STATE OF
THE FRENCH
QUANTUM
ECOSYSTEM
2023

le lab quantique

TABLE OF CONTENTS

EDITORIAL 04

State of the art of quantum technologies in France 06

- **Highlights of the year 2022 06**
  - Quantum news in France 06
  - New technological and scientific advances and use cases of quantum computing 10
- **Funding 37**
  - Public and parapublic funding 37
  - Private funding 41
- **A growing and increasingly attractive ecosystem, still in the process of being structured 46**
  - Overview of the ecosystem 47
  - France, an attractive country 52

On a global scale, where does Europe stand in the advancement of quantum technologies? 56

- **Europe's quest for a leader 56**
  - Continental Europe 56
  - United Kingdom 64
- **Europe vs USA 66**
  - Technological differences in research 66
  - The start-up ecosystem and the interest of large companies 69
- **Map of specificities according to regions of the world 73**
  - Asia 73
  - Rest of the world 82
- **Quantum and cooperation: state of the art of strategic partnerships 86**
  - Intra european partnerships 86
  - International partnerships 86

CONCLUSIONS 90

GLOSSARY 91

EDITORIAL

E. SHISHENINA

President

Quantum Computing is a rapidly evolving field holding great promise to solve complex problems and drive innovation in various industries. For the past years, we've been witnessing how major sectors such as energy, finance, healthcare, logistics, telecommunication, and art, to name a few, explored quantum in search for efficiency, accuracy and improved decision-making of new solutions. However, several technical and non-technical challenges must be overcome before the technology potential can be fully recognized.

In the quantum computing field, the crucial technical challenge is the development of stable and reliable qubits, the fundamental building blocks of quantum computers. The quantum hardware market has grown considerably in recent years, spurred by discoveries and advances in qubit technologies. Leading groups, young startups, have invested substantially in the improvement of quality and scalability of the qubits, already providing access to their systems via cloud-based services. Government and research institutions have invested heavily in the exploration of new experimental technologies to compete for the future commercialization of quantum computers. Public authorities have a role to play by supporting this emerging field at the crossroad of both Computer Science and Physics. In parallel with hardware development, various error-correction methods have been investigated to protect quantum information from environmental noise and other sources of errors that cannot be wholly eliminated by hardware.

As in any field, clear improvement metrics are crucial for the sustainable development of quantum technology and its progress. The lack of standardization and interoperability among different quantum systems makes sharing and comparing results difficult, sometimes causing confusion. Despite the several metrics established and commonly used to evaluate and compare the robustness and reliability of quantum devices, specialists agree that application-based benchmarks will allow for better interpretation of the performance and applicability of quantum computers.

The industry-specific problems offer an excellent base for the creation of such benchmarks. Although the discovery of various quantum-native applications such as cybersecurity, chemistry and materials, combinatorial optimization, most of them are still yet to be discovered. In addition, the potential of Quantum Computing to revolutionize other not-native fields, such as numerical simulations of physical processes, and AI, still needs to be clarified. In this regard, the development of quantum software and algorithms enabling full advantage of the unique capabilities of different quantum architectures still represents a barrier to widespread technology adoption.

Speaking of non-technical challenges, developing a robust ecosystem and a workforce of talents to design, build, and operate quantum computers, sensors, and networks becomes crucial for the successful growth of quantum technology and its future commercialization. This journey is long and effortful, and it is important to be conscious of the potential for hype and overpromising in the field. Having realistic expectations and a clear understanding of the technology capabilities and limitations through education and transparent communication will help to avoid disappointments, speculations and, as a result, lack of investment in the field.

Together with partners, the quantum computing pioneers, Le Lab Quantique is happy to contribute to the development and growth of the quantum ecosystem by providing a platform for collaboration and communication through various events and initiatives. Following on the important updates and progress of the quantum industry in 2022 and summarizing them in the annual report, we believe, will help the community to align on the current state of technology development, raise new questions and ideas, and motivate the new generation of specialists to explore this exciting field.

We wish you a pleasant reading!

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STATE OF THE ART OF QUANTUM TECHNOLOGIES IN FRANCE

A | HIGHLIGHTS OF THE YEAR 2022

1 QUANTUM NEWS IN FRANCE

Month	Events
January	• **Launch of the national hybrid quantum computing platform (HQI)** by Florence Parly and Fréderique Vidal which objective is to couple quantum machines to classical supercomputers by 2024 • **Merger of Pasqal and Qu&co** • **1st anniversary of the French Quantum Plan** (Le Plan Quantique National) • **Creation of the start-up WelinQ** which develops atom based quantum memory
February	• **Inauguration of Qtechs by the ONERA:** Bruno Sainjon inaugurated on the 8 of February a new cross-disciplinary laboratory dedicated to quantum technologies, called QTech, involving about thirty researchers and aimed to encourage exchanges, projects and new collaborations
March	• **Launch of the PEPR initiative:** a €150M national strategy for the development of quantum technologies led by the INRIA, the CNRS and the CEA • **Alice & Bob** raised €27M euros in their Series A round of funding with Supernova Invest, Breega, Elaia Partners and BPI France • **EuroHPC conference** at the Cité des Sciences with the participation of Le Lab Quantique • **Launching of the QuantAlps federation** on the 25th March in Grenoble aimed to gather the local quantum ecosystem
April	• **AFNOR launched a consultation** about the standardization of quantum technologies • **Launching** of Perceval, 1st photonic Qubit simulation system by Quandela
May	• **Quantum computing and technologies for the energy industry day** organized in Palaiseau by EDF

June	• **France Quantum conference** on 14th June an event aimed to highlight the french quantum ecosystem, held in the Eiffel tower • **17th edition of the Teratec forum** held in Palaiseau on the 14th and 15th June • **Quantum Technology need a Quantum Energy Initiative** published in PRX Quantum by Alexia Auffèves • **Qubit Pharmaceutical** raised $17M euros in their seed round of funding with Quantonation, Octave Klaba, Omnes, XAnge • **Raising Quantum Awareness** - a networking event organized by Le Lab Quantique, RaiseLab and BPIFrance • VivaTech conference organized by GENCI (TBC) • Quebec Quantique and QuantX co-organized the first BIG Quantum Hackathon in Montreal
July	• **Final closing of Quantonation 1 at €91M** • **Paper published** High-rate entanglement between a semiconductor spin and indistinguishable photons by Quandela • **QuantX co-organized first Quantum Hackathon in UK** together with National Quantum Computing Center (NQCC)
September	• **Pasqal announced having reached 324 atoms** • **iXBlue announces partnership with WelinQ** • **Announcement of Partnership between Le Lab Quantique and Chicago Quantum Exchange**
October	• **Alain Aspect awarded with the Nobel Prize** for its work on quantum entanglement alongside John Clauser and Anton Zeilinger • **Launching of EuryQa:** a new european infrastructure for quantum computing with Rydberg atoms led by the University of Strasbourg • **Bpifrance BIG:** europa's largest business meeting • **Meetup Le Lab Quantique** in which 50 organization have participated • **1st Quantum Hackathon by QuantX in Grenoble** organized by Le Lab Quantique, proposed by Minalogic, Atos, CEA, France Hybrid HPC-Quantum Initiative, Giant Innovation Campus and QuantAlps. • Publication of Quantum dossier by QuantX in La Jaune et la Rouge (the École Polytechnique's Alumni revue) • **Quantum Technologies Thematics Days in Grenoble** organized by Minalogic and gathering the global quantum ecosystem around conferences and workshops. • **Quantum Computing for Chemistry** - The Next Revolution - the industry training event in Strasburg co-organized by University of Strasbourg and QunaSys

November	• **Quandela Hackathon** organised alongside the QCIS (Sorbonne's quantum cluster) in Jussieu • **France and the US signed a joint statement** to enhance cooperation on Quantum • **ENI announced a partnership with Pasqal** • **Announcement of the creation of the center of excellence for algorithms (QuaTERA)** by EDF, Exaion Inc, Pasqal and the Quantum Innovation Zone • **Nvidia announced a partnership with Qubit Pharmaceutical** (paper published Accelerates Drug Discovery With Hybrid Quantum Computing in the framework of this partnership) • **Creation of the start-up Siquance** by the CNRS and the CEA • **Cooperation agreement between the University of Chicago and Pasqal** • **Paper published** Quantum Feature Maps for Graph Machine Learning on a Neutral Atom Quantum Processor by Pasqal • **Cooperation agreement between the University of Chicago and the CNRS** • **Pack Quantique (PAQ) launch of new partnership with Ile-de-France Region, TERATEC, GENCI and Le Lab Quantique to explore potential of applied quantum computing (TBC)**
December	• **Quandela launched a 5 qubits cloud computer in the cloud** • **Pasqal raised $109M in a Series B round led by Temasek** • **Paper published** Financial Risk Management on a Neutral Atom Quantum Processor by Multiverse Computing, Pasqal and CA-CIB

KEY TAKEAWAYS

Community

The quantum community has had the opportunity to gather several times during this year within conferences, forums, hackathons and seminars. After two years of social distancing due to the pandemic, these large and successful gatherings have testified of the growing attraction for quantum. Among these events was the successful France Quantum Conference, that gathered more than 150 attendees and 20 speakers among which Neil Abroug, the national coordinator for Quantum Strategy.

Start-ups have also participated in gathering the community by organizing events, of which the LOQCathon: a 3 days event, organized by Quandela, open to students, researchers and professionals interested in better understanding Linear Optical Quantum Computation.

In the meantime, Le Lab Quantique gathered its members and partners for the first face-to-face meetup of the year. This event gathered more than 50 organizations and allowed Le Lab Quantique to present its new board, its new projects as well as the new tools and means of collaboration made available to members. This meetup was followed by the opening of Le Lab Quantique's slack (100+ members) and initiated the cycle of quarterly meetings that currently prevails.

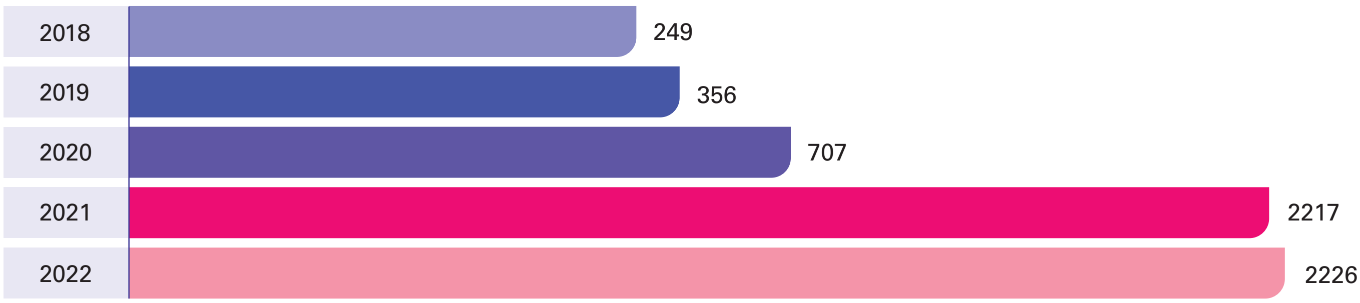
Funding

While the French Quantum Plan (Le plan quantique) celebrated its first year of existence, quantum funding showed encouraging signs during the year despite the degraded economic situation.

The French ecosystem has shown signs of resilience despite the downturn: total funding having increased by 16% in 2022 (vs. 2021). Nevertheless, worldwide quantum funding reached more than $2B[1] in 2022 while the French startup ecosystem raised only $229M this year.

On the academic side, a €150M research program (PREP initiative) has been deployed within the French Quantum under the supervision of the INRIA, the CNRS and the CEA.

Capital Invested in Quantum ($M)



Source: Capgemini

Commitment

Public authorities have maintained their political support for the quantum ecosystem mainly with the deployment of the quantum plan but also through Florence Parly's announcement of the hybrid quantum computing platform: this hybrid computing platform will interconnect classical systems and quantum computers.

These resources will be made available to an international community of laboratories, start-ups and manufacturers. The aim is to facilitate their access to quantum computing capabilities, so that they can identify, develop and test new applications. Set up by INRIA, the CEA and GENCI, in close collaboration with the CNRS, the platform will be housed at the Very Large Computing Centre located at the CEA DAM (Commissariat à l'énergie atomique et aux énergies renouvelables).

Ambitions

While Pasqal announced a successful record-breaking 324 atom manipulation, the French ecosystem continues to diversify and asserts new ambitions as evidenced by the launch of Siquance, a spin-off from the CEA and the CNRS. The start-up is devoted to developing a silicon-based quantum computer, e.g. based on the same technologies as standard integrated circuits. The company relies also on the capacities of European semiconductor producers. Siquance wishes to become a world technology leader in the field of quantum computing and to be at the forefront of French and European sovereignty in the field of quantum computing.

This year also marks the creation of WeLinQ : a Paris-based spin-out company of Sorbonne Université, CNRS, and PSL-University, founded in 2022 by Tom Darras, Julien Laurat, Eleni Diamanti and Jean Lautier-Gaud. WeLinQ provides quantum links based on cold-atom quantum memories to interconnect quantum processors and ensure access to quantum computing at a distance. WeLinQ announces that it is developing the world's most efficient industrial grade quantum memories based on cold atom technology.

Qbit Soft was also created this year. The start-up aims to provide a single cloud-based platform allowing enterprises to use Quantum powered algorithms and applications in order to boost their processes.

In the meantime, Quandela gave birth to both its own quantum photonic development software, Perceval, and its cloud quantum computer.

1. The Quantum Insider

2 NEW TECHNOLOGICAL AND SCIENTIFIC ADVANCES AND USE CASES OF QUANTUM COMPUTING

Quantum computing

a. Hardware technologies : cold atoms, photonics, silicon, superconducting, nanotubes de carbone (C12)
b. Quantum interconnects to scale
c. Quantum software

Quantum communication & security

a. QKD, Quantum internet (telecommunication market)
b. PQC

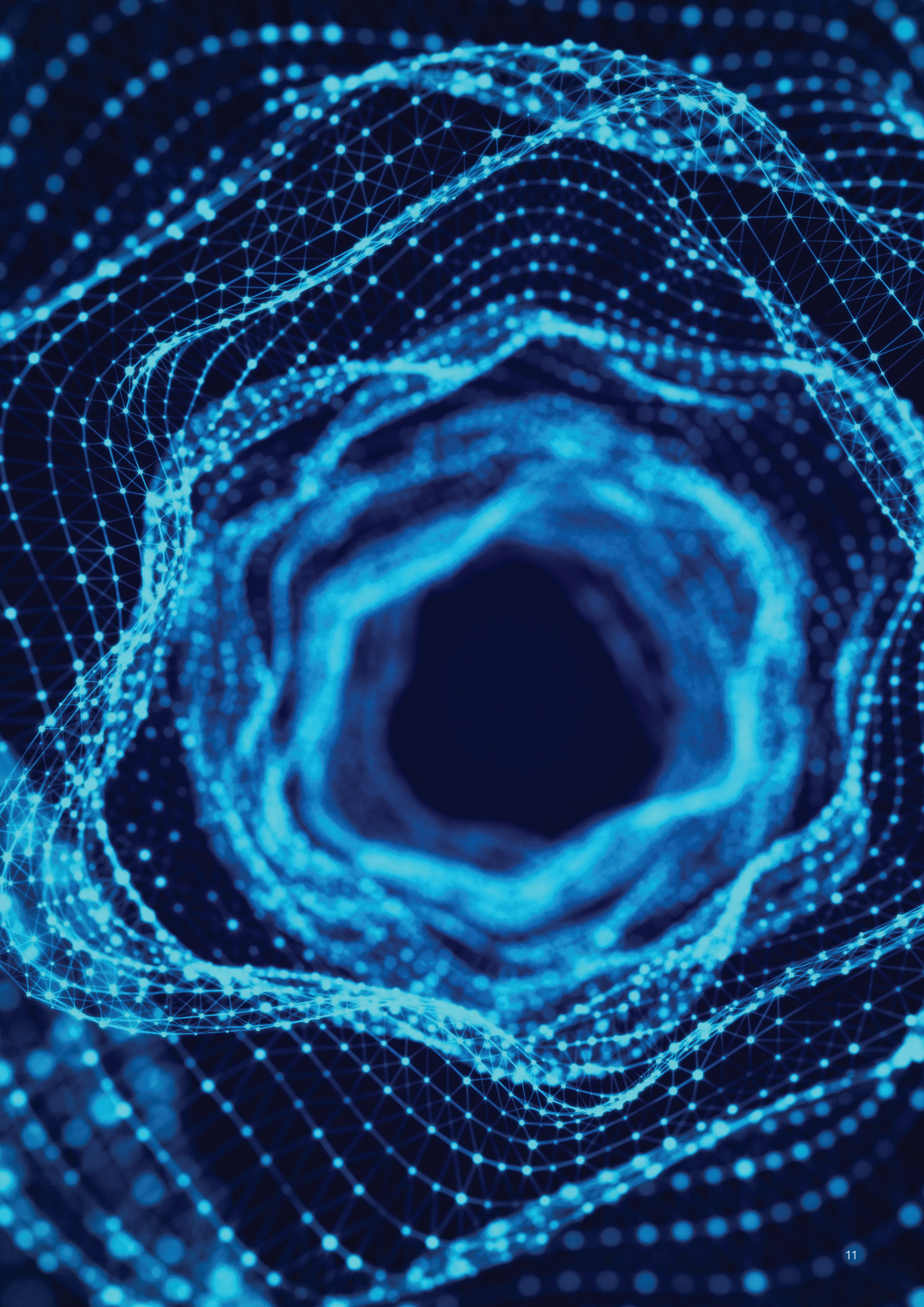
Quantum sensing

a. NV centers
b. Cold atoms
c. Superconducting (squids)

Quantum computing

a HARDWARE TECHNOLOGIES

Quantum computing is a technology which can enable new kinds of calculations but require technological breakthroughs in hardware as well as software development. We will here cover some of the promising hardware technologies as well as the algorithms which could one day be computed on it.



SUPERCONDUCTING CIRCUITS

CONTEXT

Superconducting circuits are the most prominent technology used to perform quantum computing. From Google, IBM, Intel, Rigetti, Alice&Bob to D-Wave, it has been the privileged qubit technology that most of the giants have chosen to bet on.

This choice is not arbitrary at all, and one of the intuitive reasons for which superconducting circuits make the ideal qubit candidate, is that superconductivity is essentially a Macroscopic Quantum Phenomenon. When paired with Josephson junctions[2] (for its nonlinear effect) these superconducting circuits make for a very good two state quantum system, i.e a qubit.

A simple (and simplified) model of this technology is to conceive of superconducting circuits as quantum harmonic oscillators, which is a system with quantified energies, but for which the energy levels are equidistant.

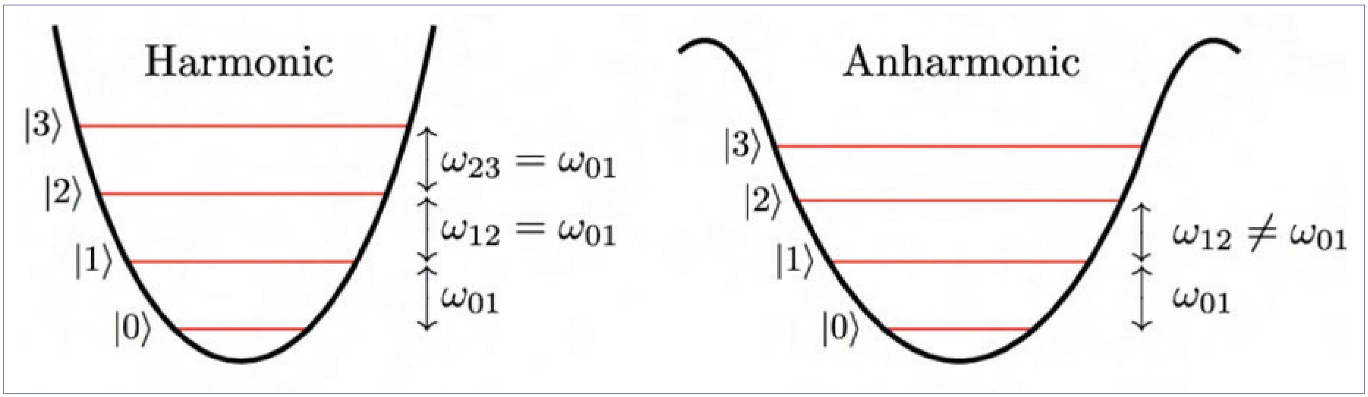
The addition of Josephson junctions adds non-linearity to the system. Transforming it into an Anharmonic oscillator that can be excited to jump from one determined state to the other.

One major inconvenience of this qubit technology is that to exhibit superconductivity, and to reduce the noise, the temperature of these circuits has to be dropped to less than a few milli Kelvins. However, one of the main advantages of superconducting circuits is that they are manufactured to a high degree of precision, which allows for a degree of control on the qubit systems that makes it easier to innovate and to enhance the circuits. When used as qubits, they also scale the best out of the other types of technologies. With IBM's Osprey having 433 qubits, and most high profile corporations exclusively focusing on this technology, it is without doubt leading the race.

In France, superconducting circuits has been an active field of study for the last twenty years, especially in cutting edge fundamental research institutes like the CEA. However, with the advent of multiple qubit systems, interest has since been rekindled in this technology. Currently, there are many labs that actively develop the technology, such as: CEA's Quantronic's team, QuantAlps and many more. In the Ecole polytechnique, a laboratory called QCMX has been dedicated to superconducting circuits in 2017.

Looking into the French Quantum Ecosystem, one of the most prominent startups focused on superconducting circuits technology is Alice&Bob. The start-up has risen to notoriety quickly thanks to their revolutionary fault-tolerant cat qubit technology, associating superconducting qubits and stabilized photon-based qubits. This technology has a much lower physical qubit to logical qubit ratio (moving from about 1000 for 1 to about 30 to 1).

2. Two (or more) superconductors coupled



A figure showing the difference between Harmonic and Anharmonic quantum oscillators. (Anton Frisk Kockum and Franco Mori)

LATEST NEWS

IBM's 433 qubit Osprey:

Osprey represents a milestone in the quest for quantum advantage. It currently holds the record for most qubits in a superconducting general purpose quantum computer, with 433 qubits. IBM plans even more bombastic models for the near future in order to reach its stated goal of 4000+ qubits by 2025. However one should not only focus on the number of qubits, but also pay attention to the error rate of those qubits, which will allow real-life use cases.

Superconducting routing platform for large-scale integration of quantum technologies:

Scalability is one of the biggest issues that impede the achievement of large-scale quantum computers. This article, published by a team in Grenoble, discusses the possibility of using superconducting interconnections as routing layers. For the advantages that they provide, in thermal management for example.

Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits:

Cosmic rays are high energy particles born through cataclysmic events like the death of stars, we are bombarded by these rays all the time. They pose no problem to regular electronic systems. But the inherent fragility of Quantum systems means that they can cause catastrophic errors by perturbing quantum states. This article, published in Nature, shows how such high energy radiation can induce error bursts that are not localized but tend to spread throughout the whole chip in a large QEC. They also provide a way to detect these error bursts.

Sources:

Ezratty https://www.researchgate.net/figure/Harmonic-and-anharmonic-systems-and-their-suitability-as-qubits-a-In-the-quadratic_fig2_335845744

https://web.physics.ucsb.edu/~martinisgroup/classnotes/finland/LesHouchesJunctionPhysics.pdf

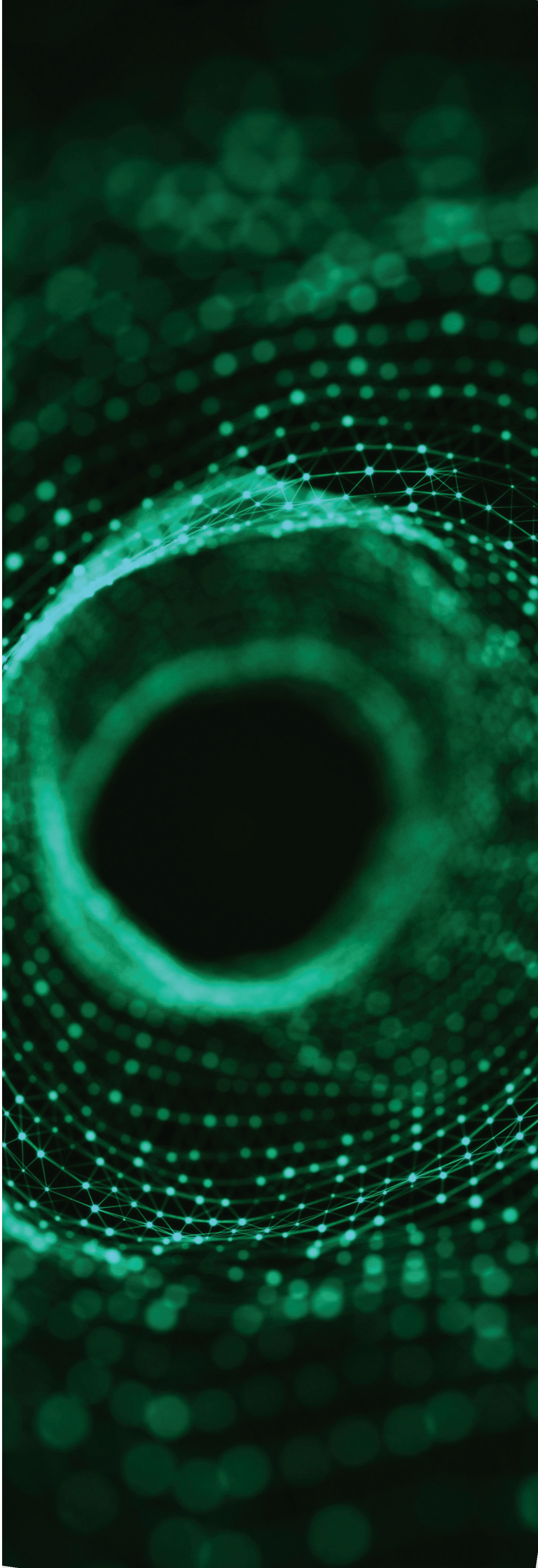
COLD ATOMS

CONTEXT

Since the 80s, the development of research around cold atoms has opened a vast range of applications including quantum simulation and computing. The improvement of experimental control over light, especially laser light, led to a lot of breakthroughs across the last fifty years or so. In the 70s, scientists discovered that laser light could be used to slow atoms down by so-called "Doppler cooling" (atoms absorbing radiation and re-emitting it differently, losing energy in the process). Combining this with a magnetic field gradient to change the energy level of the atom depending on its position (Zeeman effect) allows for a longer interaction time: these are called magneto-optical traps (MOT in short). Optical molasses can then be used to further cool the atoms (down to a few hundreds of microkelvins) by using three-dimensional Doppler cooling (Nobel prize in 1997 to Claude Cohen-Tannoudji, Steven Chu and William Daniel Phillips). Later, techniques were developed to cool atoms even closer to the absolute zero, to temperatures of around ten nanokelvins, using evaporative cooling, a technique were the energy barrier confining the atoms is slowly reduced, allowing atoms of higher energy to escape the trap, keeping only the "coldest" atoms. This cooling setup made possible in 1995 the first experimental observation of a Bose-Einstein condensate (with Rubidium atoms, Nobel Prize in 2001 for Eric Cornell et Carl Wieman and Wolfgang Ketterle), opening a whole new research field.

