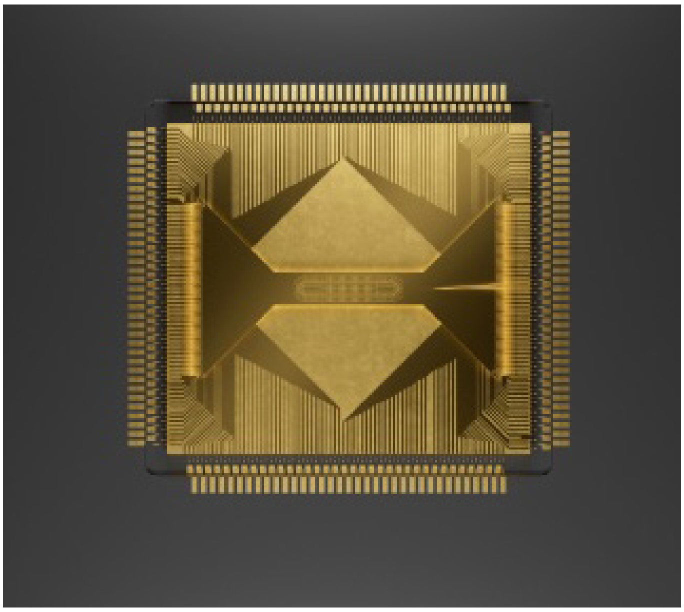
TRAPPED-ION QUBITS

Trapped-ion qubits are composed of single ions—that is, charged atoms held in position by electromagnetic fields. The ions encode quantum information into their intrinsic states, which can be manipulated very precisely with laser pulses. Ions interact via Coulomb forces, allowing 2-qubit gates to entangle and execute more complicated quantum operations. With extremely high accuracy, long coherence times, and high-fidelity entanglement, trapped-ion systems are exceptionally well-suited for implementing complicated quantum algorithms.

Though building big trapped-ion quantum computers would be easy, each ion needs its own laser control, which becomes increasingly complex with the number of qubits. Moreover, gate operations in trapped-ion systems tend to be slower than those on other platforms, such as superconducting qubits, thus reducing the rate of computation.

IonQ is one of the biggest businesses working on trapped-ion quantum computing. In 2023, it showed off a 36-qubit device named Forte that was significant for its all-to-all qubit connection and high-fidelity operations. Earlier, in 2020, Honeywell Quantum Solutions announced the H1 system, featuring 10 completely connected high-fidelity qubits. That company has also made a big difference in making trapped-ion systems that can be scaled up and are accurate. Quantinuum, founded by a merger between Honeywell Quantum Systems and Cambridge Quantum, now has the H2 system, with 56 qubits, and has set a new record for quantum volume performance.

Even though it has problems with scalability, trapped-ion technology remains a popular method because it is so accurate and reliable.



H2 quantum processor system (Source: Quantinuum)

The Quantum Race: Exploring Alternative Qubit Modalities

PHOTONIC QUBITS

Photonic qubits use photons, which are particles of light, to encode quantum information by changing the polarization, phase, or route of the light. They work well at room temperature, are not very sensitive to changes in temperature or electromagnetic fields, and can send signals over long distances over optical fibers. These features make them great for quantum communication and scalable structures. They also use linear-optical parts, including beamsplitters, phase shifters, squeezers, and single-photon detectors, to make and change quantum states. This lets them do computations based on gates, entanglement, and boson sampling.

Photons are easier to work with and less affected by changes in temperature and electromagnetic fields than other qubit approaches, which means they make fewer mistakes and are better for huge systems. Photonic qubit readout depends on very sensitive single-photon detectors, such as superconducting-nanowire single-photon detectors (SNSPDs), although the requirement for cryogenic cooling makes things harder.

Companies such as PsiQuantum are working to incorporate SNSPDs onto photonic integrated circuits so that PICs an be scaled more easily and with fewer cooling requirements. It is fair to say that qubits that are captured by lasers, transported, and cooled promise a better alternative to cryogenic cooling.

Modular quantum networks for scaling are also helped by photonics, as they let entanglement dispersion take place. The quantum photonic interface technologies from Nu Quantum, for example, interface matter-based qubits with photonic qubits in the pursuit of enabling large-scale interconnection of quantum systems.