A promising use of cold atoms is to implement quantum computation. Indeed, by preparing the atoms correctly, one can obtain a state where the atom can be seen as a two-level particle, i.e., a qubit. Using laser pulses, it is possible to implement transformations of the qubits, and entangle them. The advantage of this approach is that cold atoms can be isolated for their environment very well (preserving the system from the effects of decoherence), and that the range of transformations is extremely broad, due to the control possibilities offered by laser light (with many controllable parameters such as frequency and intensity).

Another use is quantum simulation. Indeed, using interaction between cold atoms and lasers, it is possible to create a specific evolution Hamiltonian for the system. Letting the system evolve under this Hamiltonian and measuring the outcome allows us to solve problems that follow the same equations as the one describing this quantum system. For example, cold atoms are ideal to simulate many-body problems that have a lot of applications in different domains of physics or even other sciences (superconductivity, chemistry, particle physics, …)



LATEST NEWS

Pasqal (with Laboratoire Charles Fabry de l'Institut d'Optique):

Announcement in September 2022 of a capacity of 324 qubits for quantum simulation. Since Pasqal uses Rydberg atoms placed in optical arrays, one of their goals is to improve the size of the arrays that can be created which requires new techniques to reach the hundreds of atoms in the array. To do so, they measure the evolution of the traps' power to update the array (using spatial light modulators) and guarantee an increased loading capacity. They reached a probability of obtaining a defect-free atomic array of around 300 atoms of 0.37[3].

Other improvements were made regarding the range of programmable Hamiltonians with the platform, addressing dipole-dipole interactions of the Rydberg atoms and microwave fields. This flexibility on the simulated Hamiltonians is very interesting when it comes to quantum computing and simulation[4].

Finally, new developments have been made on certain algorithms, for example the Maximum Independent Set (MIS) problem (NP-hard problem with graphs)[5]. Moreover, the development of computational capabilities with algorithms on graphs, and their use for machine learning, has allowed many applications to be found, for example in finance[6].

Therefore, many partnerships between Pasqal and companies were announced in 2022, such as ENI, Siemens, and Aramco.

WeLinq is developing quantum memories necessary to synchronize signals from different processors to make them work in parallel. Their work uses cold atoms manipulated with lasers to create entanglement between cold atoms and photons and be able to transfer information between two cold atoms-based memories.

DyTeq, in partnership with LCAR, reported the development of a new scheme to manipulate cold atoms on an optical lattice . By changing the lattice position across time, they have been able to prepare a vast range of states on the lattice, with full control over parameters such as sites populations and relative phases on their momentum. This opens interesting perspectives in quantum simulation.

French Laboratories: LKB, LNE-SYRTE, LAC, LCFIO, QTech (ONERA), LP2N, DyTeQ, CESQ, LCAR, LPTM, LPL, PhLAM

French Companies: Pasqal, WeLinq

Foreign Companies: Quera, ColdQuanta, Atom Computing

3. KN Schymik et al., In-situ equalization of single-atom loading in large-scale optical tweezers array, Phys. Rev. A 106, 022611 (2022), DOI: https://doi.org/10.1103/PhysRevA.106.022611
4. P. Scholl et al., Microwave-engineering of programmable XXZ Hamiltonians in arrays of Rydberg atoms, 2022, arXiv:2107.14459v2
5. C. Dalyac, L. Henriet, Embedding the MIS problem for non-local graphs with bounded degree using 3D arrays of atoms, 2022, arXiv:202209.05164v1
6. Leclerc et al., Financial Risk Management on a Neutral Atom Quantum Processor, 2022, arXiv:2212.03223
7. N. Dupont et al., Quantum state control of a Bose Einstein condensate in an optical lattice, 2021, https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.2.040303

PHOTONS

CONTEXT

Photonics, through the manipulation of photons, allows for many applications. One of them is quantum computing. Quantum qubits can be implemented in many ways by using photon's polarization, spatial modes, phase, frequency, or number of photons. This allows for systems using qubits with more states than the traditional two-states qubits (for example when spatial modes of the photons are used to describe the different states). This domain developed since the 60s with the discovery of the quantization of the electromagnetic field.

However, computing with photons requires very precise and controlled conditions to obtain high quality photon sources and operations preserving a maximum coherence of the system. Quandela is a leader in the domain and its approach uses extremely precise semiconductor nanostructures to create deterministic single-photon sources.

The tools necessary to implement operations on photons qubits are well-known optical components such as lasers, optical fibers and other waveguides, optico-electronics modulators, beam splitters and polarizing crystals. Nonetheless, a lot of improvements are still being made on these components to guarantee an optimal efficiency (low photon losses) and to maintain a high coherence.

Moreover, one interest of photonics is their interactions with other quantum technologies such as cold atoms, NV centers or superconducting circuits. Through light-matter interactions such as spontaneous emission, it is possible to create entanglement between photons and the state of another system. This opens interesting perspectives in the field of quantum interconnect in order to make computations with different systems in parallel, interacting through entangled photons.

Laboratories: LPA (LPENS), LKB, MPQ, INSP, C2N, LPQM, CEA IRIG, INL, ILM, LPCNO, LIP6, INRIA

Companies: Quandela

Foreign companies: Psi Quantum, Xanadu

LATEST NEWS

Quandela

(with Centre de Nanosciences et de Nanotechnologies and Institut Néel)

From a technological point of view, Quandela's studies are focused on developing high quality techniques for the manipulation of photon states. Advances were made on the entanglement of photons to create entangled multi-photons states, at the heart of quantum computing with photons. This was implemented using semiconductor spins (acting as an artificial two-level atom that can spontaneously emit photons entangled with the atom) with various uses (high fidelity three particle entanglements[8], photon-number entangled states[9], on-chip entangled four-photon states[10]).

Another axis studied is the development of techniques allowing for error mitigation. One of them uses the Accreditation protocol (method consisting of using other circuits with similar noise to test the interesting circuit and assess its quality; by selecting the circuits with only good quality, one can therefore diminish the error rate and obtain more precise values[11]). Other articles[12 13] also tackle the problem of quantum error and evaluating the quality of a photonic quantum device.

Finally, it is necessary to have a better framework to use and study photonics quantum computing. A practical software to use Quandela's photonic quantum computers was launched in 2022[14]. Moreover, a new theoretical framework was developed to better describe quantum circuits[15] and a new graphical way to represent them[16].

Having explored the big three: cold atoms, superconducting circuits and photonics. It is now time to turn to the other types of technologies that are being developed in order to yield qubits.

8. Coste et al., High-rate entanglement between a semiconductor spin and indistinguishable photons, being reviewed in Nature journal, https://arxiv.org/abs/2207.09881
9. Wein et al., Photon-number entanglement generated by sequential excitation of a two-level atom, published in Nature photonics, https://doi.org/10.48550/arXiv.2106.02049
10. Pont et al., High-fidelity generation of four-photon GHZ states on-chip, arxiv 2211:1562, https://arxiv.org/abs/2211.15626
11. Mezher et al., Mitigating errors by Quantum Verification and Postselection, Phys. Rev. A 105, https://journals.aps.org/pra/abstract/10.1103/PhysRevA.105.052608
12. Kapourniotis et al., Unifying Quantum Verification and Error-Detection: Theory and Tools for Optimisations, arXiv2206.00631, https://arxiv.org/abs/2206.00631
13. Mezher et al., Assessing the quality of near-term photonic quantum devices, arXiv:2202.04735, https://arxiv.org/abs/2202.04735
14. Heurtel et al., Perceval: A software platform for Discrete Variable Photonic Quantum Computing, arXiv:2204.00602, https://arxiv.org/abs/2204.00602
15. Clément et al., A Complete Equational Theory for Quantum Circuits, arXiv:2206.10577, https://arxiv.org/abs/2206.10577
16. Clément et al., LOv-Calculus: A Graphical Language for Linear Optical Quantum Circuits, arXiv:2204.11787, https://arxiv.org/abs/2204.11787

SILICON QUBITS

CONTEXT

Another solution to create qubits is to use spin orientation of electrons trapped in a potential well (or the inverse structure with a missing electron). This idea started in 1996. It was found that silicon had interesting properties for such uses (thanks to a lower hyperfine coupling than other materials). Moreover, the noise from the environment is less important. The first silicon qubit was demonstrated in 2012.

Operations on qubits are implemented using microwave pulses, that can modify the internal state of the electron, hence the qubit state, or using tunneling between neighboring sites (that can be manipulated by changing the characteristics of the potential well trapping the electron). This makes it possible to operate silicon qubits at temperatures around 1K (much more practical than the mili Kelvins necessary for superconducting qubits for example).

Advantages of this technology are the possibilities in terms of miniaturization (a silicon qubit having the size of a square with 100 nm sizes, it opens great possibilities in terms of qubit density), and it also benefits the already existing industrial processes. Moreover, its integration in classical computers, already based on silicon components, is easier, and might prove useful for applications and hybrid uses.

In France, the startup Siquance, founded in 2022, is taking over the research effort led by CEA-LETI and CNRS in Grenoble to industrialize the production of silicon qubits quantum computers.

LATEST NEWS

Researchers from the university of Grenoble-Alpes (with both CEA and CNRS) reported the use of a hole spin (electronic vacancy) in silicon to obtain longer coherence time when operating the qubit with a magnetic field along a specific orientation[17]. This may be used to obtain longer coherence time in qubits systems by carefully engineering the orientation of the different qubits and operating the qubits along specific orientations.

In parallel, progress has been achieved on the coupling of hole spins in silicon and photons, obtaining a high coupling rate using spin-orbit interaction[18]. This opens a new perspective in light-matter interactions and better manipulations of spin qubits in silicon.

Improvements were also made on techniques for having fast and high-fidelity measurements of electronic spins in silicon[19] with a measuring time much shorter than the coherence time of spin qubits in silicon. This measurement method also has a reduced impact on the system. This is necessary for intermediate measurements of the system, which is necessary for error correction, or certain algorithms.

Finally, new developments were made on devices using quantum-dots to generate high-frequency signals that could be integrated in silicon-based devices[20]. This is necessary for qubit readout for example.

French Laboratories: INSP, CEA-LETI, Institut Néel, LPCNO

French Companies: Siquance

Foreign Companies: Diraq, Quantum Motion, Silicon Quantum Computing

17. Yu et al., Strong coupling between a photon and a hole spin in silicon, 2022, arXiv:2206.14082v1
18. Oakes et al., Fast high-fidelity single-shot readout of spins in silicon using a single-electron box, 2022, arXiv:2203.06608v1
19. Oakes et al., A quantum dot-based frequency multiplier, 2022, arXiv:2211.14127v1
20. Oakes et al., A quantum dot-based frequency multiplier, 2022, arXiv:2211.14127v1

CARBON NANOTUBES

CONTEXT

Carbon nanotubes are another solution investigated to implement quantum computing. This technology is also based on electronic spins trapped in electrical potential wells. Carbon nanotubes (made out of the C12 isotope of carbon only) and electrodes are used to trap electrons in the nanotube. Quantum operations can then be implemented using microwave pulses.

The advantages of this method are the material chosen and its purity that reduces the noise from the environment, allowing for longer coherence times and fidelity.

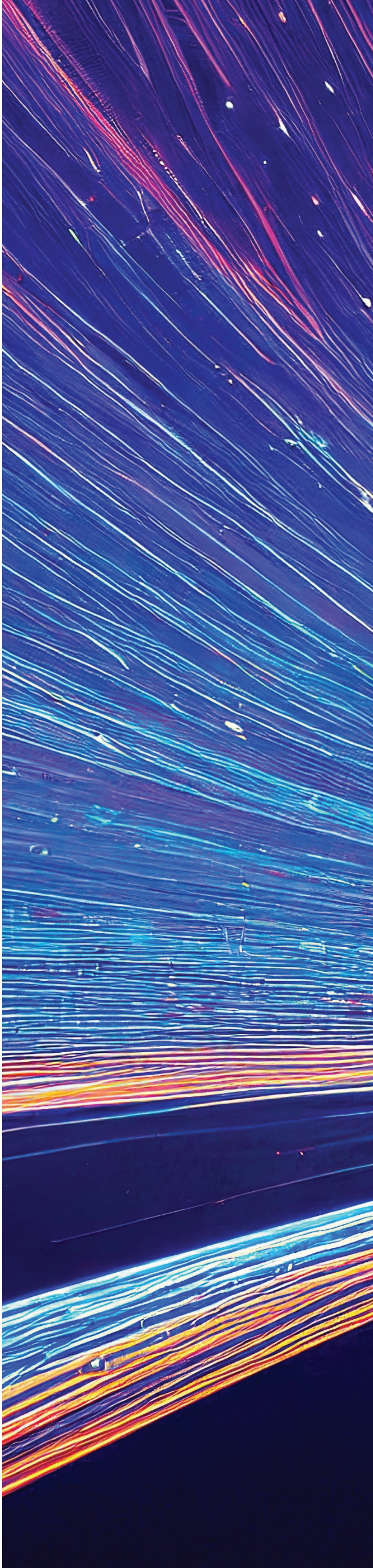
C12 Quantum Electronics (called "C12"), created in 2020, is a leader in the field, with experience coming from CNRS and ENS laboratories.

LATEST NEWS

A joint team between C12 and Lorraine University studied the design of nanomagnets that can be used to create localized magnetic field gradients with applications in the manipulation of spin qubits with high-fidelity operations[21].

Carbon nanotubes Laboratories: LPENS, LOMA

Companies: C12



21. Legrand et al., Optimal design of nanomagnets for on-chip field gradients, 2022, arXiv:2212.13156v1

b QUANTUM INTERCONNECTS TO SCALE

CONTEXT

As explained before scaling up quantum computers' computational power is a difficult task. It can be done by "scaling in" which means increasing the number of qubits in a quantum processor. However quantum computer infrastructures are complex and unwieldy; another possibility consists in "scaling out"[22]. This method consists in connecting quantum processors to combine their computational power through a quantum computing cluster known as "Quantum Interconnect".

For quantum processors to work together on the same task, qubits must be shared, therefore distant qubit entanglement must be achieved. To do so entanglement must be done between objects of different nature because of the variety of used technologies. Indeed different qubit encodings and qubit types can be optimal in different contexts depending on how they are used. Most qubit implementations are currently based on microwave photons to exchange information. However microwave photons are harder to transport on long distances than optical photons, therefore **microwave-to-optical transduction** is required for multi-processor architectures. This is already done in laboratories and startups are being developed in this area[23]. Other issues can appear when changing how qubits are encoded. Indeed discrete qubit encoding (such as polarization) is currently more optimal for transporting qubits over long distances while continuous encodings (such as cat-state qubits) are better when applying multiple qubit operations[24]. Until now these two families of qubits are relatively divided but scaling out continuous encoding based computers would require continuous to discrete encoding conversion. Proof-of-principle entanglement of such "hybrid entanglement" has already been carried out but these technologies are not mature enough to be commercialized. **Quantum memory** technologies will also have to be improved to enable quantum interconnection. Indeed scaling out requires synchronization between the QPUs. This requires quantum memory. This technology stores a qubit's state in time (mainly based on cold atoms). Fundamental research is very active in this area, to find the best way of storing quantum memory. For instance, rare earth-doped crystals properties are currently studied because of how they interact with light[25].

In the longer term, distant entanglement could also connect computers hundreds of kilometers away: Quantum Interconnect could then open new possibilities in securing "Quantum Computing as a Service" offers. Indeed the cloud providers could technically spy on their clients if they wanted. With quantum computers, a family of protocols (based on an adapted implementation of measurement-based quantum computing) called "Blind quantum computation" could protect clients from untrusted server providers. With these protocols a "client" could securely use the computational power of an untrusted "server" who would operate the calculation without being able to see what it is doing[26]. The first credible description of such a system was described in 2009 by Anne Broadbent, Joe Fitzsimons and Elham Kashefi, but as explained before it is far from being implementable.

22. Ezratty, Olivier. "Understanding Quantum Technologies 2022." arXiv e-prints (2021): arXiv-2111.
23. Weaver, M. J., Duivestein, P., Bernasconi, A. C., Scharmer, S., Lemang, M., van Thiel, T. C., ... & Stockill, R. (2022). An integrated microwave-to-optics interface for scalable quantum computing. arXiv preprint arXiv:2210.15702.
24. Jeong, H. Converting qubits. Nat. Photon. 17, 131–132 (2023). https://doi.org/10.1038/s41566-022-01147-z
25. Serrano, D., Kuppusamy, S.K., Heinrich, B. et al. Ultra-narrow optical linewidths in rare-earth molecular crystals. Nature 603, 241–246 (2022). https://doi.org/10.1038/s41586-021-04316-2
26. Herder, Charles. "Blind Quantum Computation." (2012).

LATEST NEWS

- **QPhoX, a microwave-to-optical** transduction startup, recently partnered with IQM, a quantum computer company to create the first multi-processor architecture.
- A new startup **WeLinQ** was created in 2022 based on promising research. Their goal is to develop quantum memories for synchronization between QPUs (necessary for scaling-out).
- **Conversions from discrete to continuous encoding on optical qubits** has recently been carried out in the french Laboratoire Kastler Brossel. Experimentalists managed to entangle a discretely encoded qubit and a cat-state qubit (continuous encoding) in what is known as "hybrid entanglement". Their results represent promising progress for the development of quantum interconnect, but the conversion still has low success probabilities[27].
- **A team from the University of Sussex and Universal Quantum has established groundbreaking records in the accuracy and speed of ion qubit transfer between processors.** This technology can only be used for trapped ion quantum computers, and on short distances between adjacent quantum computing modules. However it still paves the way to possible progress in the development of multi-unit architectures .

Laboratories : LKB

French companies: WelinQ Foreign companies Next Generation Quantum, PhotoniQ, Entangled Networks, Bohr Quantum Technology, QPhoX., Universal Quantum, Qunnect, NuQuantum

27. Darras, T., Asenbeck, B.E., Guccione, G. et al. A quantum-bit encoding converter. Nat. Photon. (2022). https://doi.org/10.1038/s41566-022-01117-5
28. Akhtar, M., Bonus, F., Lebrun-Gallagher, F.R. et al. A high-fidelity quantum matter-link between ion-trap microchip modules. Nat Commun 14, 531 (2023). https://doi.org/10.1038/s41467-022-35285-3

C QUANTUM SOFTWARE

The reason why we build quantum computers is to be able to run quantum algorithms, algorithms that have shown a staggering degree of promise and ingenuity in the last 3 decades.

Quantum algorithms and quantum computation:

Quantum algorithms are algorithms that run on a quantum computer, they are fundamentally different from classical algorithms, because their basic unit, the qubit, is a quantum wave function rather than one of two values.

Quantum algorithms can be described differently depending on the model of computation used. There are many such models: quantum circuits, one way quantum computation and topological quantum circuits…

Nevertheless, it has been shown that all these models are equivalent[29 30]. Therefore one needs only to explicitly study one model, this is especially the case when we look for exponential or what we call super-polynomial speedups.

Quantum algorithms use cases

Quantum algorithms emerged as a way to make efficient quantum simulations, after it was first proposed by Feynman (and independently by Yuri Manin) in the early 1980s. It wasn't until Peter Shor came up with his famous algorithm in 1994 that interest in this fringe field was rekindled[31]. This algorithm held the power to break up encryption based on prime factorization in polynomial time, and thus the potential to revolutionize cryptography as we know it. Since then, quantum algorithms have been found to offer speedups in multiple problems.

An algorithm's performance is generally measured through its asymptotic complexity, thus by speedup we mean a better complexity, that is lower running time for large enough inputs. The algorithms with exponential speedups over their classical best performing counterparts are the stars of quantum computation, and Shor's algorithm is such an example[32].

However most of the exponential or high-polynomial speedups are proven in the context of large scale and fault tolerant quantum computers. In the NISQ era (near term), researchers are actively trying to provide efficient quantum algorithms, although proving speedups is more complicated.

More prominent types of algorithms:

Search algorithms & Amplitude Amplification:

For an unstructured search problem, the existing classical solution is done in linear time. Or to put it simply, a classical computer must go through all elements in worst case scenarios to find the desired solution. Quantum search algorithms based on Grover's algorithm can solve this problem more efficiently, as the complexity for this algorithm is proportional to the square root of the size.

Amplitude Amplification is yet another algorithm which yields the same speedup, which is a fundamental routine to many other algorithms. Grover's algorithm and Amplitude Amplification can be used in a variety of tasks to provide speedups, for example in searching for minimums of unsorted lists and speeding up checking for graph connectivity.

29. By equivalent, we mean that one can simulate the other with a polynomial overhead.
30. A survey of quantum complexity theory, U. Vazirani.
31. Shor, P.W. (1994). "Algorithms for quantum computation: discrete logarithms and factoring". Proceedings 35th Annual Symposium on Foundations of Computer Science. IEEE Comput. Soc. Press: 124–134
32. Technically speaking, the speedup in Shor's algorithm is not exponential but only pseudo-exponential.

Applications in cryptography:

As mentioned previously, cryptography is predicated upon the assumption that factoring prime numbers is a hard task for classical computers . It was thus revolutionary when Shor proved that using quantum computation, one can solve this problem in a much more efficient way.

The prospect of such a result is appealing. Nevertheless, it is still practically unfeasible to use this algorithm in any way, at least in the near future. Because of hardware limitations. But the simple existence of this algorithm has given birth to a whole new field of cryptography adapted to resist it: "Post-quantum cryptography", a field that we will explore in the next chapter.

Quantum Simulation:

The Raison d'être of Quantum Computation, as envisioned by Feynman; simulating quantum systems has and always will be the end all be all of this field. And indeed, quantum computers have been shown to be able to efficiently simulate some important Hamiltonians .

In addition, there are many emerging near term algorithms combining classical optimization algorithms with tasks that quantum computers do efficiently that are very promising, such as VQE (Variational Quantum Eigensolver) , which has emerged recently and may yield potential applications in Quantum Chemistry. One other such hybrid algorithm is Hybrid Quantum Monte Carlo methods, by combining masterfully classical computers and quantum tasks, a speed up may be achieved in certain areas[39].

It is impossible to overstate how vast this field is and how rapidly it is evolving[40]. There are many other subfields that are just as promising, if not even more promising like quantum optimization, quantum machine learning, quantum random walks algorithms and many more.

French Laboratories: IRIF, LIP6, LIS, INRIA Paris, INRIA Lyon-Grenoble, PCQT (cf. liste de contact)

French Companies: QC Ware, Multiverse, ColibriTD, Pasqal, Quandela, Qubit Pharmaceutical.

33. Grover, L. Quantum mechanics helps in searching for a needle in a haystack. Phys. Rev. Lett. 79, 325–328 (1997).
34. Montanaro, A. Quantum algorithms: an overview. npj Quantum Inf 2, 15023 (2016).
35. The question of whether it is hard for classical computers – which we can define rigorously using NP-Complete or NP-hard definitions – remains an open question
36. Hamiltonians describe the environment of a quantum system, and impose its future (and past) evolution.
37. Lloyd, S. Universal quantum simulators. Science 273, 1073–1078 (1996).
38. Peruzzo, A., McClean, J., Shadbolt, P. et al. A variational eigenvalue solver on a photonic quantum processor. Nat Commun 5, 4213 (2014)
39. Huggins, W.J., O'Gorman, B.A., Rubin, N.C. et al. Unbiasing fermionic quantum Monte Carlo with a quantum computer. Nature 603, 416–420 (2022).
40. VQE, to give an example of a staple of quantum computing, was first published as recently as 2013.

Quantum communication & security

Recent innovations in the quantum industry have been disrupting our well-established telecommunications system. Previously described improvements in quantum computing technologies brings us closer to quantum computers which could break currently used cryptographic protocols. Simultaneously quantum technologies provide us with tools to overhaul our communications system into solving some of its current and future security loopholes. In the next few pages we will cover the state-of-the-art innovations which plays a role in this technological revolution.

a QKD, QUANTUM INTERNET

CONTEXT

Quantum technologies can provide new tools to improve our secure communications system. As a matter of fact, quantum key distribution (QKD) is a key distribution protocol whose security relies solely on the principles of physics rather than on the idea that computers have limited computational power. The key shared through this protocol can then be used to communicate securely.

The first and simplest QKD protocol known as BB84 (Bennett-Brassard, invented in 1984) works as follows: One of the users (Alice) encodes a randomly chosen bit into a photon polarization (with 2 different polarizations, one representing 0 and the other 1). Alice will then send this photon to the other user (Bob) through a quantum channel such as air-link or optical fiber. Bob will then measure the polarization of the photon to get access to Alice's random bit. By repeating this process the bits can be used as the common key. An eavesdropper could get access to the key by measuring the photon polarization during the photon transfer but BB84 uses the quantum proprieties of polarization to detect any eavesdropping [41].

With this protocol an eavesdropper cannot have access to the key without being detected even with infinite computational power. However in the past few decades several "side-channel attacks" have been developed. These attacks don't target the cryptographic protocol itself but its implementation which can never exactly abide by the protocol. For instance, in the years 2000, "blinding attacks" were discovered: the detectors in commercially available QKD systems could be remote-controlled by an eavesdropper to get access to the key without being detected[42 43]. In response new protocols have been created to solve these "side-channel" threats. "Fully Device Independent QKD" protocols would suppress all side-channel loopholes making QKD unbreakable, but have never been implemented yet. Currently used protocols are "Semi-device independent", which means it is resistant to some side channel attacks but not all of them.

QKD implementation also faces another main issue: on large distances, photons are lost during transmission and a phenomenon called "decoherence" destroys the photon's state. Satellite transmission can reduce the problem compared to optic fiber transmission (there is reduced absorbance and turbulence in space) but this solution is less developed than optic fiber. To cope with this difficulty, the quantum link could be extended with infrastructures known as "repeaters" which act as intermediaries for the key distribution[44]. They can have various structures depending on the chosen QKD protocol. For entanglement-based QKD, "quantum repeaters" work

41. Bennett, C. H., & Brassard, G. (2020). Quantum cryptography: Public key distribution and coin tossing. arXiv preprint arXiv:2003.06557.
42. Lydersen, Lars, et al. "Hacking commercial quantum cryptography systems by tailored bright illumination." Nature photonics 4.10 (2010): 686-689.
43. Gerhardt, Ilja, et al. "Full-field implementation of a perfect eavesdropper on a quantum cryptography system." Nature communications 2.1 (2011): 349.
44. Briegel, H-J., et al. "quantum repeaters: the role of imperfect local operations in quantum communication." Physical Review Letters 81.26 (1998): 5932.

by entangling photons in a chain of entangled photons, that way each photon has to travel a shorter distance. However, we are far from implementing these "quantum repeaters", because they are based on technologies which are not mature enough (such as error correction, entanglement purification processes, and quantum memory)[45][46]. Until we implement quantum repeaters, a substitute method called "trusted relays" is used (for instance current QKD satellites act as trusted relays [4]). These relays act as just another user which will apply a QKD with each neighboring node. The relay can then transmit information to its neighbors in such a way that the end users end up sharing a common key. The downside is that this relay introduces a potential vulnerable point at which the key can be intercepted[47].

The last obstacle to widespread QKD would be to create a network with many users. Creating a multiple-user network is not an easy task: intermediary infrastructures known as "nodes" have to be created to distribute the key to the right users. The currently investigated solutions for the nodes could use switches which can direct the signal to different users. However, these switches produce loss which make it impossible to implement on scales larger than a city or a region. Until then, the intermediary nodes are trusted repeaters. Secret key rates are hugely reduced when the number of users is increased. For instance, QKD protocols have been improved to reduce risk in node eavesdropping through multipath transmission: it forces the eavesdropper to spy on many nodes to get access to the transmitted key but it reduces the secret key rate[48]. This is why the network topologies are very studied because it has a huge influence on the QKD security and key rate. Main topologies include circle, tree, and star shaped networks, each having their advantages and disadvantages, and studies are still being carried out to find the best one.

A large variety of protocols have been developed in the past few decades to tackle the previously described challenges, each method having its advantage. They can be separated into two families of protocols. "Discrete variable QKD" (DV-QKD) methods use discrete information mediums to communicate keys (such as the previously explained BB84 protocol). Other protocols use continuous variables (CV-QKD), which encode the information on "continuous" parameters such as light amplitude. CV-QKD is compatible with standard telecom components making it cheaper to implement and it offers better secret key rates on short distances[49]. On the other hand DV-QKD can be implemented on larger ranges, so current QKD networks all use DV-QKD.

Examples of Discrete variable QKD protocols

BB84 was the first QKD protocol.

"Twin field" QKD is widely used because it has promising bit rates and record-breaking ranges[50].

The decoy-state method is now used in all protocols because it protects against the photon-number-splitting attack[51].

45. Muralidharan, Sreraman, et al. "Ultrafast and fault-tolerant quantum communication across long distances." Physical review letters 112.25 (2014): 250501.
46. Huttner, Bruno, et al. "Long-range QKD without trusted nodes is not possible with current technology." npj Quantum Information 8.1 (2022): 108.
47. Zapatero, Víctor, et al. "Advances in device-independent quantum key distribution." npj Quantum Information 9.1 (2023): 10..
48. Mehic, Miralem, et al. "Quantum key distribution: a networking perspective." ACM Computing Surveys (CSUR) 53.5 (2020): 1-41.
49. Zhang, Yichen, et al. "Continuous-variable QKD over 50 km commercial fiber." Quantum Science and Technology 4.3 (2019): 035006.
50. Lucamarini, Marco, et al. "Overcoming the rate–distance limit of quantum key distribution without quantum repeaters." Nature 557.7705 (2018): 400-403.
51. Hwang, Won-Young. "Quantum key distribution with high loss: toward global secure communication." Physical review letters 91.5 (2003): 057901.

LATEST NEWS

Several articles from 2022 have shown that the first successful proofs of concept of "fully Device independent QKD" have recently been achieved. This means the feasibility of these protocols were experimentally proven[52 53 54]. However we are still far from implementing these protocols because they require a high efficiency in detection and a low loss in the quantum channel, which is not the case yet.

In 2022 a Chinese team proposed a semi-device independent hybrid network in which CV-QKD based networks would be connected by long distance DV-QKD. This would allow long range high secret key rate QKD (with DV-QKD) and better key rates (with CV-QKD)[55].

In 2022 a Chinese team broke the record of fiber-based QKD transmission reaching a 833 km transmission distance. For this implementation they used the "twin-field QKD'' protocol. However on such distances error rates are still too high for it to be widely-used[56]. New protocols are being created to beat previous records, for example Terra Quantum recently published a new protocol which could reach 40,000km ranges without any trusted node. However this protocol has not been implemented yet, and reasonable distances for practical use still do not exceed 100 kilometers without trusted nodes[57].

Several countries are now investing a lot to develop their own QKD network based on trusted nodes, the leading country being China. Since 2017 China's government agencies, regulatory agencies and banks have used the largest QKD network in the world covering 2000km . This network uses fiber optics and 32 trusted nodes on a backbone line which connects together 4 metropolitan networks as well as a satellite link[58]. The four metropolitan networks have different topologies to compare their performances on the long term. It uses a polarization-encoding decoy BB84 implementation, and is resistant to several known attacks such as the previously described blinding-attack[59]. They also use a satellite connection, but is still limited because it only works by night when it is flying over China (4 times per night)[60]. .

Several European countries, as well as the United States, Canada, Singapore, Japan, Korea and India have functioning networks, or are developing their own projects.

The OpenQKD project gathers actors from 13 EU countries to develop QKD testbeds and demonstrators. In France a QKD backbone between Chatillon, Paris and the Plateau de Saclay is under development.

EU countries are planning to create a common European QKD network: EuroQCI (European Quantum Communication Infrastructure). The EuroQCI project is led by the European Commission, the 27 EU Members and the European Space Agency. It will use ground-networks and satellite-based QKD. Its earliest satellite-based QKD system "EAGLE-1" is expected to be launched in 2024.

Startups have also joined the race to develop quantum communications. In France VeriQloud develops data protection services based on quantum communications.

French laboratories: Centre Inria de l'Université Grenoble Alpes, CEA CNRS IPHT, Department of Applied Physics University of Geneva, Institut de Recherche de Chimie Paris, Institut des Nanotechnologies de Lyon

French companies: Orange, VeriQloud, Aurea Technology

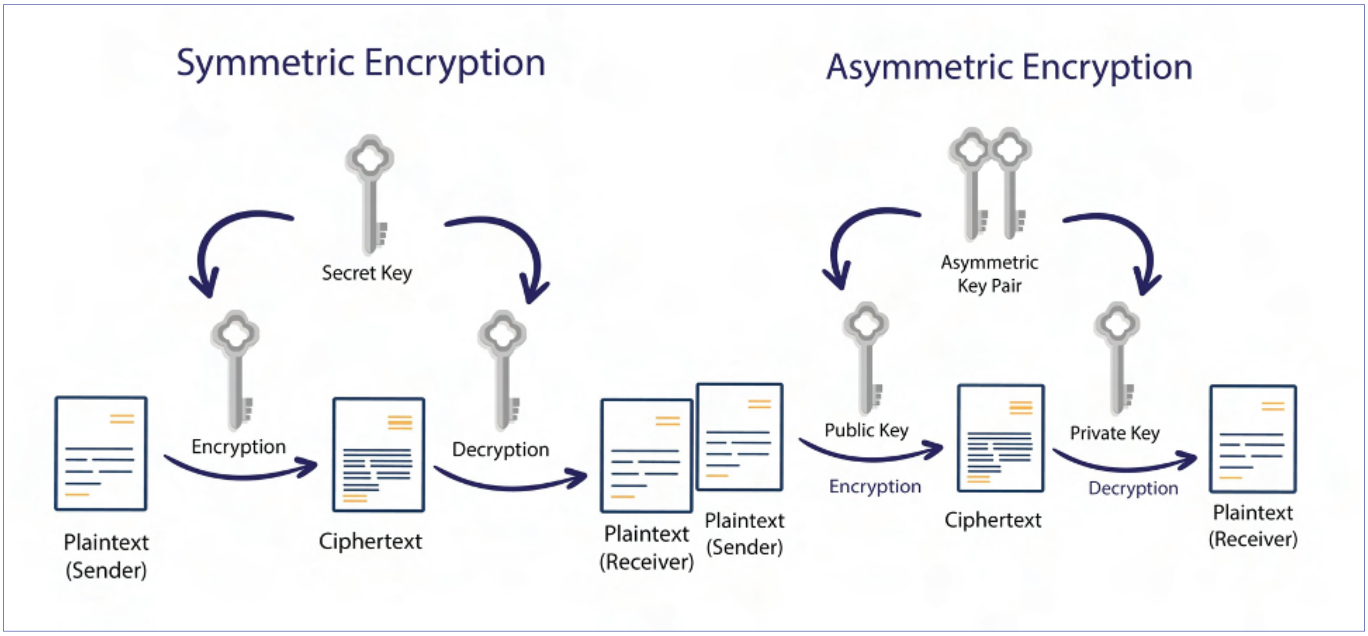
Foreign companies: Anametric, ArQit, BraneCell Systems, Ciena, Crypta labs, TOSHIBA, SAMSUNG, Keequant, Isara, Kets, Ki3 Photonics, Knot Communications, LuxQuanta, MagiQ, MtPellerin, NodeQ, Nu Quantum, QuantLR, Qasky, QEYnet, QNu Labs, QRate Quantum Communications, QSpace Technologies, Quantum Blockchains, QuantumCTek, Quantum Xchange, Qubit Reset, Quintessence Labs, Qunnect, Smarts Quanttelecom, SpeQtral Quantum technologies, Surrey Satellite Technology, ThinkQuantum, XT Quantech Toshiba, BT, Verizon, AegiQ,

52. Nadlinger, D. P., et al. "Experimental quantum key distribution certified by Bell's theorem." Nature 607.7920 (2022): 682-686.
53. Zhang, Wei, et al. "A device-independent quantum key distribution system for distant users." Nature 607.7920 (2022): 687-691.
54. Liu, Wen-Zhao, et al. "Toward a photonic demonstration of device-independent quantum key distribution." Physical Review Letters 129.5 (2022): 050502.
55. Ren, Siyu, Yu Wang, and Xiaolong Su. "Hybrid quantum key distribution network." Science China Information Sciences 65.10 (2022): 200502.
56. Wang, Shuang, et al. "Twin-field quantum key distribution over 830-km fibre." Nature Photonics 16.2 (2022): 154-161.
57. Kirsanov, N. S., et al. "Forty Thousand Kilometers Under Quantum Protection." arXiv preprint arXiv:2301.10610 (2023).
58. Zhang, Qiang, et al. "Quantum information research in China." Quantum Science and Technology 4.4 (2019): 040503.
59. Chen, Yu-Ao, et al. "An integrated space-to-ground quantum communication network over 4,600 kilometres." Nature 589.7841 (2021): 214-219.
60. Stanley, M., et al. "Recent Progress in Quantum Key Distribution Network Deployments and Standards." Journal of Physics: Conference Series. Vol. 2416. No. 1. IOP Publishing, 2022.
61. Ezratty, Olivier. "Understanding Quantum Technologies 2022." arXiv e-prints (2021): arXiv-2111.

b PQC

CONTEXT

https://www.encryptionconsulting.com/education-center/symmetric-vs-asymmetric-encryption/



Understanding how today's communications are secured is necessary to understand how quantum technologies will disrupt them. Modern cryptography largely relies on two families of algorithms: symmetric key and asymmetric key algorithms. The former method relies on a single shared key with which one can encode and decode a message. The latter one does not require such a previously shared key: two different keys are used for encryption and decryption. The encoding key can be publicly distributed to anyone, while the decoding key is kept secret by the user who generated these keys. The two keys are mathematically related but given long enough keys, it is impossible to determine the decoding key with the encoding key in reasonable time with a classical computer. This second method allows encrypted communication without having to previously share a common key. However it requires more computer power making it unusable for a systematic use. Therefore the vast majority of encoding protocols such as the TLS protocol (which secures our HTTPS Internet connections) combine the benefits of both methods: a key is shared through an asymmetric algorithm and this key is then used for symmetric-key encryption. Similar protocols are also used for user authentication with cryptographic signature keys.

Unfortunately, a gate-based quantum computer could theoretically break currently used asymmetric-key algorithms in reasonable time. For instance, the famous Shor algorithm invented in 1994 would break the widely used RSA protocol and Elliptic curve Diffie-Hellman key exchange protocol. Also, SHA algorithms which are standard hash functions (used to establish communications, for sensitive data protection and for digital signatures) could be broken by the Grover's search quantum algorithm.

These threats may seem distant as current quantum computer technologies face scalability issues. However this threat must quickly be countered because of the threat of "Store now, break later" attacks. These attacks consist of an attacker storing undeciphered information today and decrypting it when quantum computers will have reached sufficient computational power. This is a threat because some communications such as state secrets will still have value for attackers in several decades. Similarly signature keys security must also last in time to avoid identity theft based on the same principle. Many new classical cryptography protocols have therefore been created to resist the quantum threat. This new era of classical cryptography algorithms is called "post-quantum cryptography".

LATEST NEWS

Standard cryptography protocols are still not resistant to the quantum threat. This is because post-quantum protocol standardization is still under way. The American "National Institute of Standards and Technology" (NIST) has initiated a standardization process in 2017 for which a fourth and last round of candidates are currently being studied. Four candidates have been selected so far, one for encryption and the others for digital signature[62].

Several countries are starting to launch plans to protect their administrations against the quantum threat. In 2022 the Biden Administration published a Memorandum to prepare for the deployment of post quantum cryptography[63]. The French Government is currently preparing an action plan for the migration of critical infrastructures to post quantum cryptography[64]. In 2022 the Banque de France as well as the French Embassy in the United states used post quantum cryptography from CryptoNext Security.

However the transition to post-quantum cryptography must not be rushed. In 2022, the French ANSSI (Agence Nationale de la Sécurité des Systèmes d'Information) published a report giving a recommendation timeline for companies and organizations to transition to post-quantum cryptography . This report recommends a progressive transition using hybrid methods combining keys shared through a pre-quantum method and a post-quantum method. Indeed post-quantum cryptography protocols should not be trusted entirely until at least 2030 because they could be vulnerable to classical attacks (some post quantum protocols considered by the NIST have recently been cracked with classical computers).

Foresign Companies: IBM, Microsoft, AgilePQ, CyferAll, Quantum Risk Advisory, American Binary, AmbitAgnostiq, Alternatio, BlaKFX, Crypto4A Technologies, CryptoExperts, CryptoNext Security, Orange, Crypto Quantique, Cyph, Dencrypt, evolutionQ, FlipsCloud, FragmentiX, GoQuantum, HaQien, Hub Security, ID Quantique, Infotecs, Patero, PQ Solutions, PQSecure Technologies, PQShield, Qaisec, QANPlatform, Qabacus, QuantiCor Security, Quantum Impenetrable, Quantum Xchange, QuBalt, Qusecure, Ravel, SandboxAQ, Secure-IC, Sonora gold and silver corp, SSH Communications Security, Synergy Quantum, Ultimaco, ZY4

French companies: CyferAll, Quantum Risk Advisory, VeriQloud

French Laboratories: ENS Lyon, Ruhr-Universität Bochum, Radboud University, Xlim (Cryptis team), IMB (institut des Mathématiques de Bordeaux), IRISA (Rennes)

62. https://csrc.nist.gov/projects/post-quantum-cryptography/selected-algorithms-2022
63. https://www.diplomatie.gouv.fr/en/the-ministry-and-its-network/news/2022/article/france-transmits-its-first-post-quantum-cryptographic-diplomatic-message-1-dec
64. https://www.ssi.gouv.fr/agence/publication/migration-vers-la-cryptographie-post-quantique/

Quantum sensing

ⓐ NV CENTERS

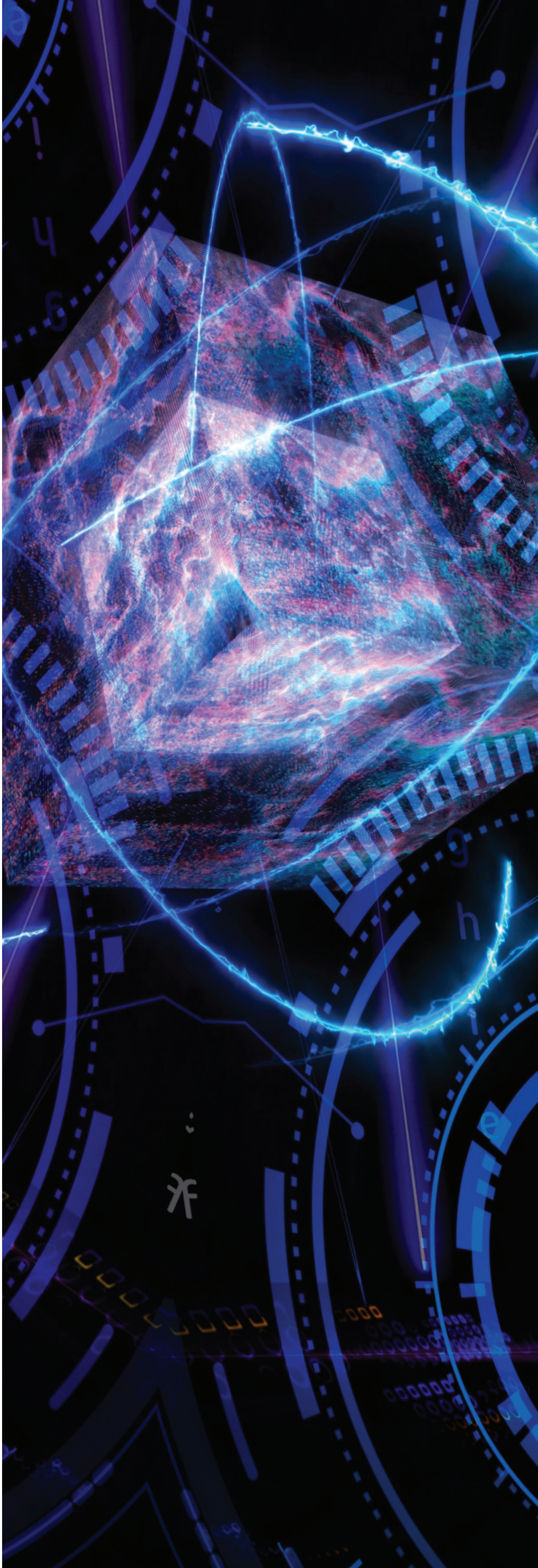
CONTEXT

NV centers (for Nitrogen-Vacancy centers) are defects that appear in diamond when a carbon atom is replaced by a nitrogen one, associated with a vacancy on a neighboring site. There are two types of NV centers: NV0 that present one unpaired electron and are paramagnetic, and NV- centers (where an extra electron forms with the vacancy's remaining electron a pair with spin 1). In a diamond crystal, these defects are randomly oriented. However, certain studies have shown the possibility of adjusting the orientation of these centers, allowing for better control of the materials properties and thus for better sensing. Its electronic properties make it interesting in quantum computing (the electronic energy levels of the NV centers allow it to use it as a qubit) and in quantum sensing (allowing for the measurement of the magnetic field with very high spatial accuracy).

Sensing with NV centers is much more developed than computing. Actually, NV centers present a high number of advantages when it comes to magnetic field sensing especially (but also for electric field sensing). How do these magnetometers work? When a free electron in the NV center is excited with a laser, it can reemit photons by fluorescence. For a certain frequency of the exciting laser, the fluorescence diminishes. But when placed in a magnetic field, this frequency is split in two frequencies, with a difference depending on the magnetic field along the main axis of the NV center (according to the Zeeman effect). This allows to deduce the magnetic field with excellent precision. The applications are numerous: creating maps of the Earth magnetic field (that can be used as reference for navigation systems with inertial sensors for example, allowing for greater independence to GNSS systems), studying the brain with magnetoencephalography, detecting cancer, etc.

Advantages of NV centers mainly reside in the fact they can be used at room temperature (no need for complex cryogenics system which allows for smaller and more practical sensors) and present extreme sensitivity (due to a very sharp resonance of the system), NV centers can measure the magnetic field produced by a single electron located tens of nanometers from the NV center.

Finally, NV centers can be used to conduct precise radio frequency measurements.



LATEST NEWS

Created in 2020, Wainvam-E is proposing various technologies based on NV-centers in micro-diamonds and nano-diamonds. They have applications in many domains. In the bio-medical domain, NV centers allow for precise and small bio-compatible sensors that can be sent in the human body to detect foreign bodies or cancerous cells, or be used as vectors to deliver medicaments in the body at accurate positions. Other applications exist in aeronautical and spatial domains, to control structures integrity with non-destructive techniques using NV-centers based magnetometers.

The LSPM (for Laboratoire des Sciences des Procédés et des Matériaux) has been studying fabrication processes for NV centers in diamond to optimize their density, their coherence time and even their preferred orientation[65] [66](which allows for improved sensitivity when used for quantum sensing). This technique uses deposition of nitrous oxide vapor.

A study has been conducted at LPENS to show that diamonds doped with NV centers present an important diamagnetism that can be used to align the main crystalline axis of micro-diamonds on the external magnetic field[67]. This allows for better magnetic sensing due to less variations of the orientation of the main axis (due to collisions and other environment interactions).

Thales Research & Technology (in partnership with LuMIn of Paris-Saclay ENS) reported the development of a Quantum Diamond Signal Analyser (Q-DiSA) platform that allows for radio frequency spectral analysis, with a frequency range of 25 GHz, with a frequency resolution of 1 MHz[68]. The setup uses the repartition of NV centers across different positions to detect resonances with the field to be analyzed and deduce from their repartition the frequency of the field.

French Companies: Wainvam-E, Thales Research & Technology

French Laboratories: INSP, IRCP, LuMIn, LPENS, LSPM

65. Balasubramanian et al., Enhancement of the creation yield of NV ensembles in a chemically vapor deposited diamond, https://doi.org/10.1016/j.carbon.2022.04.005
66. Ngandeu Ngambou et al., Improving NV centre density during diamond growth by CVD process using N2O gas, https://doi.org/10.1016/j.diamond.2022.108884
67. Perdriat et al., Angle locking of a levitating diamond using spin-diamagnetism, 2021, arXiv:2102.13637v3
68. Magaletti et al., Quantum Diamond Radio Frequency signal Analyser based on Nitrogen-Vacancy centers, 2022, arXiv:2206.06734v1

ⓑ COLD ATOMS

CONTEXT

Since the 70s, the development of optical cooling techniques for atoms has enabled the manipulation of atoms at very low temperatures, typically around the microkelvin. At these temperatures, bosonic atoms (with an integer total spin) "condensate"; an important collection of the atoms all occupy the same state. Their wave-functions coherently interfere, thus forming a very coherent wave (its wavelength is close to the thermal de Broglie wavelength).

Different technologies are based on cold atoms and are used to measure different things. The main domains of use are time measurement (with atomic clocks), gravity and acceleration measurements (with gravimeters, gyroscopes, and accelerometers), and magnetic fields measurements (with magnetometers).

The applications of these measurements are numerous. Very precise atomic clocks are essential to Global Navigation Satellite Systems (GNSS). For example, Galileo satellites are equipped with Orolia's rubidium atomic clocks. Gravimeters can be used to measure the geological structure of the subsoil and measuring geophysical movements (for example to monitor seismic and volcanic activities). This can also be used to precisely map gravity fluctuations around the globe and use these maps as references (for example in submarines to recalibrate position when not using GNSS systems). Finally, quantum accelerometers based on cold-atom interferometry have a tremendous precision, allowing for better positioning accuracy at long times, when compared with classical accelerometers (because an error on acceleration leads to errors on position that evolve like time squared).

How do these sensors work? Atomic clocks use cold atoms to precisely match an "external" oscillator frequency on the frequency of a transition of the internal state of the atom; and then counting the oscillation of this external oscillator. Gravimeters such as those developed by Muquans[69] use cold atoms (obtained with magneto-optical traps) free-falling in the gravity field g. Quantum interferences due to atom interactions with laser beams allow us to measure the gravitational field (the phase shift of the interference depends on g). Accelerometers and gyroscopes are also based on atomic interferences (in a gyroscope, the phase shift depends on the rotation speed, according to the Sagnac effect). Magnetometers are based on the energy degeneracy lift due to Zeeman effect (interaction of the electronic spin with the exterior magnetic field), the difference of energy between the states depending on the intensity of the magnetic field.

69. Mémoret V., Vermeulen P., Le Moigne N., Bonvalot S., Gravity measurements below 10-9g with a transportable absolute quantum gravimeter, 2018, DOI: 10.1038/s41598-018-30608-1

LATEST NEWS

In 2020, Muquans/iXBlue/Exail deployed its absolute quantum gravimeter (named AQG-B and based on cold atom interferometry) near the craters of Mt. Etna volcano and made measurements between August and December 2020[70]. The results, published in 2022, show that this gravimeter managed to produce high-quality measurements, despite phases of high volcanic activity, with correlated anomalies detected by other superconducting gravimeters installed elsewhere on Mt. Etna. The measurements in terms of mass changes were successfully linked to evolutions of the magmatic system, highlighting the interest of quantum gravimetry to monitor volcanic activity.

LNE-SYRTE laboratory launched in October 2022 a national comparison of absolute gravimeters to evaluate the coherence of their measurements, and check the reference given by CAG gravimeter. This study involves two quantum gravimeters by Muquans-iXBlue. A team at the laboratory also managed to precisely measure the quantum Sagnac effect with interfering cold atoms matter waves, allowing for ultraprecise measurements of rotation[71]. This is very promising for cold atoms-based gyro-meters, and for navigation systems.

SYRTE will also accompany the CHRONOS project, a partnership between Thales, Syrlinks (Safran) and the DGA, to develop new generation high-stability compact quantum clocks.

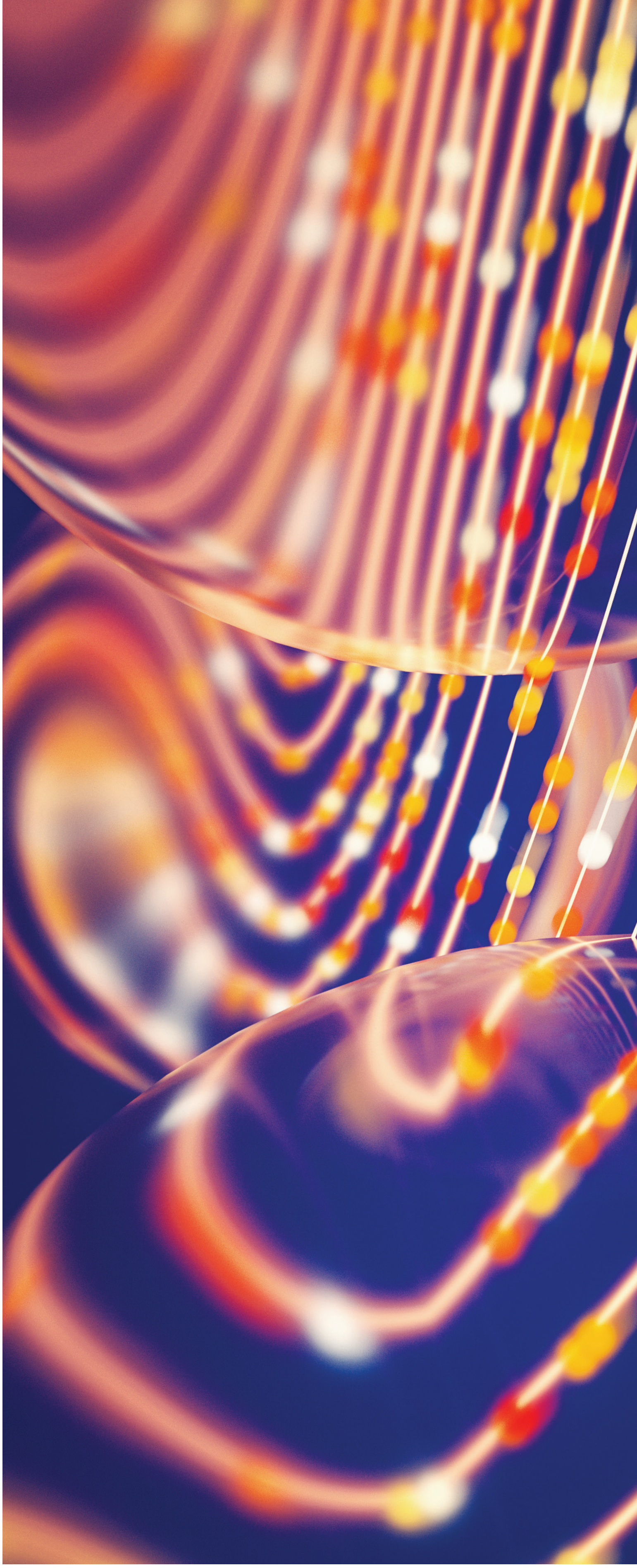
iXBlue/Exail, with L2PN, reported the development of a hybrid quantum accelerometer capable of 3D tracking of the acceleration, with a long-term bias much smaller when compared with other classical accelerometers (leading to a 50 times smaller short-term position error[72]).