In the greater scheme of things, photonics will play an important role in future quantum computing systems in reducing errors, enhancing control precision, and providing scalable networks. QuiX Quantum focuses on photon-based implementations of quantum computing, encoding, and processing of quantum information while enabling room-temperature operation and scalability.

Q.ant is a high-tech startup industrializing photonic quantum technologies in the fields of computing and sensor technology. It relies on its own technology platform for quantum chips and photonic integrated circuits. The central components of the chips are optical waveguides, modulators, beam splitters, and resonators, which enable the control of light and quantum effects in a highly integrated form. Unlike digital chips, which progress through a series of logic gates, photonic systems perform continuous analog computations, executing complex operations in a single physical step.

TOPOLOGICAL QUBITS

Topological qubits store quantum information by braiding anyons. Because they are non-local and topological, they are naturally resistant to local noise and mistakes.

The Majorana 1 quantum chip, released in February 2025, is a part of Microsoft's Station Q project, the leader in this industry. This processor, having space for a million qubits on a palm-sized chip, works with topological qubits enabled by Majorana fermions to improve error correction and push toward fault-tolerant quantum computing.

Majorana 1 uses a new material called a topoconductor, which is made of indium arsenide and aluminum and is akin to a topological superconductor. These are used to make topological superconductor nanowires housing Majorana zero-mode (MZM) quasiparticles cooled down to near absolute zero and maintained in magnetic fields. Quantum information is held in the parity of the MZMs.

An unpaired electron is shared between two MZMs, making it invisible to the outside world and protecting it from decoherence. As part of Darpa's US2QC program, Microsoft wants to construct a quantum computer that can grow in size over the next few years, not decades.

Topological qubits offer built-in fault tolerance and lower error rates, but it is still hard to make them work in real life, and they are still in the early stages of testing. Quantinuum is looking into fault-tolerant structures, such as topological methods, to make sure they can grow over time.

NEUTRAL-ATOM QUBITS

Neutral-atom qubits capture quantum information in the intrinsic states of single neutral atoms, held suspended by laser light. They are suitable for large-scale quantum computing because of their long coherence times. Optical lattices serve as the scaling mechanism, influencing the atoms' behavior in a nondestructive way, and the approach offers plenty of ways to couple different qubits. Precise control of neutral atoms is still a big challenge, however. Gate speed also remains an issue: Slow gates prevent faster calculations. Prominent players in the field include QuEra, Infleqtion, Atom Computing, and Pasqal.

Pasqal quantum computer (Source: Pasqal)

Pasqal uses neutral-atom technology to chill and trap rubidium atoms. The quantum information is stored in the atoms' energy states of these atoms. The atoms are then moved about with precise laser pulses, which perform quantum operations and entangle them. Arrays of optical tweezers hold atoms in shapes that can be changed with time, for enlarging purposes.

Rydberg states, wherein excited atoms experience strong interactions, are important for quantum logic circuits. Natural homogeneity, long coherence times, and many links among the qubits are some of the virtues of the approach. One can also design large and fully programmable quantum registers to simulate complicated quantum systems and execute complicated algorithms. Because a typical neutral-atom quantum computing system operates at room temperature, it is even more attractive, making it simpler and less expensive than other quantum computing platforms.

"The main advantage of the neutral-atom scheme of Antoine

Browaeys used in Pasqal is the possibility of a 3D structure, which means scaling can be easily achieved," Pasqal co-founder Alain Aspects said in an exclusive interview with EE Times Europe.

SILICON AND SPIN QUBITS

Silicon-based quantum computing employs silicon semiconductor technology to make qubits, which is possible because CMOS production is already well-established. Spin qubits are the most common type of qubit. They are either electrons that are trapped in silicon quantum dots or spins from dopant atoms such as phosphorus. In this case, the spin state (up/down) stands for the quantum states $|0\rangle$ and $|1\rangle$.

Silicon is attractive because it can be made in large quantities and can be added to existing infrastructure. Isotopically pure silicon makes the surroundings almost noise-free, which allows long spin coherence durations. Silicon qubits are not a different kind of qubit than spin qubits; rather, they make spin qubits possible. Most of the silicon qubits that are used today are spin qubits.

Spin qubits store quantum information by exploiting the spin states of electrons or nuclei, which can be "up" or "down." Silicon is a common material for this. These qubits have long coherence periods and work well with existing CMOS technology, which makes them perfect for large-scale integration. A silicon qubit holds one electron in a quantum well, and antennas or micromagnets change the spin states by changing the magnetic fields. States can be made to overlap by changing the pulse time.