Finally, Mag4Health, a spin-off from CEA-LETI, uses helium-based magnetometers to record the brain activity in real time.

French Laboratories: LKB, LNE-SYRTE, LAC, LCFIO, QTech (ONERA), LP2N, DyTeQ, CESQ, LCAR, LPTM, LPL, PhLAM

French Companies: Orolia, Syrlinks, Muquans/iXBlue/Exail, Thales, Mag4Health

Muquans' quantum gravimeter at Mt. Etna



70. L. Antoni-Micollier et al., Detecting volcano-related underground mass changes with a quantum gravimeter, GRL 097814, 2022, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022GL097814
71. Gautier R. et al., Accurate measurement of the Sagnac effect for matter waves, 2022, DOI: 10.1126/sciadv.abn8009
72. S. Templier et al., Tracking the vector acceleration with a hybrid quantum accelerometer triad, 2022, https://doi.org/10.1126/sciadv.add3854

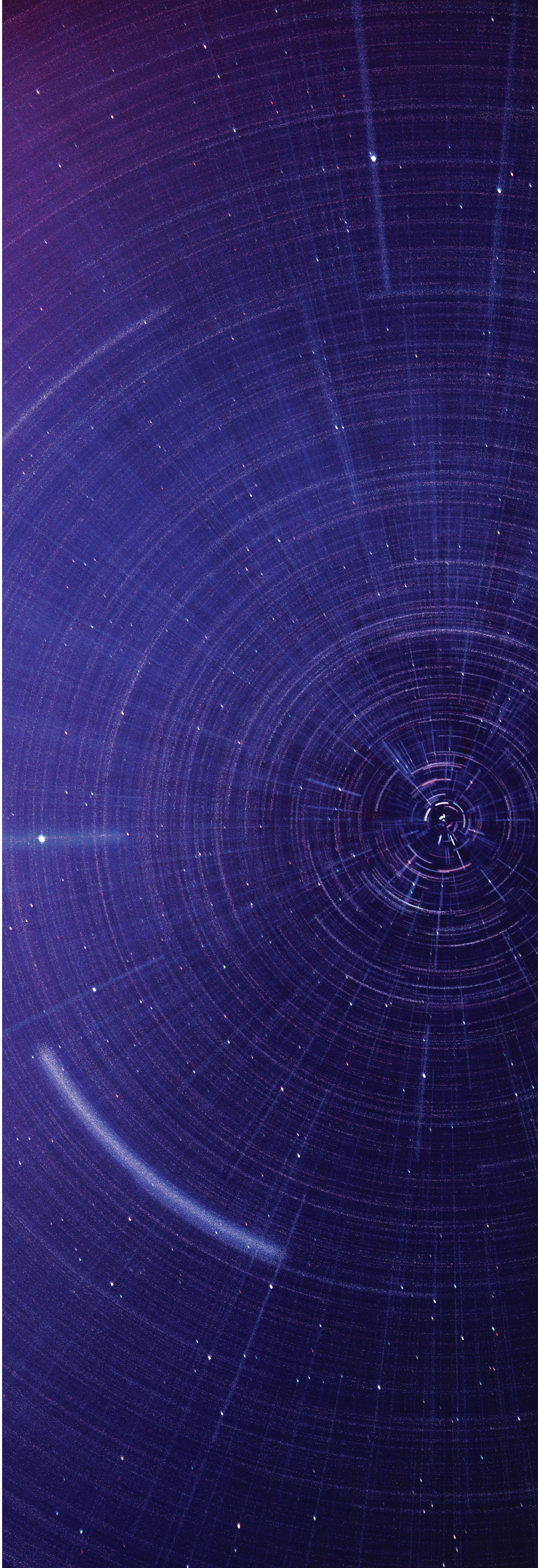
References

[5] Weaver, M. J., Duivestein, P., Bernasconi, A. C., Scharmer, S., Lemang, M., van Thiel, T. C., ... & Stockill, R. (2022). An integrated microwave-to-optics interface for scalable quantum computing. arXiv preprint arXiv:2210.15702.

[6] Serrano, D., Kuppusamy, S.K., Heinrich, B. et al. Ultra-narrow optical linewidths in rare-earth molecular crystals. Nature 603, 241–246 (2022). https://doi.org/10.1038/s41586-021-04316-2

[7] Akhtar, M., Bonus, F., Lebrun-Gallagher, F.R. et al. A high-fidelity quantum matter-link between ion-trap microchip modules. Nat Commun 14, 531 (2023). https://doi.org/10.1038/s41467-022-35285-3

[30] Zapatero, V., van Leent, T., Arnon-Friedman, R., Liu, W. Z., Zhang, Q., Weinfurter, H., & Curty, M. (2022). Advances in device-independent quantum key distribution. arXiv preprint arXiv:2208.12842.



B | FUNDING

1 PUBLIC AND PARAPUBLIC FUNDING

The French Quantum Plan

The French Quantum Strategy was defined after a parliamentary investigation commissioned by the Prime Minister in March 2019 and led by MP Apula Forteza, accompanied by Iordanis Kerenidis (CNRS researcher specialized in quantum machine learning) and Jean-Paul Herteman (former CEO of Safran). The commission submitted a report titled "Quantum: the technology disruption that France will not miss". In January 2021, Président Emmanuel Macron announced a total amount of €1.8B to finance the french quantum strategy, coordinated by Neil Abroug. The strategy is included in the "France 2030" program. The fundings include €1B financed by the State, via the Programme d'Investissement d'Avenir (PIA), to the development of quantum technologies over the period 2021-2025, and €850M funding expected from European funds and the private sector (industry R&D and startups funding). Moreover, €150M will be dedicated to develop post-quantum cryptographic methods. Even before the launch of the French National Quantum Plan, €60M of public money was used to finance quantum technologies research, placing France at the 6th rank of World's main investor in quantum. Therefore, the French Quantum Plan is to accelerate the deployment of quantum technologies with 3 main goals :

- Conquer; market shares on the world market in quantum computing, sensing, cryptography and enabling technologies
- Develop; education and communication about quantum to sensitize the society
- Strengthen and leverage the french academic research in the international competition.

French quantum start-ups are generally spin-offs from academic research laboratories and can even compete with American big tech companies such as Google and Intel. The challenge will be to boost specific quantum fields where France already has an advantage and can leverage to weight at an international scale.

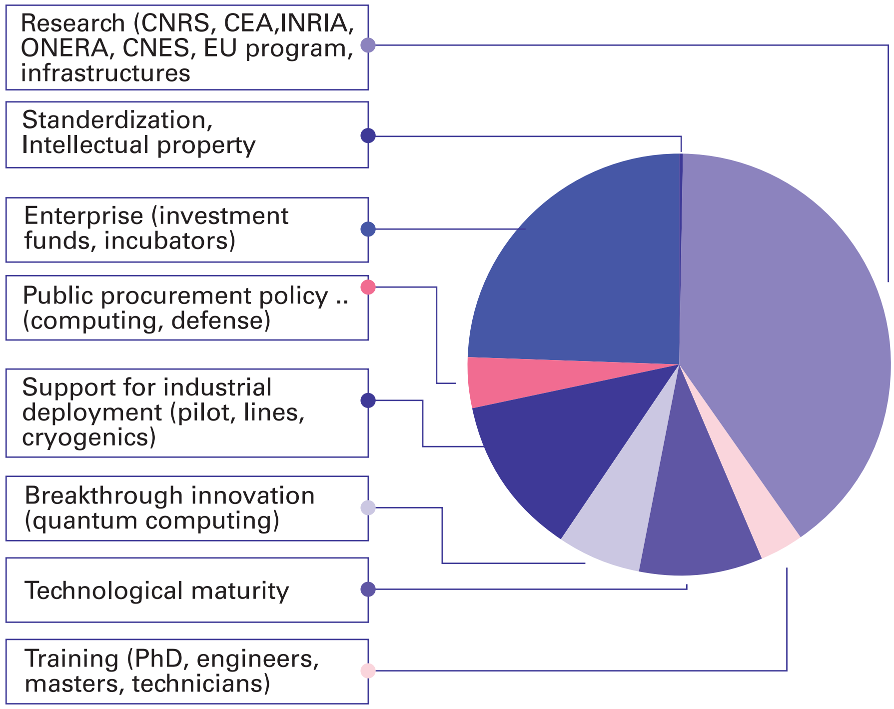
The ambitions of the strategy is to allow the quantum industry to have a 2% contribution of French exports to the quantum industry, to create 16,000 direct and indirect jobs, and to create three French unicorns. In terms of technological developments, the strategy aims to:

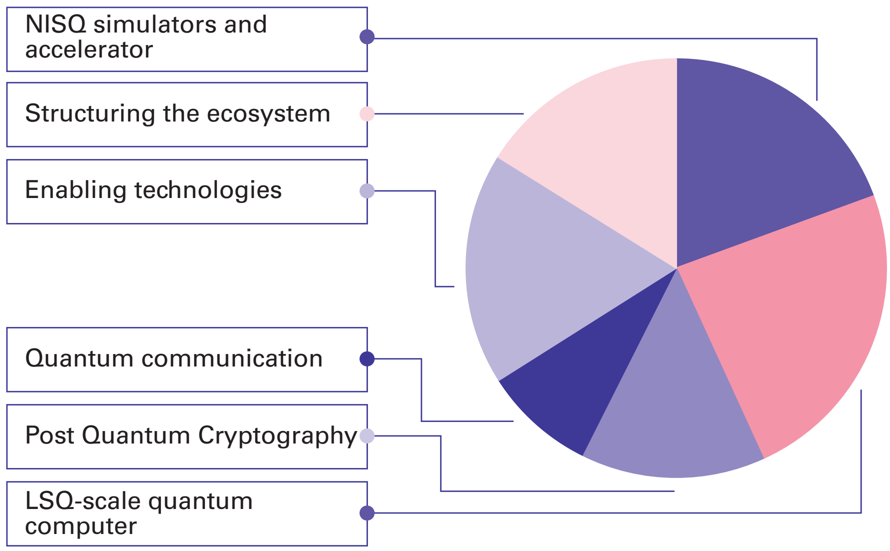
- Develop and spread the use of NISQ simulators and gas pedals;
- Develop the Universal Scalable Quantum Computer;
- Develop the technologies and applications of Quantum Sensors;
- Develop the Post-Quantum Cryptography offer;
- Develop quantum communication systems;
- Develop a competitive enabling technology offering.

In 2022, many components of the French Quantum Strategy were launched. There was an incremental €150M research program handled by CNRS, CEA, and Inria announced in 2021 and launched in 2022. Moreover, a hybrid classical/quantum platform has been announced in January 2022, located at the TGCC supercomputing center handled by CEA. It will use the Joliot-Curie supercomputer in association with a QLM classical server from Atos for emulation and QPU drive, and a Pascal quantum simulator. This HQI (Hybrid HPC quantum Infrastructure) project is partly funded by the EU HPC-QS program.

Furthermore, €3M were given to Paris, Grenoble and Saclay via the PIA to finance thesis and master scholarships, summer schools and introductory quantum modules.

Another program was launched to enable the deployment of Post-Quantum Cryptography systems which is included in the French government's cybersecurity strategy. This program aims to create €25Md revenues in the field, double the number of employees and create cybersecurity unicorns.





From the €1.8B plan budget, €352M will be invested to develop quantum simulators, NISQ calculator, the first hybrid computer with 100 qubits, in order to anticipate and prepare the fault tolerant quantum computer. €432M will be dedicated to scale-up the solution developed and to develop the first prototype of a LSQ quantum computer. This amount will therefore finance public and private research, as well as industrial partnerships between Atos and Pasqal for instance. Additionally, €250M will finance the development and the integration of quantum sensors, in particular in the defense and health market. This National Strategy has already led to a fourfold increase in public investment in research and a twofold increase in investment in training.

As one of the most dynamic region in terms of innovation and research, the French Quantum Funds also go to the Paris Region through the ParisRegionQCI (Quantum Communication Infrastructure), a project coordinated by telco operator Orange,

French Quantum Plan - Budget in terms of target	
Research (CNRS, CEA, INRIA, ONERA, CNES, EU program, infrastructures)	72,50,00,000 million €
Traning (PhD, engineers, masters, technicians)	6,10,00,000 million €
Technological maturity	17,10,00,000 million €
Breakthrough innovation (quantum computing)	11,40,00,000 million €
Support for industrial deployment (pilot lines, cryogenics)	22,40,00,000 million €
Public procurement policy (computing, defense)	7,20,00,000 million €
Enterprise (investment funds, incubators)	43,90,00,000 million €
Standardization, intellectual property	90,00,000 million €
Total	1,81,50,00,000 million €

French Quantum Plan - Budget in terms of technology focus	
NISQ simulators and accelerators	35,20,00,000 million €
LSQ-scale quantum computer	43,20,00,000 million €
Post Quantum Cryptography	25,80,00,000 million €
Quantum communication	15,60,00,000 million €
Enabling technologies	32,50,00,000 million €
Structuring the ecosystem	29,20,00,000 million €
Total	1,81,50,00,000 million €

French Quantum Plan budget from 2021 to 2025[73](in terms of target and technology)

which aims to deploy a quantum communication network between Saclay, Châtillon and Paris to test secure communication solutions.

Bpifrance (Public Investment Bank)

Bpifrance can also contribute via the €500M National Seed Fund 2, which co-invest with private funds. As a result, "we have the largest number of start-ups in Europe. And the national plan is to have a hundred in five years" says Neil Abroug, national coordinator of the quantum strategy. Bpifrance also indirectly finances French quantum start-ups through grants and the French Tech Seed Program. Start-ups such as Quandela and Pasqal will also benefit from public funding via the purchase of machines by GENCI (the national supercomputing organization), financed by the national quantum strategy.

French defense department fundings

Quantum technology and its applications has also attracted military and army interest. For instance, quantum-based sensors would eventually deliver “unparalleled” levels of precision for sophisticated weapon and navigation systems that would no longer need to rely on satellite signals but could function by measuring the tiny variations in the Earth’s gravity. The communication domain is also a key area of military interest for quantum computers, including breaking cryptographic algorithms for intelligence purposes.

In December 2020, Florence Parly, Minister of the Armed Forces, signed the letter of intent to create the Defense Innovation Fund (FID) up to €400M that will be operated by the BPI and partly funded by the Ministry of the Armed Forces (€200M) and other investors (industrialists for €200M). Quantum technology will be one of the types of technologies that will be funded through the FID. Moreover, DGA has a participation up to 5% in the French Quantum Plan €1.8B budget.

European Union support

The European Union wants to consolidate its effort in quantum technologies. French and European start-ups and research can benefit from EU fundings. The european “FET Flagship”, launched in 2018 is dedicated to fund research on all aspects of quantum information: sensing, communications, computing and simulation. It is endowed with €1B spread over 10 years. The goal of the flagship is to consolidate and expand European scientific leadership and excellence in this research

73. https://www.gouvernement.fr/france-2030-strategie-quantique-lancement-d-une-plateforme-nationale-de-calcul-quantique

area, to kick-start a competitive European Industry in Quantum Technologies and to make Europe an attractive region for innovative research, business and investments in quantum. However, this flagship is far from being the sole source of EU funding for quantum research and technologies. There are also ERC grants for individual researchers, other multi-partite projects such as Europe Next, Qureca, H2020, and startups funding via the EIC Accelerator.

The quantum Technologies flagship is one of the three European flagships that aim to place Europe at the forefront of major technological breakthroughs with strong community investment in research. The two other flagships are the "Human Brain Project" led by the Swiss Henri Markram and the Graphene project in nanotechnologies. The first phase of the Flagship included €132M spread onto 20 projects selected out of 140 applicants and for a period of three years. 130 additional projects will be later selected.

the European Quantum flagship projects as of 2022. (cc) Olivier Ezratty, 2022.

There is a strong dominance of projects piloted by German, France and the Netherlands research laboratories. In France, the CNRS is involved in 14 of the 20 projects. These projects do not yet include efforts in software, to create algorithms, development tools and business software solutions adapted to quantum computers.

In addition, European quantum projects are funded with other vehicles than the Flagship, such as:

» QuantERA, an alliance of research funders from member states created to reinforce transnational collaborations in inspiring multidisciplinary quantum research. This program complements the Quantum flagship projects but comes from participating countries.

» EQUIPE (Enable Quantum Information Processing in Europe) project aims to advance the industrialization of the creation of quantum computing and telecommunications solutions for industry.

» EuroHPC projects include quantum computing deployments in hybrid data centers with first deployments of quantum simulators planned in Germany and France as part of the HPCQS project. In october 2022, six other EU HPC sites were selected for these deployments in Czechia, Germany, Spain, France, Italy and Poland with a total investment of €100M.

» EuroQCI: to bring the first steps toward European quantum internet. Airbus is a partner of the project. The goal is to have a first demonstrator in 2024, and then to have an operational system quantum key exchange in 2028.

» EIC Accelerator contributes to the objectives of the Chips Act by supporting the development of critical technologies where start-ups and SMEs with disruptive innovations have the potential to scale up and help ensure the future open strategic autonomy of the Union. The budget is up to €100M and at least 30% of it will be allocated to the Quantum technology components and 30% to the semiconductor chip development areas. As Europe is a global leader in research in quantum technologies, the focus is to translate the level of R&D excellence into market innovation.

European commitment in the quantum field is still in its infancy, but it shows the will to create real European champions. And the European Commission is working to create a deep-tech fund. Despite the French Quantum strategy and European scale fundings, The scientific and industrial French ecosystem of quantum technologies can only grow if sufficient talent is available to provide academic research, start-ups and large companies with the resources they need. It is therefore essential to bring out these talents through a dynamic training policy supported by specific funding and to pursue effort in public and private funding to keep up with the international development of quantum technologies.

2 PRIVATE FUNDING

VENTURE CAPITAL FUNDS

Quantonation

Quantonation Ventures is the leading VC dedicated to Quantum Technologies, counting the largest portfolio in the field with +25 Quantum startups. The team invests globally, targeting pre-seed/seed companies in Quantum Computing, Quantum Communication, Quantum Sensing and Deep physics. Fields such as molecular design, high performance calculation, cybersecurity, or ultra-precise sensing are now driven by innovation based on Deep Physics and Quantum Technologies. Thanks to its scientific expertise Quantonation aims at supporting the transition of these technologies into commercially available products for industry.

Elaia Partners

Elaia is a French VC specializing in deep-tech firms from early stage to growth development that processed about 100 investments and has more than $700M of assets under management. Elaia has invested in three quantum start-ups, one of them being Alice & Bob.

Supernova Invest

Supernova Invest describes itself as the leader in deep tech investment in France. It emerged from the alliance of the CEA, the French Alternatives Energy and Atomic Energy and Amundi. They boast a 70+ portfolio company and have invested in both Alice & Bob, Quantum Dice and Aqemia.

Serena Capital

Since 2008, Serena has been investing in high-growth tech companies, providing them not only with funding but also operational resources. Very early on, they launched vertical funds to deepen their expertise on transformational topics and therefore better serve their entrepreneurs. In August 2022, Serena raised the second generation of its Data Ventures seed fund (Data Ventures II) to back DeepTech startups in France, adding a quantum computing vertical in this €100 million fund thesis. The team has already developed different initiatives in quantum to unleash the opportunities it promises and is set to join forces with promising teams in this field.

Other French VC players

VC	Funded	Quantum Portfolio (stage, date, total funding)
360 Capital	1997	C12 Quantum Electronics (Seed, 2021, $10M)
Breega	2013	Alice & Bob (Seed, 2020, €3,3M and Series A, 2022, $30M)
Daphni	2015	Pasqal (Series A, 2021, $30M)
Fluxus Ventures	2015	1QBit (Series B, 2017, $35M)
Generis Capital Partners	2009	Teem Photonics (N/A, 2003, $11M)
HCVC	2014	Anello (Series A, 2021, $28M)
Innovacom	1988	Scintil photonics (Seed, 2019,$4M and Series A, 2022, $14M), Cailabs (Seed, 2013, $1M ; Series A, 2016, $5M ; Series B, 2019, $9M and Series C, 2022, $28M)
Innovation Capital	1996	Teem Photonics (N/A, 2003, $11M)
Kima Ventures	2010	Cailabs (Seed, 2013, $1M)
Omnes	1999	Qubit Pharmaceuticals (Seed, 2022, $17M) and Quandela, Series A, 2021, $10M)
Pléiade Venture	1999	Abbelight (Seed, 2018, Unknown)
Starquest Capital	2018	Cailabs (Seed, 2013, $1M ; Series A, 2016, $5M ; Series B, 2019, $9M and Series C, 2022, $28M)
Xange	2004	Qubit Pharmaceuticals (Qubit Pharmaceuticals (Seed, 2022, $17M)

Corporate activity

Committed companies

France boasts an ecosystem of large corporations involved in the quantum ecosystem. With 23% of French corporations working or planning to work with quantum technologies, France ranks among Europe's best performers.

Share of corporations planning to work with quantum technologies in 2021, by country

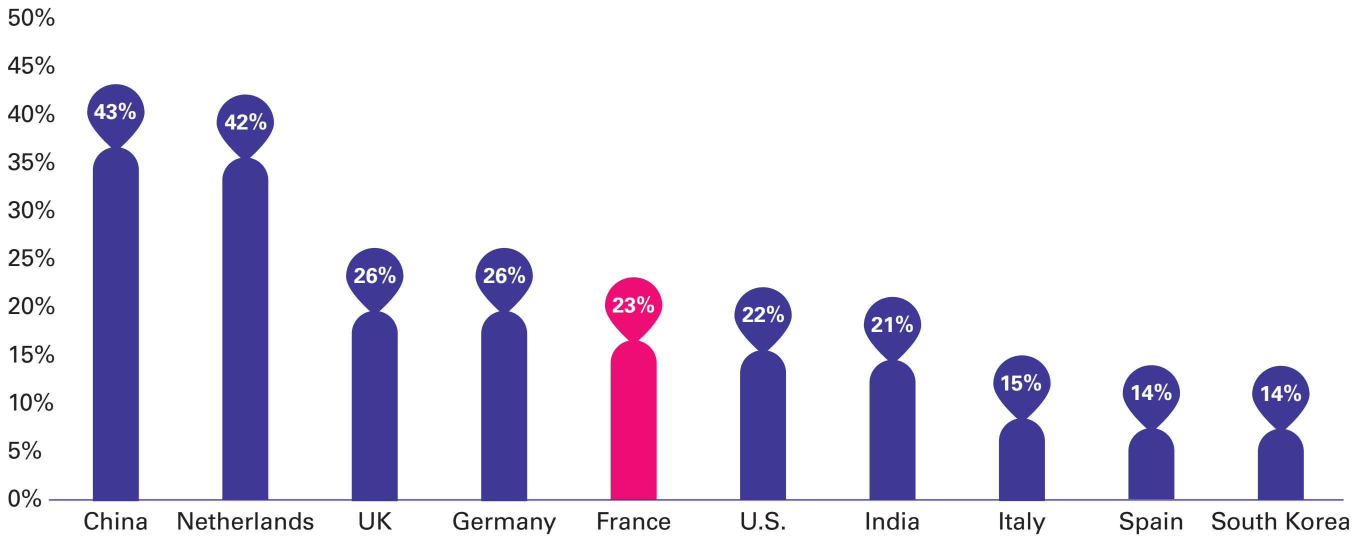


Figure 3: Share of corporations planning to work with quantum technologies in 2021
Source: Capgemini

ATOS

Many companies have been investing in the quantum field, beginning with Atos, which launched the Atos Quantum programme in 2016 in anticipation of the development of quantum computing. This initiative has resulted in a number of investments, including the opening of an R&D center dedicated to cybersecurity, high-performance computing and quantum computing in Les Clayes-sous-Bois. The 8,000 square meter facility will employ nearly 350 people, at a cost of over €5 million.

Atos has also developed a module for simulating quantum noise in its Atos QLM range, which is now used in many countries such as France, India, Japan, United-Kingdom or the US.

Finally, Atos recently launched Q-score, the first universal quantum metric, applicable to all programmable quantum processors, which measures the efficiency of a quantum system to handle real-life problems, rather than just measuring its theoretical performance.

Capgemini's Quantum Lab

Capgemini launched their dedicated Quantum Lab in January 2022 to demonstrate the relevance of quantum technologies and bring real advantage to business and societal problems closer. Capgemini's Quantum Lab is a global network of quantum experts, partners, and specialist research facilities, exploring the potential of three quantum technology areas: computing, safe communications, and sensing. The Lab's approach is to partner with commercial organizations, consortia, and pan-government research initiatives to explore the potential of quantum technology through key business use cases, showcasing the applications of quantum technology with the most potential into quantum algorithms that can run on today's hardware. Discovering what is actually possible and what the world might look like in the future. Capgemini's Quantum Lab carries out early experimentation and incubation. A clear example is a Horizon Europe Project. Capgemini is leading and coordinating the EQUALITY consortium of industry partners, which is targeting eight industrial use cases that are computationally complex and can benefit from the quantum-enabled speed-up.

EDF

EDF (Electricité de France) is very involved in the quantum field: EDF, Pasqal and the Quantum Innovation Zone in Canada are joining forces to create the first center of excellence for open algorithms, called QuaTERA - Quantum Technologies Energy Result Accelerator. This initiative aims to form an ecosystem of partnerships at the intersection of the energy industry, classical/quantum technologies, and hybrid algorithms to design and develop solutions that solve the energy industry's real challenges in the near term.

In the meantime, EDF started a four year R&D plan: The Quantum Computing and Technologies project (2020-2024) which is aimed to enable EDF to identify all the possibilities of quantum computing and to apply them to its needs. It also aims to monitor the threat that quantum computing poses to cryptography.

THALES

Thales is also a key player in the quantum field: among the 3,000 employees assigned to upstream research and technology, about 100 engineers and physics researchers are dedicated to the future of quantum science.

The group has a dedicated quantum physics laboratory in its technology research center on the campus of the Ecole Polytechnique in Saclay and has set up a joint laboratory with the CNRS of which Albert Fert, winner of the 2007 Nobel Prize in Physics, is the scientific director.