Intel and the University of Sydney are overseeing development, and imec is putting a lot of money into silicon spin qubits. Imec makes single-electron transistors with overlapping gates and e-beam lithography, which creates isolated qubits with very high accuracy.

Because silicon spin qubits can be fabricated and integrated into other systems, their potential is enormous, although they face environmental noise and fine control issues. The researchers are still working with silicon, silicon germanium, and pure germanium to arrive at the best platform for future quantum processors that can be scaled and stabilized.

Quantum Motion Technologies, founded in 2017, is working on a way to make a large number of silicon qubits using a technology that works with CMOS. The company is now making a testbed for the U.K.'s National Quantum Computing Centre that uses silicon spin qubits to make quantum processors.

Equal1 combines quantum and classical computing parts into a single silicon chip, making it possible to build small quantum computers that can be installed on racks. The Bell-1 6-qubit rack-mounted quantum computer is the company's most important product. It can run CPU and GPU workloads at the same time. It has a closed-cycle cryo-cooler that lets the machine run at 0.3 K.

You can download the full Silicon 100 report, which details EE Times' 100 startups to watch in 2025, for free here.

Scan the QR codes to find all articles by Maurizio Di Paolo Emilio, editor-in-chief of embedded.com and Power Electronics News, on quantum computing.

embedded.com

Power Electronics News

SemiQon is making progress in quantum computing by making silicon-based quantum processors that are cheap, scalable, and long-lasting. SemiQon makes high-density quantum chips with integrated quantum dot qubits and cryogenic ultra-low-dissipation CMOS hardware by using standard semiconductor materials and processes.

Photonic, founded in 2016, is working on quantum computing that can handle errors using silicon spin qubits and photonic networks. Silicon "color centers" are long-lasting qubits that can be addressed with light. This means that millions of qubits might be put on a single device and work with telecom networks right away.

In 2022, CEA-Leti and CNRS started Quobly as a spinout. The company makes quantum processors out of silicon spin qubits utilizing tried-and-true semiconductor manufacturing methods, such as fully depleted silicon-on-insulator technology. Quobly wants to break the 1-million-qubit barrier by 2031. To do so, it has teamed up with STMicroelectronics to create a special manufacturing method that can handle large-scale quantum computing solutions.

Quantum dot qubits employ tiny semiconductor structures to trap single electrons. The quantum information is stored in the electron's charge or spin. Intel and the University of Sydney are two big entities that are using this method. Issues still to be addressed include quantum dot qubits' short coherence durations and the necessity for very precise control and noise isolation.

Diraq is a quantum computing startup that started in 2022. It focuses on silicon-based quantum processors that use quantum dot technology. The company uses its own technology—which it has been working on for more than 20 years, mostly at the University of New South Wales—to make quantum computers that can be scaled up and that use less energy.

Diraq is also in charge of a group of companies from Australia, the U.K., and the U.S. that are working together to speed development of qubit fabrication and control systems, hoping to shorten the time to production of quantum computers that are useful to industry.

OTHERS

Diamond nitrogen-vacancy (NV) center qubits use flaws in diamond lattices, wherein a nitrogen atom takes the place of a carbon atom and leaves a vacancy. You can change these qubits using light and microwaves, and they are the only ones that can work at room temperature. Element Six and the University of California, Berkeley are two of the most prominent players in this field.

NV centers are good quantum sensors because they sense magnetic fields, but scaling and calculation error rates are issues. Nuclear-magnetic-resonance qubits depend on nuclear spins, such as those of hydrogen or carbon, governed by magnetic and radio-frequency pulses. In small systems, they are exceedingly precise and stable, but they are difficult to scale, and their slowness transitions them into the realm of impracticality for large-scale quantum computing.

Qubits are very fragile entities and lose their coherence with noise coming from the environment. Hence, error correction of a particular kind is needed, which adds more work and complexity to the process. It is somewhat difficult for engineers to scale the quantum systems while preserving qubit fidelity and precise control, particularly when the systems have dozens or millions of interconnected qubits. Also, as a new field of research, quantum software lacks a sufficient collection of algorithms that can fully harness quantum hardware.

We must break through these barriers of coherence, scalability, and algorithm development to realize quantum computing that solves real-world problems. ■

Maurizio Di Paolo Emilio *is editor-in-chief of embedded.com and Power Electronics News. This article originally ran on embedded.com.*