AIRBUS

The French aircraft manufacturer is very involved in the ecosystem: Airbus launched an international competition (2019) in the field of quantum computing, inviting experts to propose and develop complex modeling and optimisation solutions for the entire life cycle of aircraft. The winners, unveiled in December 2020, are expected to begin working with Airbus experts as early as January 2021 to test and compare their solution.

In parallel, Airbus has been selected to lead a consortium of companies and research institutes to design a European quantum communication network. This work will serve as the basis for the creation of a common quantum internet for the member countries of the European Union.

In parallel, their corporate VC fund Airbus Ventures has invested in six quantum start-ups.

SAFRAN

Safran went for quantum technologies very early by investing in the start-up Cailab : a spinoff from the Kastler Brossel Laboratory (a joint research unit between the Ecole Normale Supérieure, Pierre et Marie Curie University and French national scientific research agency CNRS), specialized in quantum physics and optics. Cailabs has developed a patented disruptive technology, called Multi Plane Light Conversion, based on the manipulation of light. The company designs and sells photonic products, including components, modules and subassemblies for the telecommunications and industrial laser markets.

ORANO

Orano, formerly Areva, a nuclear fuel specialist, is also very involved in quantum research. For example, the group has inaugurated a stable isotope laboratory at the Tricastin site (Drôme) for a total investment of €15M.

CONCLUSION:

The French ecosystem attracts a lot of funding : private, public and European. The total amount invested in French start-ups rose from $104M in 2021 to $120M in 2022. At the same time, UK start-ups has had $112M in funding[74].

While funding is progressing, the battle is not yet over for the French ecosystem. One of the challenges, if not the main one, is education: French start-ups are already facing a "talent shortage" that could eventually penalize them. Nevertheless, the French education system has many assets that should be highlighted.

74. The Quantum Insider

C | A GROWING AND INCREASINGLY ATTRACTIVE ECOSYSTEM, STILL IN THE PROCESS OF BEING STRUCTURED

France is one of the world key players in the quantum ecosystem, especially in academic research with many renowned quantum researchers. However, France is accelerating after a delay in structuring its quantum ecosystem. The €1.8B French National Quantum Plan is focusing on 3 main areas of quantum innovation being Paris, Saclay and Grenoble.

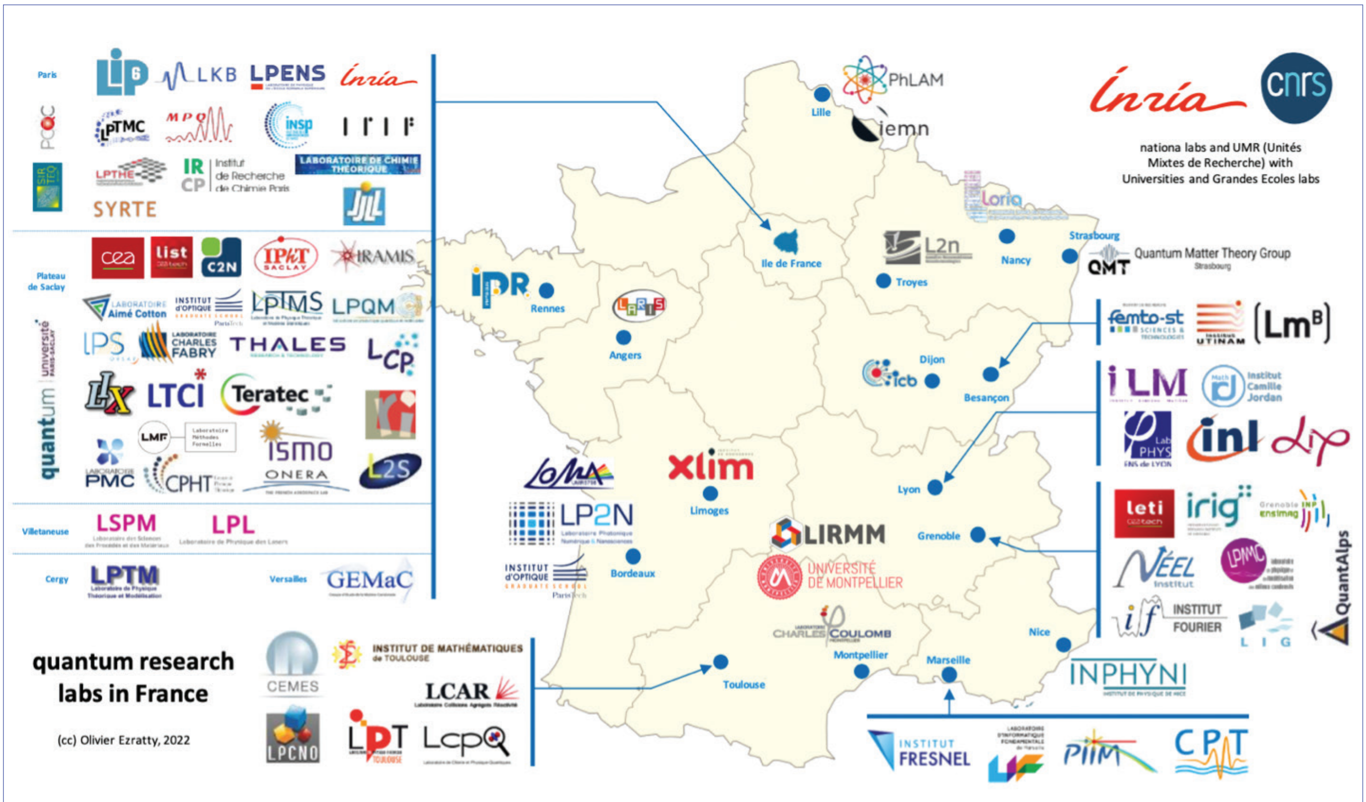


Figure 4 : a map of France's research labs, by Olivier Ezratty, 2022

1 OVERVIEW OF THE ECOSYSTEM

Quantum Hubs

Even if the French quantum ecosystem is not yet perfectly structured, four clusters: “PCQT” in central Paris, “Quantum Paris-Saclay”, “QuEnG” in Grenoble, concentrate between 70% and 80% of academic resources and skills. They have been formed with the ambition of becoming the privileged operators of the quantum ecosystem development, within the deployment of the national strategy on quantum technologies.

The Paris Region, as a key center of research with many labs and universities, has been supporting Quantum Technologies. The program to finance academic research networks amounts to €25M in total since 2017. Boosted by the French National Quantum Plan, the Paris Region is now also supporting industrial actors thanks to a new regional plan with an initial investment of €2.5M.

In 2020, La région Ile-de-France initiated the Pack Quantique (PAQ), which will fund three new initiatives aimed at exploring the benefits of quantum computing for the needs of ASD industries. These involve both major industry players (Airbus, MBDA and Naval Group), leading academic players (ONERA and Inria) and innovative technology start-ups (Pasqal, Quandela and Alice & Bob) to provide innovative solutions to concrete problems. To strengthen its leadership to reach quantum advantage, La région Ile-de-France partners with Teratec, GENCI and Le Lab Quantique. This PAQ has materialized into concrete and promising partnerships: Pasqal/ONERA/Airbus, Quandela/ONERA/MBDA and Alice&Bob/Naval Group/INRIA.

Since 2017, the “Quantum Engineering Grenoble” (QuEnG) program, with a €8.2M budget, has contributed to consolidating the Grenoble ecosystem for quantum technologies, via the awarding of thesis grants and the installation of Chairs of

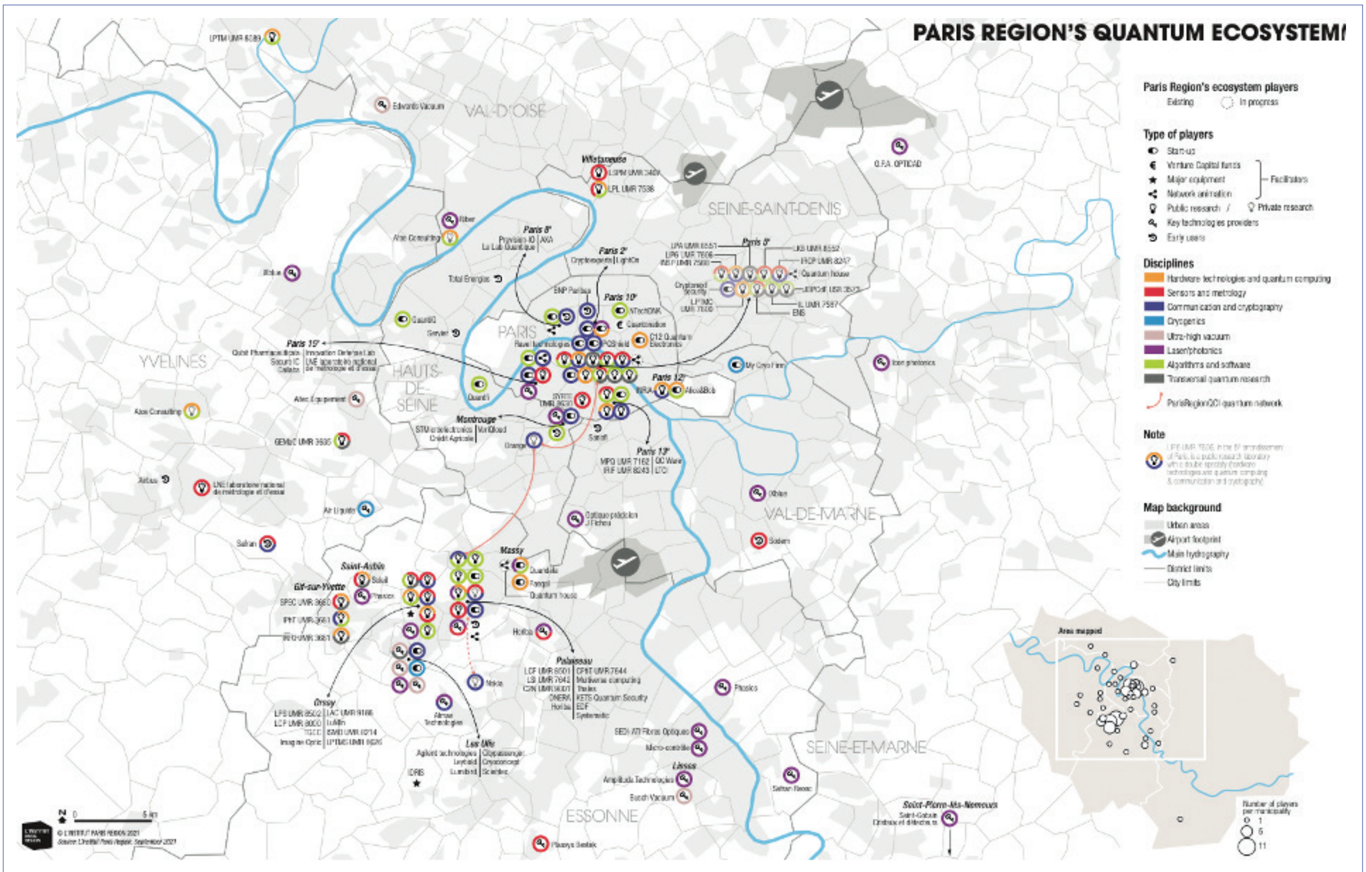


Figure 5 : paris region’s quantum ecosystem, by L’institut Paris Region, 2021

Excellence on interdisciplinary projects, and the implementation of seminars. The actions were initiated and supported by the Université Grenoble Alpes and the European Union. This program was built thanks to the structuring of the Grenoble site through federative actions of excellence (Grenoble Nanosciences FOundation, Labex LANEF). These initiatives have created a synergy between the University and major research organizations.

Grenoble also wants to leverage its expertise in Silicon as an advantage to develop silicon qubits. In 2019, the Quantum Silicon Grenoble (QSG) consortium has been launched and is composed of Institut de recherche interdisciplinaire de Grenoble (Irig-CEA), CEA Leti, CEA-List and Institut Néel (CNRS). The goal of this consortium is to develop a quantum computer with silicon qubits leveraging expertise of the semiconductor industry. Moreover, Global Foundries and STMicroelectronics will set up their foundries in Grenoble. The total investment, estimated at €5.7B, will be a significant advantage for Grenoble to stand out as a quantum hub as it will benefit from a favorable environment for collaboration between academic research, foundries and start-ups such as Siquance.

Within the Grand Sud hub, the project brings together academic partners from Marseille (Centrale Marseille and Aix-Marseille University), Nice, Montpellier, Toulouse and Bordeaux. Thus, Quantum research is not absent in the cities of the South, but it is more scattered than in the other hubs of the country, for reasons related to the geographical dispersion of research establishments: covering the territory from Nice to Bordeaux, the Grand Sud hub is thus nicknamed "the banana"

Launched the 4th of march 2021, NAQUIDIS is an initiative of six partners Nouvelle-Aquitaine représentative of the local politics, the academic excellence and the industrial ecosystem (Regional Council, IOGS, CNRS, the university of Bordeaux, the university of Limoges and the ALPHA-RLH cluster). The focus of the NAQUIDIS Center is to build collaborations between industries and research to accelerate the time to market for disruptive quantum products in Nouvelle-Aquitaine Region..

Research workforce and job prospects[75]

As quantum technology attracts growing interest from industry, talent shortage in the field is a major concern. Indeed, this business boom would require an exponential growth of jobs in quantum technologies over the next two decades. However, the talent gap for Quantum computing jobs is wide, with university capacity only about a third of the demand; upskilling programs could address the challenge. The European Union also has the highest concentration of QT Talent followed by the United Kingdom and Russia. The EU also have the highest number of Quantum-relevant graduates educated in the European Union, followed by India and China.

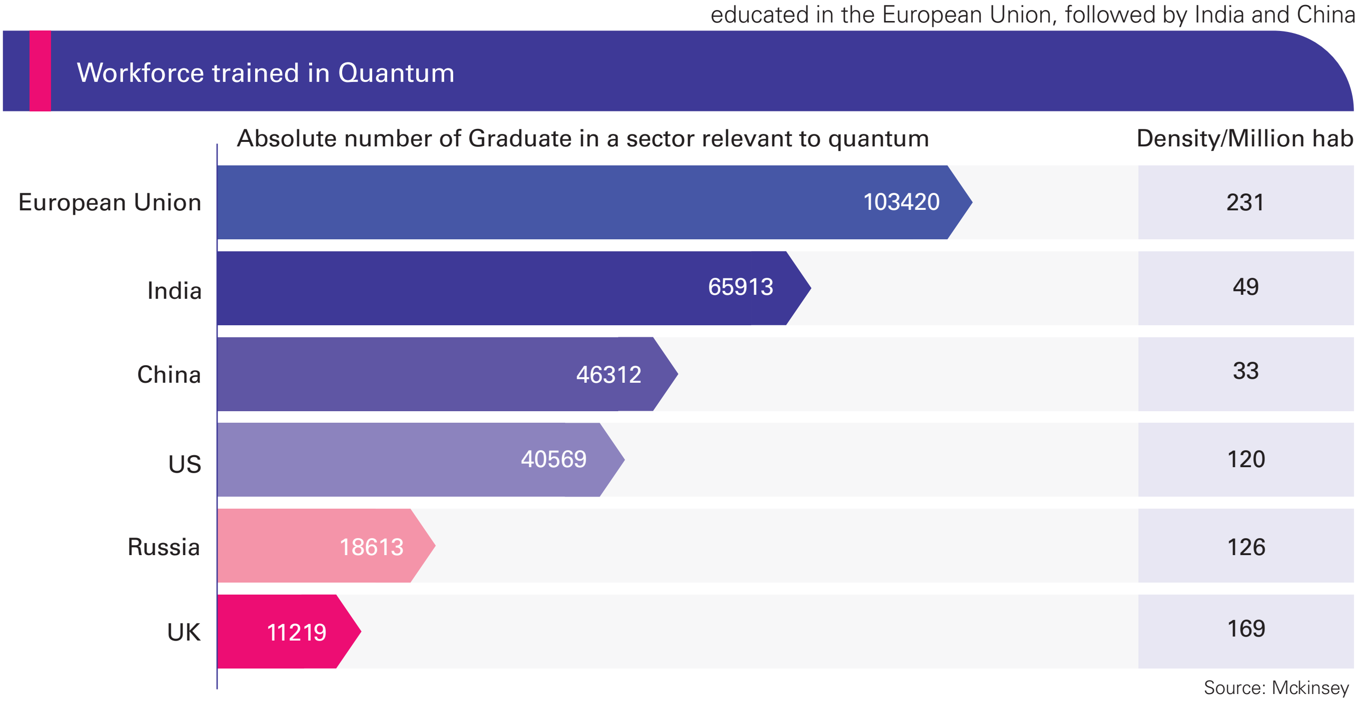


Figure 6: Workforce trained in Quantum
Source: Mckinsey

75. https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-computing-funding-remains-strong-but-talent-gap-raises-concern

There is also a talent gap for QC jobs that could be addressed with an upskilling educational program.

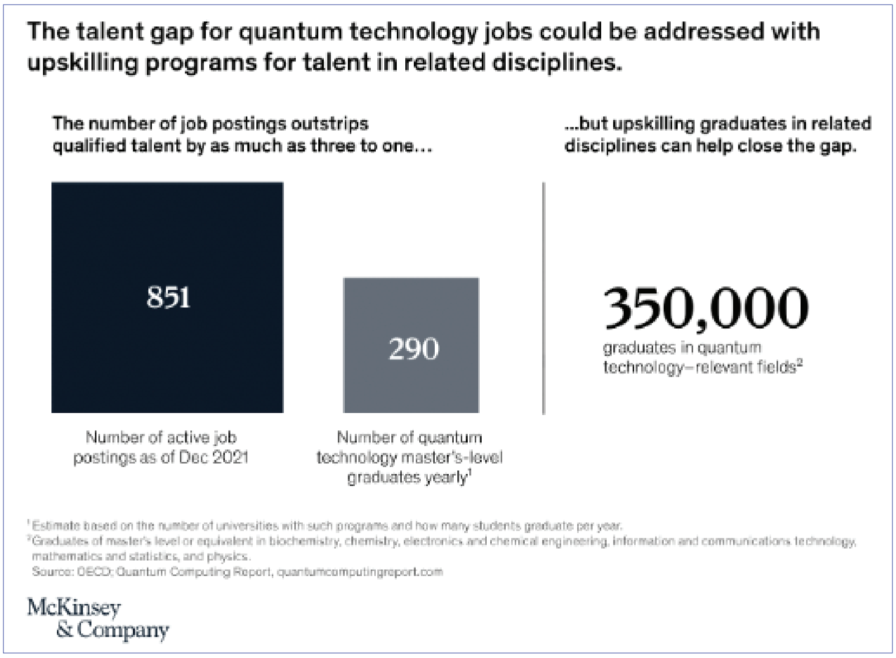


Figure 7: Talent gap for quantum tech
Source: Mckinsey

Thus, it seems that quantum companies struggle to find people with the right skills for new positions in the emerging quantum job market. The fact that this field is still in its infancy means that most current jobs are highly technical, especially with academic specializations and PhDs. Moreover, the only people trained in the field of quantum technologies are highly academic, that is, at the doctoral level. Finding qualified individuals with previous work experience in the world of business or engineering in an already scarce talent pool is proving increasingly difficult.

Moreover, a focus should be placed on ensuring that there are enough people with the right skills to fill this explosion of jobs in the next twenty years. The only way to educate the workforce of the future is by introducing quantum concepts at the primary and secondary education levels and creating more programmes to specialize in quantum engineering. Educating the future workforce is a long process, but there are already several higher education programmes worldwide focusing on quantum engineering. The quantum workforce includes a wide range of skilled workers, such as quantum technicians and people with business, sales and policy backgrounds.

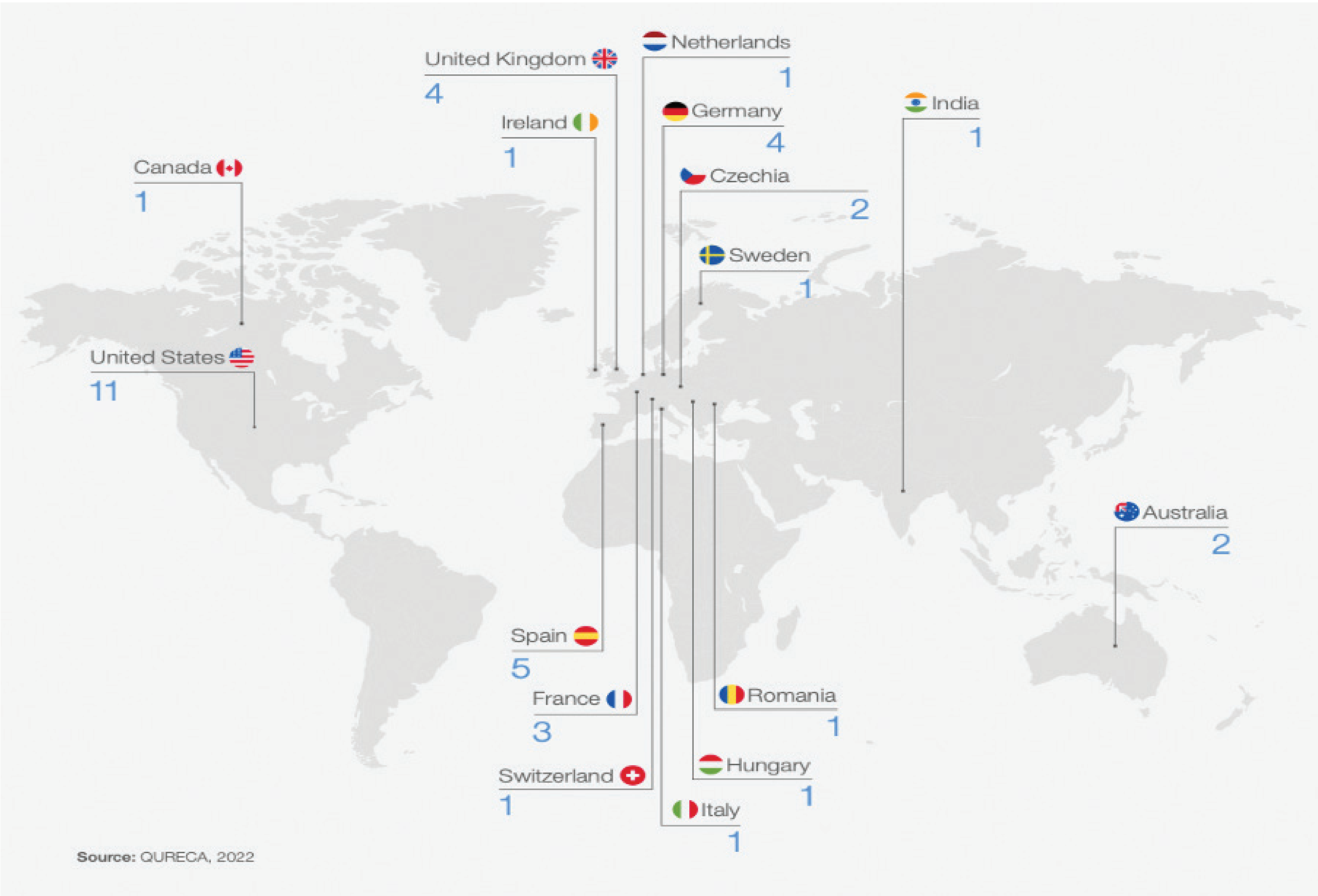


Figure 8: Master's programmes around the world with a focus on quantum technologies
Source: Qureca

Globally, many individuals are looking for additional resources to build their careers in the field of quantum technologies. Opportunities to build and sustain a quantum-ready workforce are abundant including public-private partnerships, industry-academia collaboration, development of national quantum education programmes.

Programmes and evolution

In May, 2022, QuanTEdu that won the AMI (Appel à manifestation d'intérêt) is a consortium of 21 French universities, designated to coordinate quantum trainings in France following the launch of the French Quantum Plan. The initiative is headed by Franck Ballestro. QuanTEdu is focused on teaching and training in quantum physics more than on research. It also aims to create synergies between actors.

The funding of QuanTEdu coming from the ANR (Agence Nationale de la Recherche) will allow the program to promote student mobility, to offer MOOC courses, to supervise a PhD thesis, to equip the photonics platform with high-level quantum "kits" (entanglement between pairs of photons, single-photon interference, etc.), to organize summer schools, and create courses within Universities.

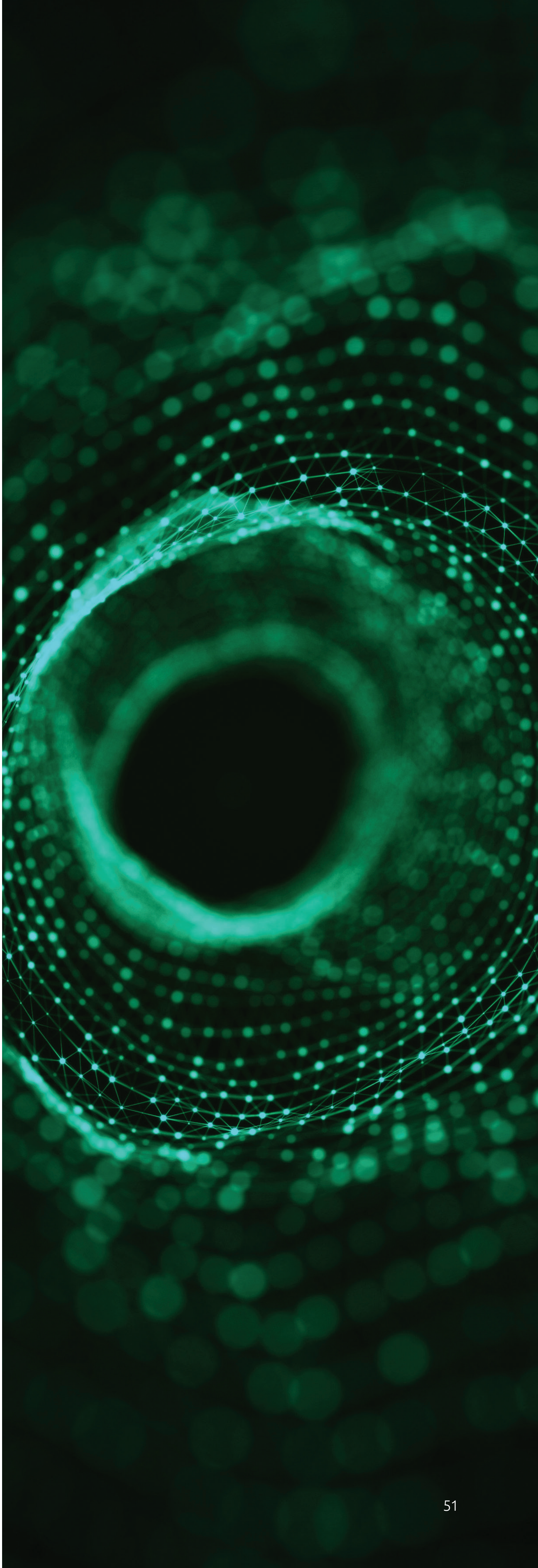
The challenge for QuanTEdu is to structure and increase the number of training and education programs on quantum subjects in order to increase the attractiveness for students. Moreover, the challenge for QuanTEdu will also be to increase the number of permanent professors in order to teach and share their knowledge to the young generations. QuanTEdu is first focusing its efforts on the four hubs that will show the path for other French Universities.

Top French universities are already designing new master programs in order to train the quantum workforce for tomorrow's needs. Paris-Saclay university including Institut d'Optique, CentraleSupélec, Ecole Normale Paris Saclay, and its universities, Versailles Saint-Quentin-en-Yvelines have launch a program which provides initial training for a large number of students participating in the research and development effort in quantum technologies. These initial training programs include a high-level fundamental dimension and also focus on engineering and nanotechnology aspects. This comprehensive and demanding offer ideally positions a campus in close interaction with industry, for the development of interdisciplinary programs adapted to the major challenges of quantum technologies for our societies of today and tomorrow.

Telecom Paris has also launched its own Quantum Engineering program that offers training in the theoretical and experimental foundations of the field: quantum computation and algorithms, quantum communications, quantum and post-quantum cryptography. The program begins with a tutorial devoted to a refresher course on the quantum information formalism. Two of the four courses are shared with the LOM master (Institut d'Optique) and the AFP master (University of Paris). These courses are coupled with training through research (4-month project) and an opening towards international, industrial and academic actors of the quantum revolution, in particular with a view to an internship in this field at the end of the option.

In septembre 2022, PSL University has launched a new interdisciplinary training programme in quantum technologies which results from an unprecedented synergy between between "École Normale Supérieure" and "ESPCI" Paris, Mines Paris, Ecole Nationale Supérieure de Chimie Paris and the Observatoire de Paris. This training program is now part of PSL's graduate program in physics.

Conclusion : France is at the forefront, but these technologies are aimed at a global market and in this context we must succeed in capitalizing on Europe's strengths to meet the challenges of this new technological revolution at an international scale.



2 FRANCE, AN ATTRACTIVE COUNTRY

Many start-ups choose France for their headquarters in order to strengthen their ties with French academic research and laboratories, industries and investors. After KETS (UK), IQM (Finland) , which develops superconducting quantum computers, decided to settle one of its subsidiaries in France. Indeed, the french ecosystem can count among the most renowned in terms of academic research and quantum experts. Moreover, the quality of education in this field makes the country very attractive for foreign start-ups. Many top quantum engineers are educated in France in schools like Ecole Normale Supérieure (ENS), Ecole Polytechnique, Institut d'Optique, etc. Qunasys and Classiq, two startups specialized in software, respectively Japanese and Israeli, also aim to open a market in France. They have recruited French researchers and joined Le Lab Quantique in 2022. Therefore, France should capitalize on this strength and keep improving its quantum courses.

The French National Quantum Strategy is supporting the French ecosystem to help structuring the quantum field and fostering synergies between academics, start-ups and corporates.

France's quantum industry ecosystem. (cc) Olivier Ezratty, 2022.

An attractive ecosystem that is structuring itself

The French quantum ecosystem is very rich thanks to the excellence of scientific training and research, illustrated by several renowned figures (Serge Haroche and Alain Aspect, Nobel Prize in Physics). As breakthroughs accelerate, investment is pouring in, and quantum computing start-ups are proliferating, such as Pasqal and Quandela, that President Emmanuel Macron mentioned in a few speeches. Accelerating advances in quantum computing need to be use case oriented in order to reach a quantum advantage in the long run. To achieve this goal, start-ups, academics and big corporations are joining forces to build and improve error correction in quantum systems and potentially make large-scale quantum computers. The French quantum ecosystem is also structuring itself with few mergers and acquisitions exploring new synergies between complementary expertises. Corporates interest is also thriving as quantum brings great hopes. Indeed, quantum promise is to help businesses solve problems that are beyond the reach and speed of conventional high-performance computers. Thus, many companies in many sectors (from finance to pharmaceuticals) are starting to develop their quantum capabilities in partnering with start-ups that offer promising technologies.

SUMMARY OF KEY MERGERS AND ACQUISITIONS:

M&A Pasqal and Q&Co

On Jan, 2022, Pasqal merged with Qu&Co. This merger was expected to create technological and economic synergies between the two companies. On the one hand, Pasqal is a hardware player. Indeed, the start-up, which uses neutral atom technology, is designing a quantum processor with a power of more than 100 qubits and hopes to reach 1,000 qubits by 2023. On the other hand, Qu&Co is a software specialist and develops quantum algorithms. Qu&Co will bring Pasqal a portfolio of customers. Indeed, the Amsterdam-based company works with Johnson & Johnson, Airbus, LG, and Siemens. For its part, Pasqal works with EDF and Crédit Agricole. Thus, this merger is a great opportunity for the two companies in order to become a European leader in quantum technology.

SUMMARY OF KEY SCIENTIFIC PARTNERSHIPS:

CNRS and UChicago

The CNRS has just opened its fourth International Research Centre (IRC), this time with the University of Chicago, one of its leading partners in the United States. The agreement to create the International Research Centre for Fundamental Scientific Discovery (IRC Discovery) was signed on 30th November in Washington DC, by the CNRS Chairman and CEO Antoine Petit and UChicago President Paul Alivisatos, during the state visit of French President Emmanuel Macron.

Pasqal and Chicago

PASQAL, a leader in neutral atoms quantum computing research headquartered in Paris, announced a collaboration agreement with Professor Hannes Bernien at the University of Chicago. The collaboration aims to advance neutral atom quantum computing. PASQAL and Bernien will accomplish this by developing new techniques for enabling high-fidelity qubit control.

ParisRegionQCI

In this project Orange, Thales and Nokia, as several region-based startups, work together with CNRS-Sorbonne Université, Télécom Paris, and IOGS. With a budget from the Paris Region of €1M.

Le Lab Quantique

While academic research remains the fundamental foundation of the quantum industry, it is also time to create startups, industrialize products, find use cases, recruit talent and build a patent portfolio. The entire "downstream" part of the industry needs to be built. From this observation, the Le Lab Quantique (LLQ) was created in 2018. Its purpose is to create synergy between a national quantum community by developing close links between academic, industrial and investment players. It leads, with and for these actors, field initiatives oriented "value creation". LLQ also sees itself as a Think Tank intended to produce high-level content. To date, the actions have been mainly devoted to the creation of an international network and to the sharing of information, crucial to appreciate the stakes but also the limitations of the technologies. Le Lab Quantique can also count on the help of QuantX, the association of Ecole Polytechnique (X) alumni that counts 150+ quantum computing specialists worldwide: representatives of industrial groups and academia, startups, investors and consulting firms, media, and the government. QuantX frequently organizes hackathons and networking events to gather the quantum community.

The challenge is also to build bridges with the international community in order to increase the visibility of all national quantum resources and skills, which are considerable. The stakes and markets are global, and we are learning a lot from other, often more advanced, ecosystems.

SUMMARY OF MAIN START-UPS PARTNERSHIPS IN 2022:

Qubit pharmaceuticals and Nvidia

Last December, Qubit pharmaceuticals started a collaboration with Nvidia to create Hybrid Computing Platform to accelerate Drug Discovery and the amount of investment required by a factor of 10. Nvidia will use Qubit Pharmaceuticals' platform on its Quantum Optimized Device Architecture. Indeed, Qubit Pharmaceuticals has one of the largest GPU supercomputers for drug discovery in France. This high-performance platform built in collaboration with Nvidia, with a power of several petaflops enables massive acceleration of classical calculations and emulates future quantum computers. By 2023, the first drug candidates resulting from this collaboration should be tested by pharmaceutical companies.

Pasqal, Multiverse and CACIB

In 2021, Pasqal, Multiverse and Crédit Agricole CIB have launched a partnership in order to design and develop new approaches between classical and quantum computing in order to enhance its algorithms for capital market and risk management applications. This project aims at developing financial applications for quantum computing. A new paper on "Financial Risk Management on a Neutral Atom Quantum Processor" has been released in 2022, which looks like a promising perspective for the research in this field of quantum computing application research.

Pasqal and BMW Group

BMW Group and Pasqal expand collaboration to apply Quantum Computing to improve car design and manufacturing processes. More specifically, BMW Group wants to use Pasqal's algorithm for solving differential equations (a type of mathematical problem where a change in one of the variables does not uniformly affect the outcome) for metal forming applications modeling.

Pasqal and ENI

The Italian oil & gas company announced a collaboration on the use of a hybrid HPC+quantum computing system. Pasqal's quantum computers will allow ENI to complement their conventional HPC workflows in areas such as optimization and machine learning and accelerate our research to create new solutions to the most pressing issues in the energy industry.

Pasqal, EDF, Exaion Inc

EDF, a French energy company, Exaion, a French Cloud company, Pasqal and the Quantum Innovation Zone in Canada are joining forces to create the first center of excellence for open algorithms, called QuaTERA - Quantum Technologies Energy Result Accelerator. These algorithms will be designed to develop solutions for the energy industry using the combined capabilities of high performance computing and quantum computing. This collaboration is promising as it will leverage both Exaion expertise in HPC and Pasqal one in quantum computing to deliver unprecedented computing potential power.

Pasqal and Siemens[76]

Pasqal collaborates with Siemens to develop multi-physics simulation solutions based on their quantum simulators. The collaboration also includes researchers from the University of Exeter in the United Kingdom. Siemens is a global leader in the field of computer-aided engineering. Pasqal's proprietary quantum methods to solve complex nonlinear differential equations are expected to enhance the performance of Siemens' software solutions which are used for computer aided product design and testing in amongst others the automotive, electronics, energy and aerospace sectors. The first phase of this 3-years collaboration will be fully funded by Siemens and includes a sponsored academic working in the research group of theoretical physics professor Oleksandr Kryiienko. Siemens will leverage Pasqal knowledge and technology which stands a promising candidate for near-term quantum advantage. Indeed, Pasqal researchers have developed a novel digital-analog implementation tailored for its neutral-atoms quantum processors, which makes these implementations 30 times more efficient than on superconducting quantum processors.

Pasqal's quantum computing technology to build a full stack processor has the advantage of having a high scalability potential, unprecedented connectivity and long coherence times. It can operate at room temperature with lower energy, allowing the company to address complex problems more efficiently than classical computers, having a strong focus on industrial applications.

C12 and Air Liquide

C12 Quantum Electronics is developing a high fidelity quantum processor thanks to its carbon nanotubes technology. The C12 approach is based on the fact that today's qubits are very sensitive to the environment which causes errors. Thus, carbon nanotubes which are very pure material with very little interaction possible with its environment is an optimal candidate to build a fault-tolerant computer. C12 processors are aiming to accelerate today's complex industrial problems which are intractable for classic computers. C12 is currently working on a hydrogen-related project with Air Liquide.

Pack Quantique in Quandela/MBDA

The goal of this partnership is to enhance digital simulation for complex combustion phenomena in the aerospace industry. Quandela and MBDA have signed a partnership contract for 18 months to investigate the possibility of a Quantum Advantage for Engine Design in Aeronautics which is supported by the Ile-de-France region. Indeed, as MBDA has reached some limitations in terms of simulation for its Engine conception, quantum computing will help the company to higher up its precision level in solving nonlinear differential equation which describe thermal and chemical phenomena, but is also used in the fluid mechanics taking place in the combustion chambers of aircraft.

Quandela and EDF

In Nov 2022, Quandela and EDF, the french leader in the energetic field, signed a partnership contract. The goal for those companies is to study the usefulness of quantum computers based on photonics in simulations for hydroelectric dams deformation. This collaboration could help EDF to higher up the precision level of its simulation and speed up the calculation in order to reduce energy consumption for this kind of operation. This partnership is also a great opportunity for the French start-up in order to expand its expertise in concrete use cases.

Alice&Bob and Naval Group

One of the projects of the Pack Quantique (PAQ), launched in 2020 by the Ile-de-France region, is the collaboration between Naval Group and Alice&Bob to explore the potential of Alice&Bob's "cat qubits" in the field of Machine Learning. This collaboration aims to leverage the considerable volume of data created by the platforms of ships designed by Naval Group to offer predictive maintenance, obstacle classification or trajectory prediction services.

76. https://www.pasqal.com/articles/siemens-collaborates-with-pasqal-to-research-quantum-applications-in-computer-aided-engineering-simulation-and-testing

A slow-down in start-ups creation

However, the rate of publicly announced Quantum Computing (QC) start-up funding has slowed over the past three years. According to Mckinsey, this slow down which is an international trend could have several causes:

- » Lack of talent as most experienced specialists (generally academics with research focus in QC) already work in a start-up.
- » Market maturity in hardware solutions as the market has become saturated with solutions creating higher entry demands from newcomers
- » Few working use cases. Indeed more application start-ups are not created because working use cases are very limited with current hardware and working ideas are already patented
- » Investor trends as investors prefer to invest in scale-ups and later-stage start-ups limiting capital for a company that is just starting.

Quantum incubators and accelerators

There are already a few incubation and acceleration programs for deep tech startups which host quantum startups in the world. One of the most famous is the Creative Destruction Lab, based in Toronto and other cities in Canada. Xanadu and Nord Quantique came out of it. Similarly, Unit DX is a deep tech incubator based in Bristol, UK, which started in the biotech industry and also helped some quantum startups. Duality is a quantum dedicated startup accelerator in the USA sponsored by Amazon. Quantum Startup Foundry is the University of Maryland accelerator which was completed in 2022 by Q-Cat (Quantum Catalyzer), a startup studio.

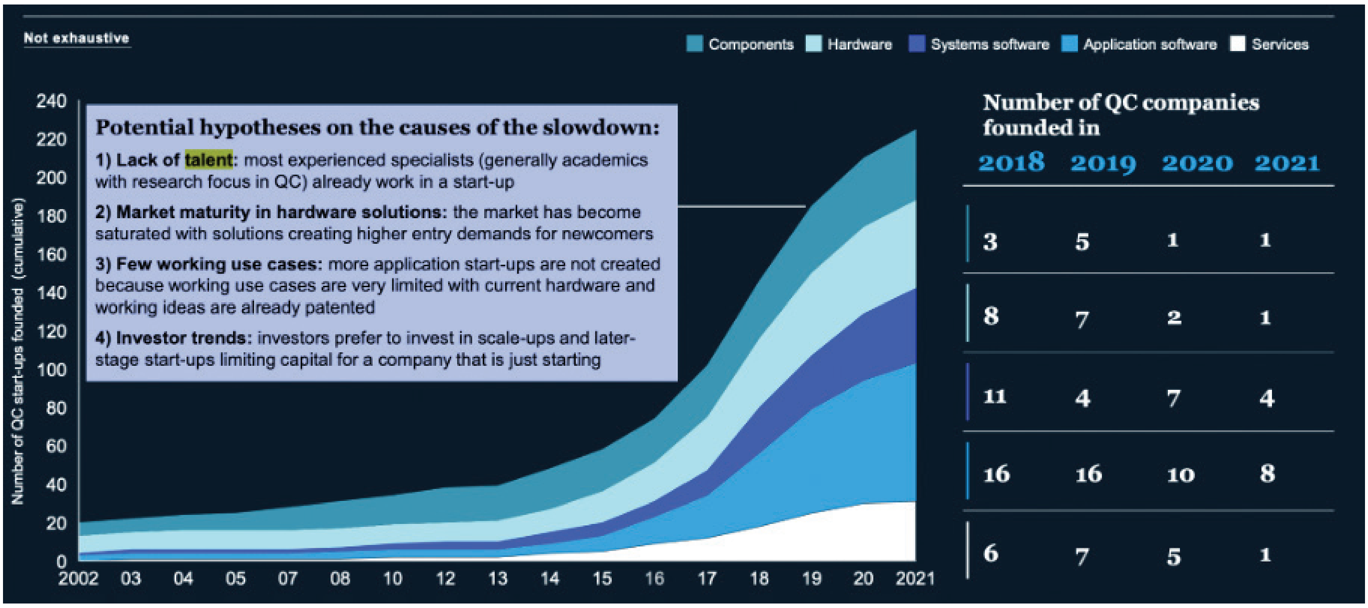


Figure 9: Slowdown on the QC companies creation front
Source: Mckinsey

In France, the HEC Challenge+ program and the Deeptech Founder program created by the team behind the deep tech Hello Tomorrow event, accelerated a big share of France's quantum startups like Quandela, Pasqal and Alice & Bob, Siquance. To create such acceleration programs, you need to be close to a critical pool of talents, such as a dynamic academic and research zone. Starburst, a startup accelerator specialized in Aerospace and Defense (ASD), has for the first time supported a French quantum startup, ColibriTD, via its BLAST program, conducted jointly with École Polytechique, ONERA, SATT Paris-Saclay. This support has allowed to explore common use cases with ASD.

There are also many competitions for start-ups to get visibility and fundings. For instance, the i-Lab Innovation Contest, which is part of the France 2030 plan and operated by Bpi-France, aims to detect innovative technology business creation projects and support the best of them with financial aid and adapted support.

CCL : 2022 is a structuring year for the sector thanks to technological advances that combine with a market in full construction with startups offering solutions and proof of concepts to corporate end customers. To accelerate the development of the sector, we need to get everyone around the table. France stands as a nation with a fertile ground for the development of this economy.

ON A GLOBAL SCALE, WHERE DOES EUROPE STAND IN THE ADVANCEMENT OF QUANTUM TECHNOLOGIES ?

A | EUROPE'S QUEST FOR A LEADER

1 CONTINENTAL EUROPE

European scientists have flooded the field of quantum knowledge for years, to the point that Europe can be described as the cradle of quantum theories.

Let us quote in particular Thomas Young (1773-1829), Henri Poincaré (1854- 1912), Max Planck (1858 - 1947), Louis de Broglie (1892-1987), Werner Heisenberg (1901 - 1976), Paul Dirac (1902-1984), Alfred Kastler (1902-1984, Nobel Prize in Physics in 1966), Jean Brossel (1918-2003) and more recently Serge Haroche (1944, Nobel Prize in Physics in 2012) and Alain Aspect (1947, Nobel Prize in Physics in 2022).

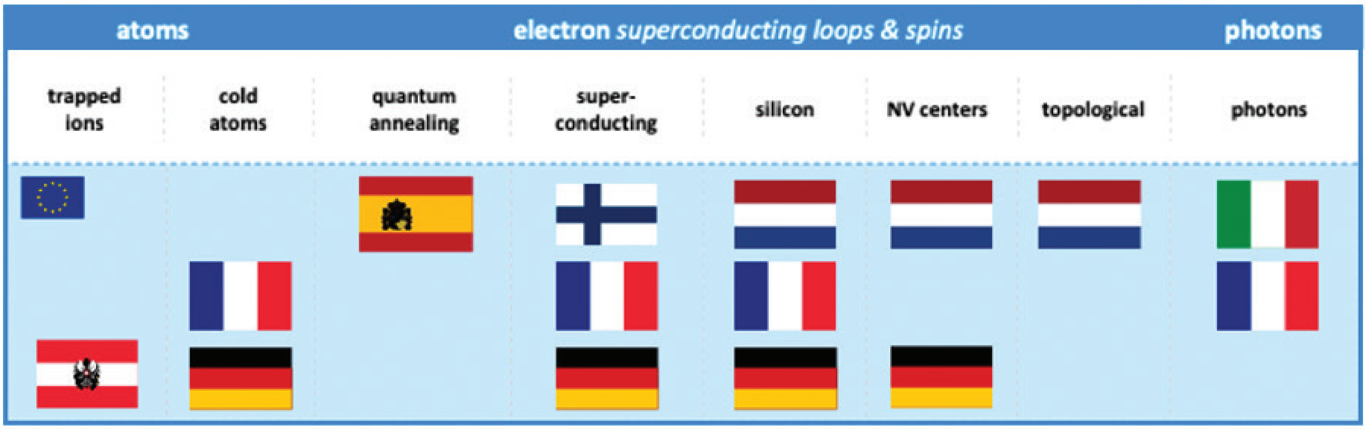
Nevertheless, outside the field of fundamental and academic research, Europe is not in a leadership position on quantum issues regarding the lead taken by American companies on quantum subjects. Georges-Olivier Reymond, CEO of Pasqal said "the first quantum revolution was developed by European physicists, but the market is essentially positioned in the United States. For the second revolution, let's try to keep a bigger piece of the cake !".

Dedicated national QT programmes, QuantERA

Country	Dedicated national QT programme
Austria	Quantum science and Technology (QFTE) programme
France	Quantum Plan (Plan quantique)
Germany	Quantum Technologies - from basic research to market programme
Hungary	HunQuTech programme
Italy	QT represented within the National Research Plan
Netherlands	National Agenda for Quantum Technology
Sweden	Wallenberg Centre for Quantum Technology (WACQT)
Switzerland	Quantum Science and Technology (NCCR-QSIT) programme
U.K.	UK National Quantum Programme
Finland	Quantum Technology Finland

Today, Europe has global ambitions but struggles to show a united front on this issue, while EU members seem to favor national approaches.

This observation calls for the creation of an intra-European leadership to compete with the United States and China. The bulk of European research is centered on the Franco-German axis, with an important role for the Netherlands.



This observation seems to be consistent with the volumes of public funding allocated to quantum…

Country (EU)	National funding (€M)	Share (%)
France	1 800	30
Germany	3 000	49
Nederland	670	11
Austria	157	3
Other[77] (cumulative)	473	8

Quantum National funding of EU's members per country[78]

77. On a basis of a €6,1b cumulative budget of EU's members (excluding european funding) source : Mckinsey
78. The Quantum Insider Database

…and the absolute number of quantum start-ups by country within the EU.

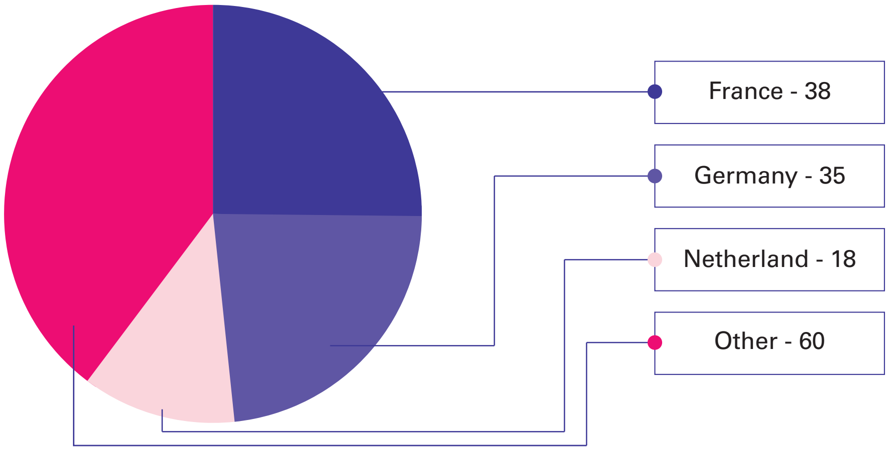


Figure 10: Number of Quantum start-ups in the EU Number of quantum start-up by country in the EU, 2022[79]

Germany

Germany clearly states its ambitions in quantum technology. In 2018, the German Federal government launched the Quantum Technologies program, which is implemented under the Federal Ministry of Education and Research and operationally supported by QuantERA. At this occasion, the Federal Government announced it would provide funds of approximately €650M between 2018 and 2022. In 2021, the federal government announced an additional €2B to support the quantum ecosystem.

On the academic side, there is no doubt that Germany has strengths in quantum physics fundamental research, following the legacy of its brilliant physicist. The German research apparatus appears as the most competitive in Europe, as evidenced by the recent appointment of the French scientist Emmanuelle Charpentier, expatriated to Berlin to work at the Max Planck Institute, where she won the Nobel Prize in Chemistry in 2020.

According to several sources, the monthly net salary of a postdoctoral researcher is about €2,000 in France, compared to €3,600 in Germany[80] (2018 figures).

79. The Quantum Insider Database
80. French Embassy in Germany

German Quantum Industry

Despite Germany's leader position in research, the same cannot be said for industrial applications.

The German start-up ecosystem has had a slow start and has not produced leaders in key quantum fields yet. Nevertheless, the recent massive influx of public money has allowed the emergence of many promising companies, some with international ambitions.

Overview of the German start-up ecosystem

There are two main consortium and network gathering players from the German quantum industry. For instance, the Quantum Business Network (QBN) promotes networking, business creating and the development of organizations. The QBN brings together people from industry, science and politics and connect you with the entire value chain to build a strong quantum Industry in Europe such as (classiq, electron, IQM, PASQAL, Qnami, Quandela, Rigetti, VeriQloud, etc.). The QUTAC (Quantum Technology & Application Consortium) aims to strengthen Germany's digital sovereignty, develop applications to market maturity and highlight opportunities for funding. The QUTAC is carrying several projects through different working groups :

- optimizing clinical trials with Merck
- optimizing paint shops at automobile production plants with Volkswagen
- chemical catalysts with BASF, etc.

HQS

HQS provides a software aimed to help solving issues in the chemical industry at a quantum-level (properties of molecules and materials, etc.). It was cofounded in 2017 by Michael Marthaler, Sebastian Zanker, Iris Schwenk and Jan Reiner in the city of Karlsruhe. As of today, HQS has raised a +$16M funding. Quantonation has participated in the series A.

Q.ANT

Q.ANT was founded in 2018, they are developing quantum sensors and photonic computing chips based on their Quantum Photonic Framework. The start-up is supported by the Federal Ministry of Education and Research that participated in a €M8.8 funding round.

PlanQC

Planqc's founding team combines decades of international research on neutral-atom quantum technologies. Planqc's quantum computers store information in individual atoms - nature's best qubits. Quantum information is processed by arranging these qubits in highly scalable arrays and manipulating them with precisely controlled laser pulses. Planqc is the first start-up to emerge from the Munich Quantum Valley, which with its vast network of research institutes and industrial partners fosters a unique quantum ecosystem for startups. In 2022, Planqc raised a €4.6M funding round led by UVC Partners (Munich based) and SpeedInvest (Austrian).

Finland

IQM

IQM provides on-premises quantum computers for superconducting data centers and research labs and offers full access to its hardware. IQM's second-generation quantum processors use proprietary on-chip components to increase the QPU clock speed for error correction.

IQM's co-design strategy aims to deliver quantum advantage to its customers, using novel chip architecture, application-specific processors, and ultrafast quantum operations. IBM is building Finland's first 54-qubit quantum computer with VTT and an IQM-led consortium (Q-Exa) is also building a quantum computer in Germany. This computer will be integrated into an HPC supercomputer to create a quantum accelerator for future scientific research. IQM has over 180+ employees with offices in Paris, Madrid, Munich and Espoo.

In July 2022, IQM raised €128 million in Series A2 funding led by World Fund to expand its international business and accelerate product development. The funding, which follows a €39m Series A1 announcement in 2020 and includes part of a €35m venture loan from the European Investment Bank (EIB), makes it the largest ever funding round raised by a European quantum computing company. The round included participation from Bayern Kapital, EIC Fund, OurCrowd, QCI SPV, Tofino and Varma.

The Netherlands

The Netherlands have a strong ambition in the field of quantum. They are one of the pioneers of quantum technology by launching, as of 2015, a €135M plan aimed to develop a quantum computer.

On the research and academic side, the country can rely on two major assets: the University of Delft and its quantum branch, QuTech, the main national quantum research center. Knowing that, one can say the country's main strength in quantum technology is the attraction of talent: as an example 63% of the researchers of QuTech are foreigners.

In 2021, the government announced a 7 years €670M national plan, piloted by the state agency Quantum Delta NL, which probably makes the Netherlands the country that spends the most on quantum in proportion to its GDP. This plan aims to reach 100 start-ups, 2,000 doctors and engineers and three major corporate R&D laboratories by 2027. This promising ecosystem has given rise to many start-ups, among which :

Quix Quantum

Quix Quantum is a spin-off of the University of Twente and the AMOLF laboratory in Amsterdam, and is a subsidiary of the fab Lionix, located in Enschede and founded in 2019. The start-ups aims to develop a photonic based quantum hardware and announced in 2022 having built the "world's largest photonic quantum processor".

Qblox

Qblox, co-founded in 2018 by Jules Van Oven and Niels Butlink, is a spin-off from QuTech that develops scalable control for superconducting qubits.

AQA

AQA (Applied Quantum Algorithms) studies quantum algorithms and their applications to problems in natural sciences (physics, chemistry) and practical computing (machine learning, AI, optimization), and methods to make them compatible with near-term quantum devices.

Delft Circuits

Delft Circuits was founded in 2016, by Sal Jua Bosman, Paulianne Brouwer and Daan Kuitenbrouwer. Delft circuits develops superconducting cables which transmit microwave signals to and from qubits at cryogenic temperatures. In 2017, Delft circuits b.v. was formally founded with beta-testing in progress for our Cri/oFlex Products. They had their first sales in 2019. Delft Circuits rapidly grew to a team of over 40 people and completed in-house production and testing facilities.

Sweden

In Sweden, a 12 year 1 billion SEK research programme (c. €90M) aims to take Swedish research and industry to the forefront of quantum technology. Through this extensive research programme, the focus lies in developing and securing Swedish expertise within the main areas of quantum technology: quantum computing and simulation, quantum communications and quantum sensing. The main project is to develop a high-end quantum computer that can solve problems far beyond the reach of the best conventional supercomputers.

Hungary

The Hungarian HunQuTech is a four-year (2017-2021) national quantum program that offers €11M funding for Quantum Technologies research and development. It brings together outstanding research groups in Hungary, as well as a number of industrial partners. The strategic research agenda is defined by the consortium implementing the programme and is aligned with the European Quantum Technologies Flagship.

Austria

Austria has been a leading country in quantum science and technology research since the early 1990s. First experiments made in quantum sciences were at the University of Innsbruck and the Technical University of Vienna. Experiments were made in photons, trapped ions and neutrons. Today, a sizable research community is distributed over Innsbruck, Linz and Vienna working on various topics.

Austria has launched, under the supervision of the The Austrian Research Promotion Agency (FFG), the state-funded agency. Austrian's national quantum programme "Quantum science and technology" (QFTE) is run by the FFG in cooperation with FWF. This plan aims to fund the quantum research and quantum ecosystem by €107M.

Denmark

Denmark has a long history of quantum technologies coming from the legacy of Niels Bohr, a Danish Nobel prize laureate and founding father of quantum theory. University of Copenhagen houses the Niels Bohr Institute, which today ranks seventh in terms of number of unique researchers publishing quantum research in renowned journals in the past five years. Some of the best use cases for quantum technology relate to Danish key industries lies in :

- life sciences industry : quantum-enabled chemical simulation
- logistics and transportation industry : optimisation
- Danish green technology industry : measurement accuracy by quantum sensors

Denmark is growingly attractive in terms of foreign investment. For instance, in 2018, Microsoft established its quantum materials lab in Lyngby. The strong research community attracts international attention, but the extended enterprise of the business ecosystem is currently immature. However, Denmark also has notable suppliers to the quantum technology industry, such as NKT photonics, which provide sensitive lasers useful in a number of quantum technologies. Government support comes essentially from Innovation Fund Denmark (80m DKK committed from 2017 to 2019) and the Ministry of Foreign Affairs, but stakeholders consider the government's official stance on quantum technology and support for funding to be weaker than in other European countries.

Conclusion

Within the EU, Germany has the lion's share of public funding, but France has a more mature start-up ecosystem, with established leaders (especially in quantum computing). Intra-European competition cannot be reduced to a binary confrontation between Germany and France, as countries such as the Netherlands are demonstrating their ability to forge a very dynamic quantum ecosystem.

Nevertheless, France is already exporting some of its technologies and know-how which means that it has a real chance to unite the European ecosystem behind it. Moreover, France has a very complete ecosystem, and is present on almost all quantum subjects from fundamental research to industrial applications.

Summary of research priority areas in countries with dedicated national QT programs, Quantera

	Austria	France	Germany	Ireland	Italy	Netherlands	Switzerland	U.K.
Quantum communication	+		+		+			+
Quantum cryptography		+	+					
Quantum computing and simulation	+	+	+		+	+	+	+
Quantum information sciences	+	+		+			+	
Quantum metrology, sensing and imaging	+	+	+	+	+	+		+
QT for energy and environment		+			+			
Quantum infrastructures		+			+			

The main issue would be to go beyond the competition aspect in favor of cooperation, to compete with the US, UK and China.

At the European scale : Quantum Technologies Flagship

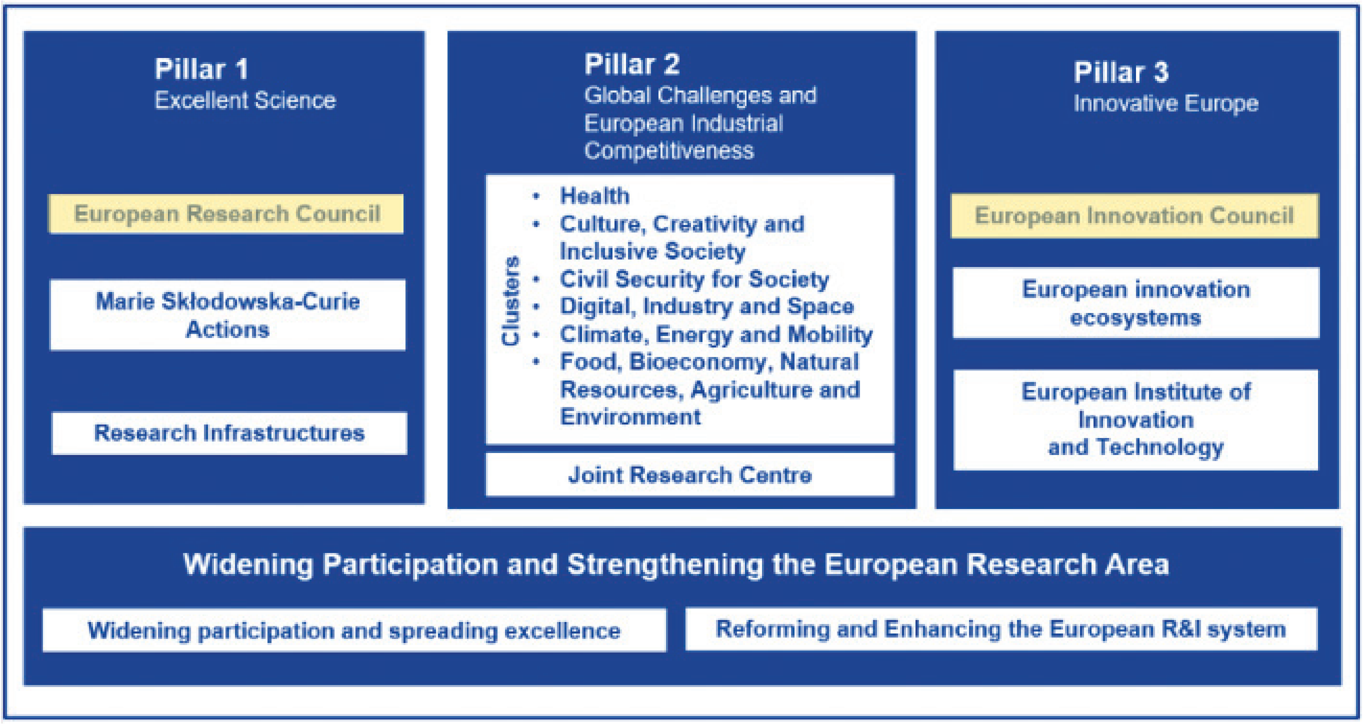
In the Quantum race, the European Union has also launched some initiatives at the European scale. Following the Quantum Manifesto in 2016, The Quantum Technologies Flagship was launched and funded under Horizon Europe.

What is a flagship? (Def. European Commission)

The European Commission has launched various flagships to address the major science and technology challenges. Flagships refer to long-term and large-scale research initiatives, paving the way with an ambitious vision. The EU's flagships in digital focus on future and emerging technologies and run for around 10 years. They mobilize researchers, academics, industry and national programmes to tackle major challenges in science and technology. The result can bring positive changes that benefit society and the economy, and advance EU leadership in technology and industry.

This initiative is a long-term research and innovation initiative that aims to put Europe at the forefront of the second quantum revolution. The Quantum Technologies Flagship has an expected budget of €1 billion over ten years from the EU to support hundreds of researchers' works and to transform it into commercial applications. Thus, the Quantum Flagship brings together research institutions, academia, industry, enterprises, and policy makers, in a joint and collaborative initiative. The projects supported by this initiative encompass quantum computing, quantum simulation, quantum communication, quantum metrology and sensing. However, the funds also go to basic science projects behind quantum technologies, education and international cooperation activities related to the quantum ecosystem and industry. During the first phase €154 million have been deployed to finance 24 projects. Among them, 3 projects were particularly outstanding :

- The OpenSuperQ project goal was to build a hybrid high-performance open quantum computer of up to 100 qubits and to sustainably make it available at a central site for external users. The aim is really to be among the leading platforms in the world and presumably the first one developed in Europe. The platform is available at Forschungszentrum Jülich (DE).
- AQTION is also a major research project which aims to develop and exploit a robust, compact ion-trap quantum computer based on scalable quantum hardware and widespread industry standards. One of the most notable features of this system is that it's powered from a single wall-mounted plug, and with an extremely low power consumption of 1.5kW (amount of energy to boil a kettle).
- QuIC (European Quantum Industry Consortium) is an initiative under the Quantum Technologies flagship which aims to bring forward innovative breakthroughs in science and technology to shape the industry and the society. QuIC operates as a collaborative hub throughout Europe between SMEs, large corporations, investors, and leading researchers.



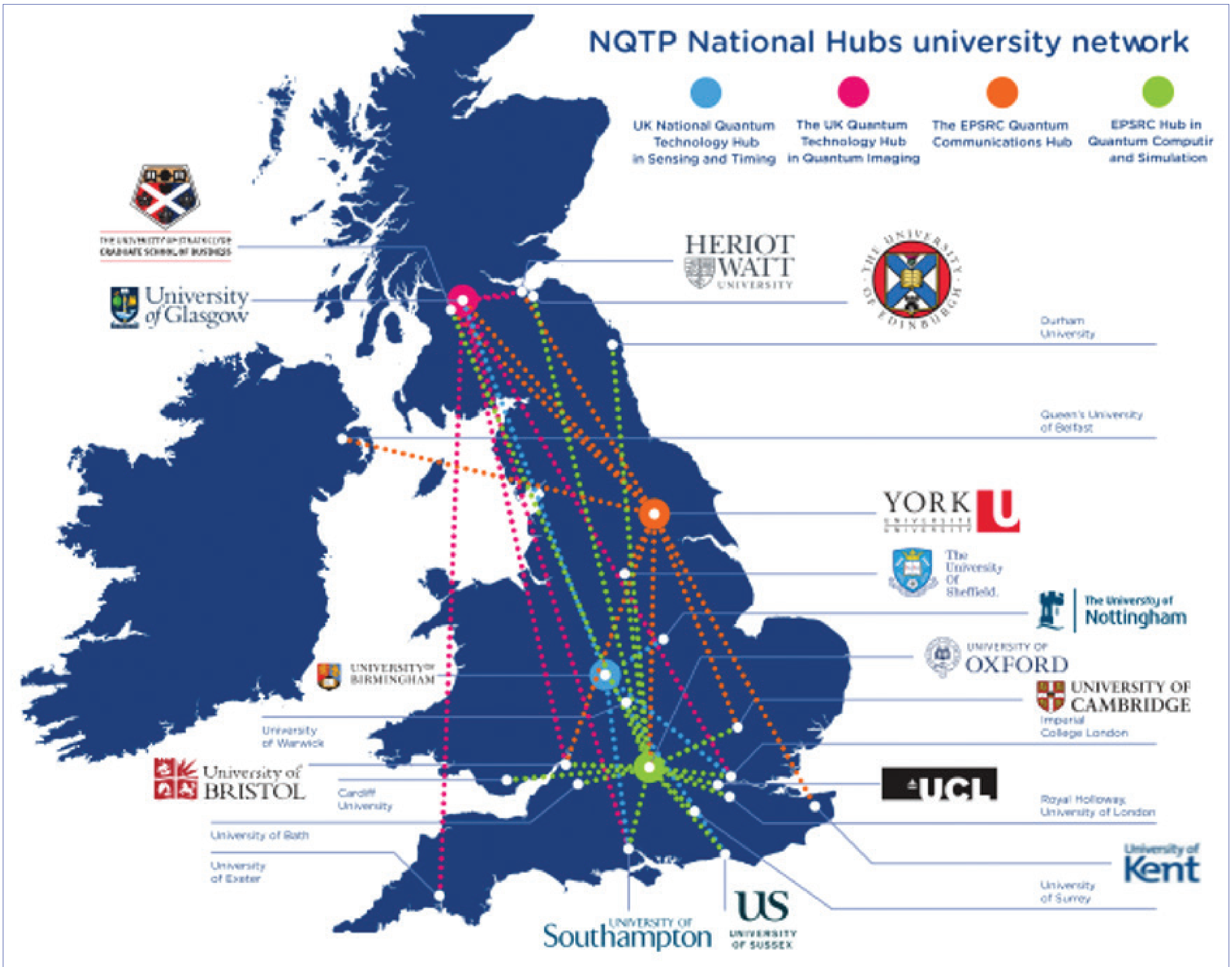
Horizon Europe strategy

2 UNITED KINGDOM

Like France and Germany, the United Kingdom bases its quantum legitimacy on its long and rich scientific history.

The United Kingdom has taken the lead of the quantum race by setting up the UK National Quantum Technologies Programme as of 2013. It was coordinated by the EPSRC (Engineering and Physical Sciences Research Council), a non-governmental organization funded and supervised by the government. The first phase of this plan (2014-2019) consisted of a £120M investment, completed by a second phase that started at the end of 2019 and was a £94M investment. This plan was aimed to maintain the technological research leadership that the UK has established in Quantum Technologies. More recently, the British government promised an additional $1B investment in the quantum field.

That context led to the creation of a very successful quantum ecosystem, both in terms of fundamental research and in emerging industrial applications.



the UK universities map. Source: UKRI and logos added by Olivier Ezratty, 2021.

Supported by leading universities such as Oxford, Cambridge, Bristol (Heilbronn Institute) from which many promising startups are being created.

the UK startup scene is the most active in Europe (the old Europe, with them, before Brexit...). (cc) Olivier Ezratty, 2022.

The most promising of these start-ups are:

- **Oxford Quantum Circuits** (superconducting qubits, raised $45M in a Series A funding in 2022)
- **Quantum Motion Technologies** (silicon qubits, raised $10M in a Series A funding in 2022)
- **Cambridge Quantum Computing** (operating system, software, services, which merged with Honeywell Quantum Systems in 2021 and raised $45M in 2020) - now Quantinuum (merge with Honeywell 2021). The company has 500 employees today including 350 Phds.
- **Orca Computing** (photon qubits, raised $15M in a Series A funding in 2022)

One of the largest Quantum consortium is the UKQuantum consortium which unites the UK quantum industry with one voice. Among their members, there are outstanding start-ups (KETS, ORCA, etc.) but also big corporations (TOSHIBA, BAE systems) and quantum consortium and press such as The Quantum Insider and QURECA.

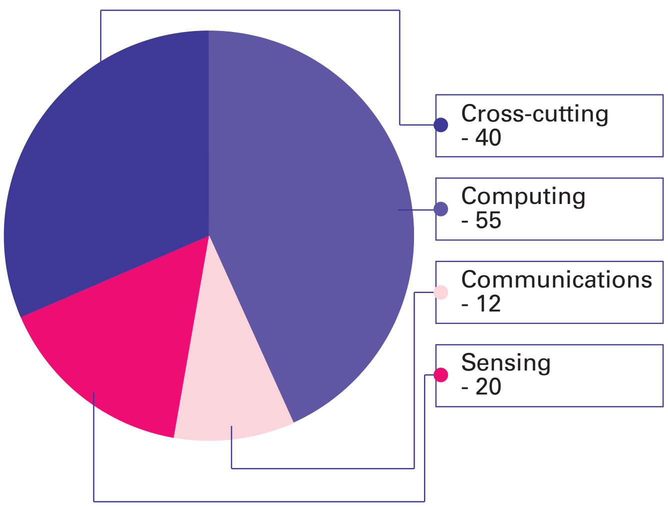
B | EUROPE VS USA

1 TECHNOLOGICAL DIFFERENCES IN RESEARCH (DIFFERENT FOCUS OR US ADVANCES)

The US has long been a global leader in the development of quantum technology and is home to incumbent companies such as IBM, Microsoft, Google, AWS, Intel and Nvidia actively working on quantum technologies. IonQ, ColdQuanta, QC Ware, Rigetti and Zapata Computing are some of the leading start-ups driving innovation in quantum computing. IBM has been an innovator in quantum computing and leads a network of more than 200 organizations dedicated to the advancement of quantum computing. IBM Quantum possesses the largest number of quantum computers globally and is constantly working to increase or enhance this collection. Out of the first four quantum-resistant cryptographic algorithms announced by National Institute of Standards and Technology (NIST) in July 2022, three standards were developed by IBM, in collaboration with several industry and academic partners.

Google is developing its own quantum computer with the aim of enhancing its stability and advancing the development of quantum AI. In July 2022, Google Quantum AI unveiled Quantum Virtual Machine (QVM) available to the public free of cost. The QVM emulates the experience and results of programming one of the quantum computers in Google's lab, from circuit validation to processor infidelity. In 2021, Microsoft made its cloud-based quantum computing service accessible to the public. Intel aims to make quantum computers more widely available for commercial use by bringing them out of specialized research labs. AWS has a fully managed quantum computing service designed to help speed up scientific research and software development for quantum computing.

Distribution of QED-C Companies by Quantum Application Domain



Total Publications by Highest-Publishing Countries, 2011-2020

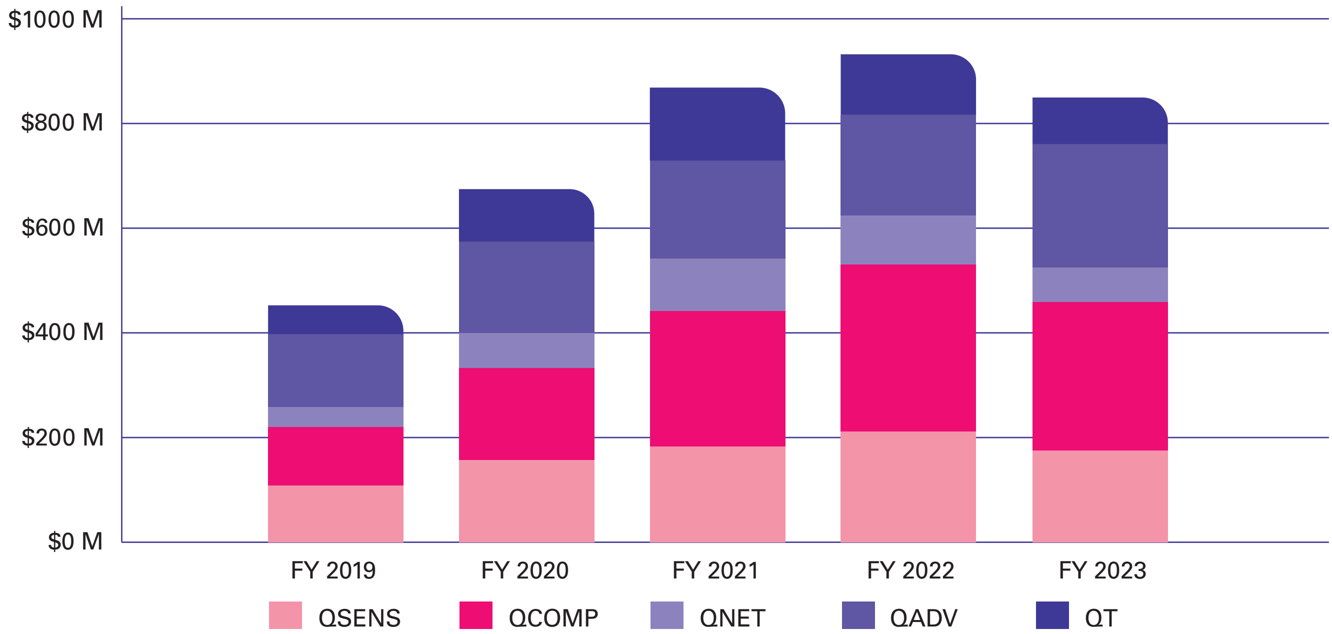
	Quantum Computing Publications	Quantum Communications Publications	Quantum Sensing Publications
USA	7319	2524	1240
China	7050	6440	1539
Germany	2749	1258	648
Japan	2275	936	334
UK	2203	1395	545
Canada	1584	983	224
Italy	1115	678	371
France	1347	554	328
India	1419	655	90
Russia	1030	556	236

(Number of publications produced by the top ten publishing countries by application domain over the 2011–2020 period of analysis.)

43% of the QED-C companies worked on quantum computing, and 31% of the companies "cross-cutting" produced products and services fall into two or three application domains. The US excels in quantum computing and sensing but lags behind Europe and China in quantum communications. Majority of US private industry's focus is on quantum computing, where almost half of the companies and the majority of venture capital investment is directed. Researchers in the US are currently developing networks to test new communication devices, security protocols, and algorithms that will eventually connect distant quantum computers. In April 2022, Chicago Quantum Exchange in partnership with Toshiba activated a 35 mile (56km) quantum link between Argonne National Laboratory and the University of Chicago. They also added to it a 89 mile (144 km) quantum loop that Argonne had previously installed. The total network spans 124 miles (200km) which is the largest quantum network currently deployed in the United States. This quantum network has a key distribution protocol over optic cable at a speed of over 80,000 quantum bits per second. Similarly, a team of researchers with the Illinois Express Quantum Network (IEQNET) successfully deployed a long-distance Quantum Network between Fermi National Accelerator and Argonne National laboratories using local fiber optics.

Between 2011 and 2020, the US was the global leader in quantum computing publishing while China led in Quantum sensing and communication publications. Number of publications produced together by Germany, France, and Italy is close to the US in quantum communications and superior than the US in quantum sensing.

US QIS R&D Breakout by PCA



Total US Federal Government Investment in QIS R&D, 2019–2023

The US government has launched several initiatives to ensure continued leadership in Information Science (QIS) and its technology applications. The National Quantum Initiative (NQI) Act enacted in December 2018 authorizes the National Institute of Standards and Technology (NIST), National Science Foundation (NSF), and Department of Energy (DOE) to strengthen QIS programs, centers, and consortia. The US budget for QIS research and development was roughly $900 million in fiscal 2022 that has roughly doubled since 2019. There is also an increased and sustained investment in QIS R&D across each Program Component Area (PCA) to accelerate quantum R&D. NQI PCA include Quantum Sensing and Metrology (QSENS), Quantum Computing (QCOMP), Quantum Networking (QNET), QIS for Advancing Fundamental Science (QADV), and Quantum Technology (QT).

NIST initiated a process to solicit, evaluate, and standardize one or more quantum-resistant public-key cryptographic algorithms. In July 2022, NIST announced the first four Quantum-Resistant Cryptographic algorithms that are designed to withstand the attacks from a future quantum computer. NIST selected the CRYSTALS-Kybe for general encryption and CRYSTALS-Dilithium, FALCON, and SPHINCS+ for digital signature. The CRYSTALS team includes researchers from European organizations such as NXP Semiconductor, CWI Amsterdam, Ruhr University Bochum, Radboud University in the Netherlands, IBM research in Zurich and ENS Lyon.

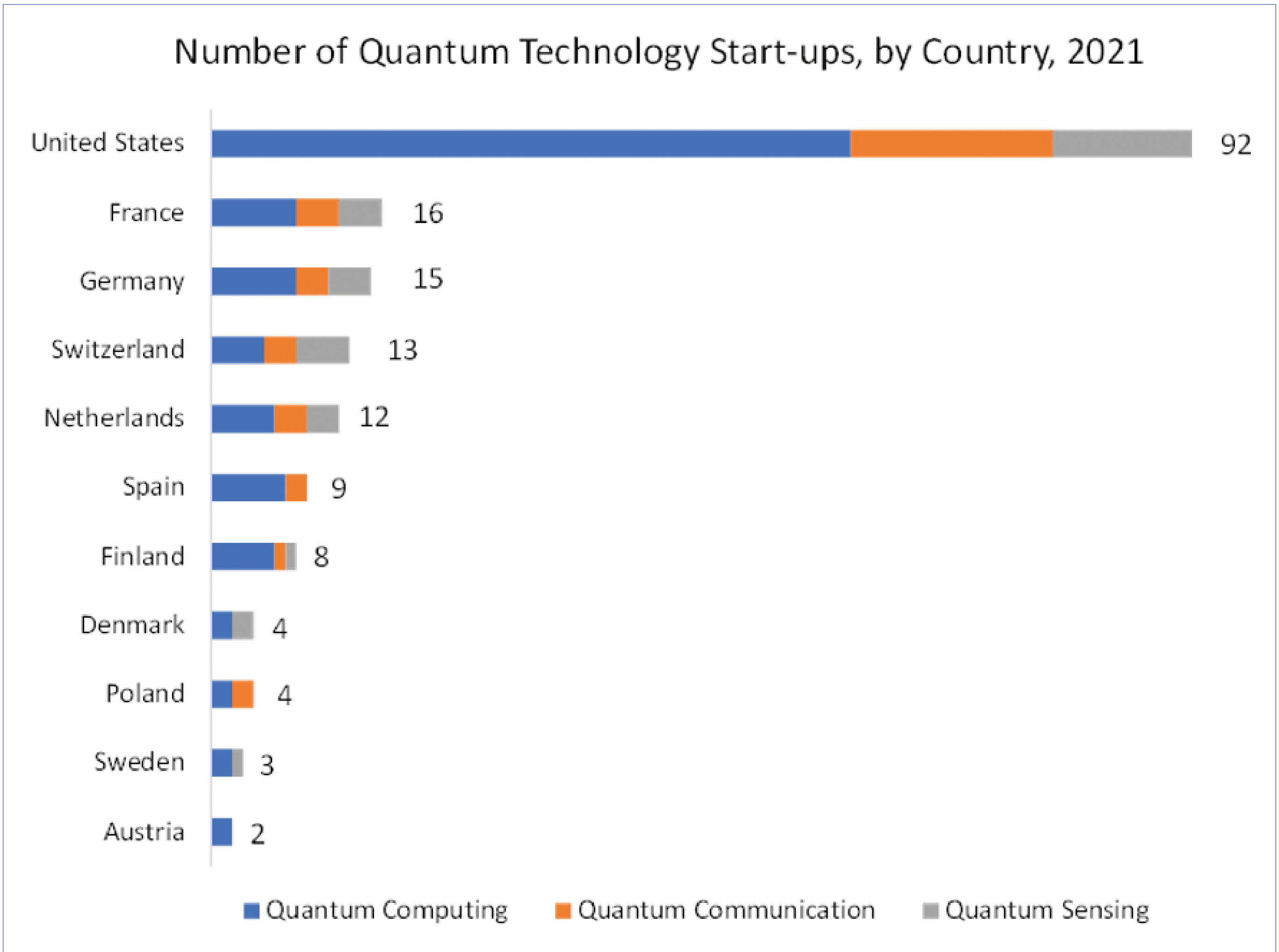
Although Europe appears to be lagging behind the US in areas such as quantum computing on superconducting-circuit platforms, Europe is strong in terms of platforms based on qubits made of trapped ions and neutral atoms. European leaders such as Airbus, Bosch, EDF, TotalEnergies, Volkswagen, BMW, Thales, Airbus, ENI, L'Oréal, CA-CIB, Société Générale, Saint Gobain, Roche, Schlumberger, Vodafone and LVMH are looking to harness the benefits from commercializing quantum-computing applications.

While Europe has a strong foundation in quantum technology research, it needs to develop a strong industrial base. European Quantum Industry Consortium (QuIC) is one such initiative that brings together enterprises, SMEs, investors, and start-ups from across Europe aims to build a strong ecosystem. The EU aims to be a key player in the global quantum market, with more sovereignty. Its Recovery Plan and twin digital-green transition are well in line with the opportunities of quantum computing, driven by the Quantum Technologies Flagship. Moreover, the Digital Compass has set the target that: "By 2025, Europe will have its first computer with quantum acceleration paving the way for Europe to be at the cutting edge of quantum capabilities by 2030."

In terms of investments and EU policy interventions, the Commission's Quantum Flagship Programme in particular helps to boost research and market uptake of quantum technologies, including quantum computing. Given the interlinkage between quantum and classical (high performing) computing, initiatives such as the EuroHPC JU, EuroQCI, European Chips Act and various Horizon Europe projects help to build a quantum enabling infrastructure, as well as to consolidate and materialize Europe's quantum efforts.

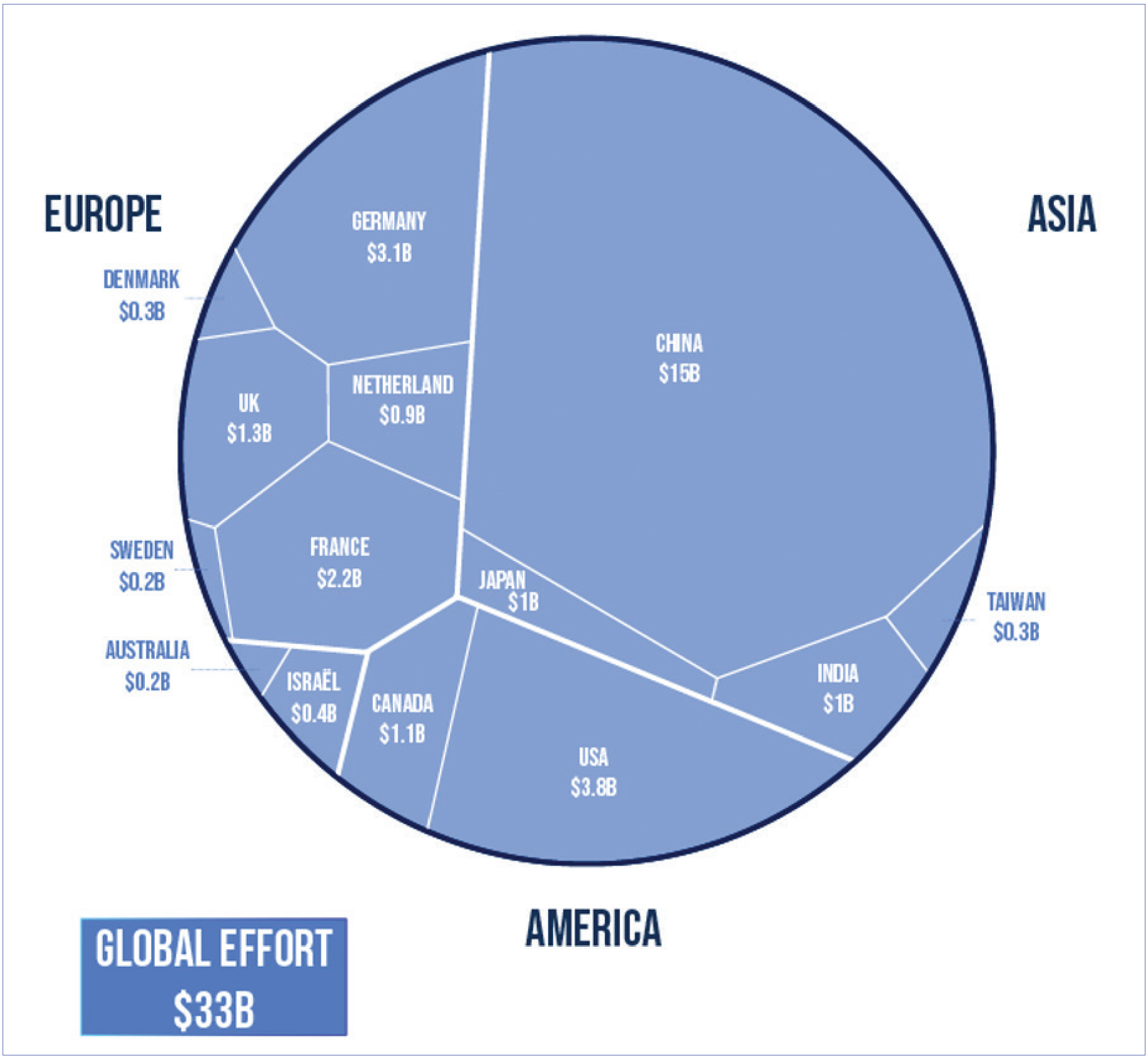
2 THE START-UP ECOSYSTEM AND THE INTEREST OF LARGE COMPANIES

The US has the largest number of quantum technology start-ups. Some of the leading quantum computing start-ups such as IonQ, ColdQuanta, QC Ware, Zapata Computing, PsiQuantum, and Atom Computing are in the US. However, it is worth noting that the number of start-ups in this field is growing rapidly in the EU. The EU has created initiatives to support and promote the development of start-ups, but the ecosystem takes time to mature and for start-ups to gain the resources and support they need to scale and become successful. Pasqal, Alice & Bob, Quandela, IQM, planqc, C12, Siquance, Alpine Quantum Technology are some of the major EU based start-ups developing quantum computers.



(Mckinsey, Quantum technology monitor)

EU lead significantly on public funding of Quantum Technology. Total historic announced funding by the EU was estimated to be USD 7.2 billion as compared to USD 1.9 billion announced by the US government.



Overview of the worldwide public funding, per continents and per country, 2023 figures
Source: Quantonation Analysis, Qureca

The EU allocates a significant portion of its public investment towards academic institutions and research efforts, which sets it apart from its peers such as the US and China, who direct more funding towards state-sponsored initiatives. The role of companies and startups will be crucial in the advancement of quantum technology systems, which will play a critical role in turning quantum research into valuable products and services for other industries.

Private investments by investor and investee country (%)

Sources: PitchBook; BCG analysis.

Note: The data in this exhibit represents investments since 2010 for which investors were disclosed and whose country could be determined. Only percentages larger than 20% are highlighted.

The US dominance in this field is undeniable because of the large investments in American startups. The US has a large number of companies working in the field of quantum computing and its startups receive the majority of the investments in this field. According to BCG, startups in the US attract a large amount of seed capital as compared to the EU. From 2010 onwards, American venture capitalists invested roughly $1.8B in quantum computing startups whereas European startups have only received around $300M in investments, with very little going towards Series C or Series D funding.

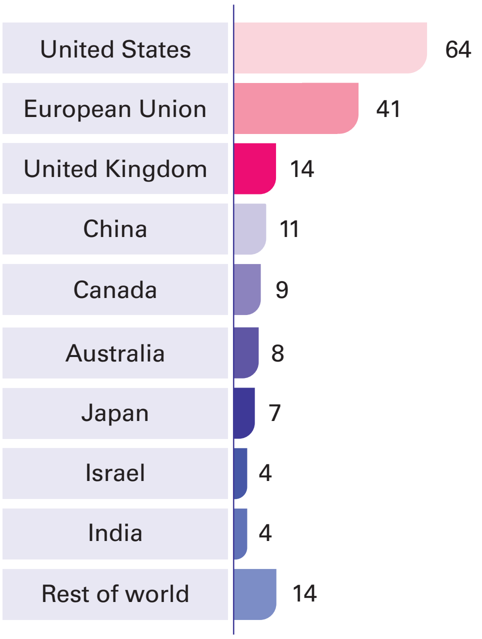
Quantum computing startups in the EU have attracted less than 2% of their investments from US firms while the US has drawn 25% of its investments from EU-based funds, even though the US CFIUS regulation on foreign investment is the strictest among more technologically advanced countries.

The EU's policies restricting foreign investment in quantum computing are aimed at fostering self-reliance, however, it may also have negative impacts by restricting the flow of investment and expertise from outside the EU, slowing down the growth of the industry. Furthermore, other countries may also adopt similar policies, resulting in fragmentation of the global quantum computing sector. The laws have also discouraged investors in the EU as they tend to view foreign companies as more attractive investment options due to their capacity to secure funding from larger funds, particularly in the US.

Having a talent ecosystem in place is crucial for the growth and development of the quantum technology industry. Countries around the world are working to develop and nurture their talent ecosystems in order to prepare for the future needs of the quantum technology industry. The US is frontrunner and accounts for over a third of all universities with Quantum Technology research programs. As of 2021, the US had 64 universities offering quantum technology research programs while the EU had 41 universities. 12 out of 29 universities that offer master's degrees in quantum technology are from the US. However, the EU is not left behind. Indeed, Spain, Germany, France, Switzerland, and the Netherlands together have 10 universities offering master's degrees in quantum technology.

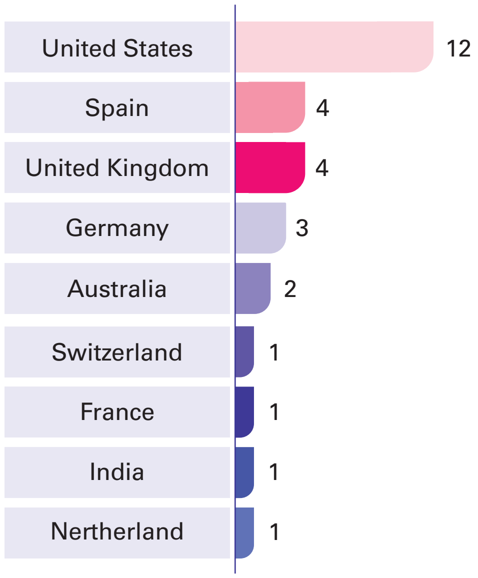
Top 10 countries worldwide 2021 by number of universities with QT research programs

Number of universities per country



2021 universities with QT master's degree offering

Number of universities per country



Source: Web search; McKinsey analysis

By fostering the talent ecosystem, Countries are positioning themselves to meet the challenge of supplying the talent necessary for the growth of the quantum technology industry. In Nov 2022, Quantum Flagship announced that 20 universities from ten European countries will offer 16 new specialized master's degree programs. DigiQ (Digitally Enhanced Quantum Technology Master) and Quantum Technology Open Master workforce development projects aim to prepare the workforce and talent for the future quantum technologies in Europe. Similarly, The US has formed the National Q-12 Education Partnership with major tech firms to produce educational materials and carry out outreach programs in middle and high schools, aimed at increasing society's understanding of quantum computing.

C | MAP OF SPECIFICITIES ACCORDING TO REGIONS OF THE WORLD (JAPAN, CHINA, SOUTH KOREA, AUSTRALIA)

1 ASIA

China

The presence of a quantum computer in the Chinese blockbuster action movie Wandering Earth 2, broadcasted in February 2023, would suggest that China is producing quantum computers. The quantum computer was delivered by Hefei city (Anhui province), where the government has funded a quantum computing lab. The computer has been supposedly developed by Origin Quantum, which made China the third country after Canada and the US to deliver a quantum computer. How are quantum technologies financed in China? where does China stand at the global scale in terms of start-up creation and research works?

The Chinese quantum ecosystem is characterized by a significant public sector effort in the field of quantum. The figure of €15B of investment is put forward, although it is strongly questioned. It is more in the $4B range over a 5 year period. Public money is allocated according to five-year plans under the aegis of the USTC (University of Science and Technology of China) and the CAS (Chinese Academy of Sciences).

In terms of fundamental research, China is present on the entire spectrum of quantum technologies, and regularly announces significant advances

Share of quantum patents by company headquarters, 2000-21, %

	Overall	Quantum Computing	Quantum Communications	Quantum Sensors
China	53.8	54.1	46.2	59.7
Japan	15.2	15.4	18.4	14.8
European Union	11.2	11.5	10	14.8
United States	10	9.6	6.5	4.5
South Korea	4.0	3.9	6.2	3.4
Taiwan	1.8	1.8	4.5	2.3
United Kingdom	1.2	1.0	3.4	0
Canada	0.8	0.6	1.6	0
Switzerland	0.6	0.6	1.0	0
Russia	0.6	0.6	0.6	0

Share of quantum patents by company headquarters (2000-21), McKinsey

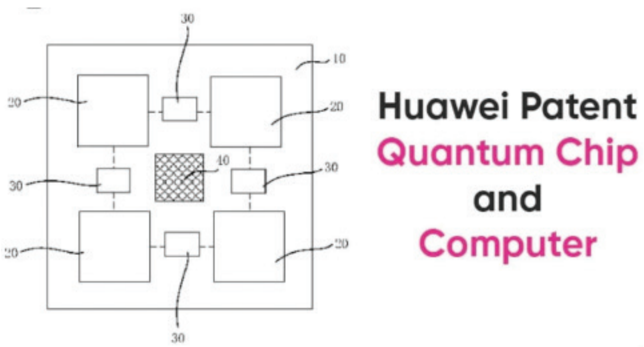
The Chinese ecosystem can also count on the support of private organizations, including Alibaba, which launched the Alibaba Quantum Computing Laboratory in 2015 with the aim of studying quantum cryptography and quantum computing, particularly with a view to securing e-commerce. Baidu launched the Institute for Quantum Computing in 2018 with a focus on software development. Huawei has also launched its Huawei HiQ or Huawei Cloud, a quantum simulation platform which enables quantum computing research. Huawei also shows huge interest in quantum hardware as well. Indeed, in June 2022, the company officially published a new patent in China for its quantum chip and computer (number CN114613758A). This new quantum chip aims to solve current issues of quantum chipsets production including the complexity of manufacturing a quantum chipset and the low yields of the quantum chipsets compared to the existing mainstream computing chipsets.

Origin Quantum[81]

Origin Quantum is based in Hefei (Anhui Province, China), established in 2017, is a spin-off from the Key Laboratory of Quantum Information at the CAS. The company is led by Guo Guangcan and Guo Guoping, eminent Chinese quantum computing scientists. In February 2023, the company unveiled "Wu Yuan", its quantum computer with 24-qubit superconducting quantum processor. The computer uses an unspecified number of quantum processing units (QPUs), but comes with a custom operating Origin Quantum develops quantum software, quantum chips, quantum measurement devices, quantum control systems, quantum cloud service and novel IP in quantum AI. In a roadmap published in 2022, the company said it hoped to realize 1,024-qubit quantum processors by 2025, which would allow it to solve specialized problems in various industries and develop new industry fields. In 2022, Origin Quantum raised $148.2m.

QBoson, Bose Quantum[82]

QBoson is based in Beijing and was founded in 2020 by Wen Kai (CEO) who hold a doctorate in quantum computing from Stanford University and previously worked at Google. Bose Quantum raised CNY 10m ($1.6m) in pre-Series A financing [83] from Seashell Capital, Litbyn and Born Capital. The company is developing an optical quantum computing platform with a classical computer + quantum AI architecture approach: the classical computer is responsible for the traditional general computing part, and the AI-based quantum computing is responsible for the huge computing power and accelerating problem solving. QBoson is equipped with a 1,000 qubit quan-



tum computer. The plan is to expand that quantum computer to a 1m-qubit prototype in the next three to four years, according to KR Asia.

SpinQ

SpinQ is a company based in Shenzhen which develops practical superconducting quantum computers, desktop NMR quantum computer and quantum computing cloud platform. Its field of application encompasses scientific research, education, drug research and development, finance and AI. SpinQ promises to put a quantum computer on your desktop at a $5,000 price. The company protected its innovations with patents. They already have their product, called Triangulum, available on the market. Triangulum is a desktop quantum computer that uses nuclear magnetic resonance (NMR) technology and has three qubits. It allows users to customize quantum circuits at the hardware level through pulse sequence engineering and external port programming. Triangulum is a low cost, no maintenance, and stable equipment, which is suitable for quantum computing education and simple scientific research. SpinQ's Chief Scientist nomination, as new Fellow of the American Physical Society for his pioneering work, has shed light on the company at the global scale.

TuringQ

TuringQ develops optical quantum chips and optical quantum computers. The company is developing optical quantum computer chips that can integrate large-scale photonic circuits based on lithium niobate on insulator photonic chips and femtosecond laser direct writing technology. In 2022, the company has completed a third round of Pre-Series A financing . The $40M-round was led by Oriza Holdings and followed by Wuxi Binhu State-owned Capital investment corporation, Legend Capital and Ambrum Capital. The company has now raised a total funding of $79M. The company is considered as a global leader in optical quantum chip technology, optical quantum measurement and control systems, optical quantum EDA software and quantum cloud platforms.

81. https://thequantuminsider.com/2021/04/20/9-companies-leading-the-quantum-technologies-race-in-china/
82. https://thequantuminsider.com/2021/06/28/reports-say-beijing-based-quantum-computing-startup-enters-angel-financing-round/
83. https://finance.sina.com.cn/tech/2022-02-28/doc-imcwipih5765844.shtml

Huayi Quantum

Huayi Quantum raised over CNY 100m ($15.6m) in angel financing led by Gaorong Capital and joined by Sequoia Capital China, Turing Ventures, Aurisco, and MiraclePlus. The company is a spin-off from Tsinghua University and is developing modular, standardized and large-scale quantum computers based on ion trap technology. The company aims to have a quantum system of 100 to 200 qubits and plans to have its own quantum cloud computing platform.

Centre de recherche en ingénierie de l'informatique quantique d'Anhui

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South Korea[84]

In January 2023, President Yoon Suk visited the Swiss Federal Institute of Technology in Zurich and met leading experts in quantum technologies in order to expand Korean strategy in the quantum field. This event shows the Korean government's interest in being an industrial game changer within the next 10 years.

In recent years, there has been an increasing number of companies and research labs focusing on developing quantum technologies, especially quantum computing.

The quantum computing research field will benefit from a state support for a 5 years of research KRW 44.5B (US$39.7M). By 2023, the government hopes to have completed a demonstration of a realistic 5-qubit quantum computer system. The government also unveiled its plan to have a superconducting 50-qubit quantum computer by 2026 to catch up with the US, China and Europe.

Among the main Korean players in the field, the Korean Advanced Institute of Science and Technology (KAIST) is leading the way in quantum computing research. One of their subjects of interest is QKD implementation technologies. KAIST also works with the IBM Quantum Network, in order to improve Korean technology's global position in quantum computing.

SK Telecom is very dedicated to quantum communication networks. The company also expanded its expertise to quantum cryptography. SK telecom has become a leading company in the sector as two of their technologies have been approved worldwide as the standard for quantum cryptography communication networks.

The Korean Ministry of Science and ICT announced in 2022 that quantum cryptography communication networks are in the process of testing at a total of 26 organizations in the public and private sectors. SK broadband, a broadband internet service operator in South Korea, has applied quantum cryptography communication technology to a newly established national convergence network as a perfect firewall against eavesdropping or hacking attacks to steal national confidentiality and information.

Samsung is also exploring the possibilities that Quantum Technology is offering. Indeed, In April, 2022, SK Telecom, Samsung and ID Quantique (acquired by SK Telecom in 2018) have worked together to release the "Galaxy Quantum 3", the third Samsung smartphone equipped with the world's smallest Quantum Random Number Generator (QRNG) chipset designed by ID Quantique.

Japan

Japan's quantum ecosystem stands out for its richness, both on the academic and the industrial sides. Government of Japan has initiatives several program to enhance quantum technology ecosystem as well as quantum workforce in Japan.

Through Moonshot 2050 program, Japan aims to achieve large-scale fault-tolerant quantum computers by 2050. Under Integrated Innovation Strategy 2022, government has set the target of 10 million quantum technology users, achieve production on the scale of 50 trillion yen, and create quantum unicorn startups by 2030. On April 2022, the Integrated Innovation Strategy Promotion Council as part of its "Vision for the Quantum Future Society" proposed the creation of a Quantum Technology International Collaboration Hub at Okinawa Institute of Science and Technology (OIST). In October 2022, OIST launched the OIST Center for Quantum Technologies (OQT) to drive research and innovation for the Quantum Technology International Collaboration Hub.

MEXT - Quantum Leap Flagship Program (MEXT Q-LEAP), a ten-year R&D program started in 2018, to invest in Quantum simulator, Quantum computer, Quantum metrology & sensing, and next generation laser. MEXT Q-LEAP has further set up the Human Resources Development Program to prepare workforce who will lead quantum technology in future and will also promote the development of common education programs. The Quantum Academy of Science and Technology, a common core program of the Q-LEAP, creates a curriculum for quantum technology, provide online education, intern program, develop online courses and an educational material database, as well as other activities in partnership with member universities such as Quantum Academy of Science and Technology are currently the University of Tokyo, Nagoya University, Kyushu University, and Keio University.

As of January 2023, there are 66 registered quantum technol-

84. https://ethz.ch/en/news-and-events/eth-news/news/2023/01/visit-of-the-president-of-the-republic-of-korea-to-eth-zurich.html

ogy projects under Future Society Initiative (FSI) of the University of Tokyo. In September 2021, major Japanese companies such as Toshiba, Toyota, Nippon, Hitachi, Mitsubishi Chemical, and Fujitsu came together to establish the Quantum Strategic Industry Alliance for Revolution (Q-STAR) to promote initiatives in quantum technologies.

Japanese quantum public research is conducted by a number of independent agencies, including the Japan Science and Technology Agency (JST) and the Institute of Physical and Chemical Research (RIKEN), both under the aegis of the Ministry of Research. These agencies then divide the areas of quantum research thematically.

Major Japanese players offering Quantum Computer components

Device	Companies
Refrigeration System	Ulvac Crygenics
Control Unit	QuEl, Inc.
Cryoresistive Cable	CoaxCo., Ltd, Kawashina Packaging Machinery Ltd
Low-noise Power Source	NF Holdings Corporation
Low-noise Amplifier	Japan Communication Equipment
Magnetic Shield	Ohtama Co., Ltd.
Measuring Equipment	Anritsu Corporation

Diamond Reporting

Hub Site	Organization	Contact Information
Quantum computer development hub	RIKEN	Office of the Center Director, RIKEN Center for Quantum Computing: quantum_info[at]ml.riken.jp
Quantum life science hub	QST	Quantum Life Science Research Hub, Head Quarter of Research Hub: qlsrh-info[at]qst.go.jp
Quantum secure network hub	NICT	NICT Quantum ICT Collaboration Center, General Planning Office: qictcc-info[at]ml.nict.go.jp
Quantum devices development hub	AIST	Department of Electronics and Manufacturing, Research Planning Office: rp-eleman-ml[at]aist.go.jp
Quantum materials hub	NIMS	Corporate Strategy Office, Corporate Planning Division: nims_qmh[at]ml.nims.go.jp
Quantum computing application hub	University of Tokyo and business alliance	University Corporate Collaboration Department, Corporate Partnership Group (Quantum Innovation Initiative Consortium Office) : kyosokenkyu.adm[at]gs.mail.u-tokyo.ac.jp
Quantum software research hub	Osaka University	Center for Quantum Information and Quantum Biology (QIQB) : hp[at]qiqb.osaka-u.ac.jp
Quantum sensors hub	Tokyo Institute of Technology	?Quantum navigation unit? Mikio Kozuma, Professor, Institute of Innovative Research (Quantum navigation unit) : kozuma[at]nav.iir.titech.ac.jp ?Q-LEAP? Mutsuko Hatano, Professor, Department of Electrical and Electronic Engineering (Q-LEAP) : hatano.m.ab[at]m.titech.ac.jp

Overview of the Japanese quantum research apparatus by quantum fields

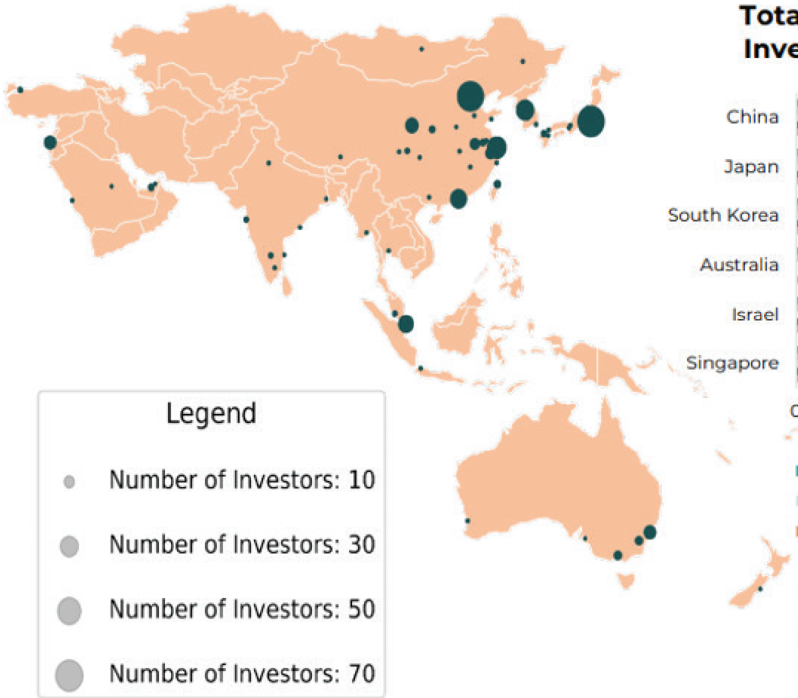
Quantum Information Company Ecosystem in Asia[85]

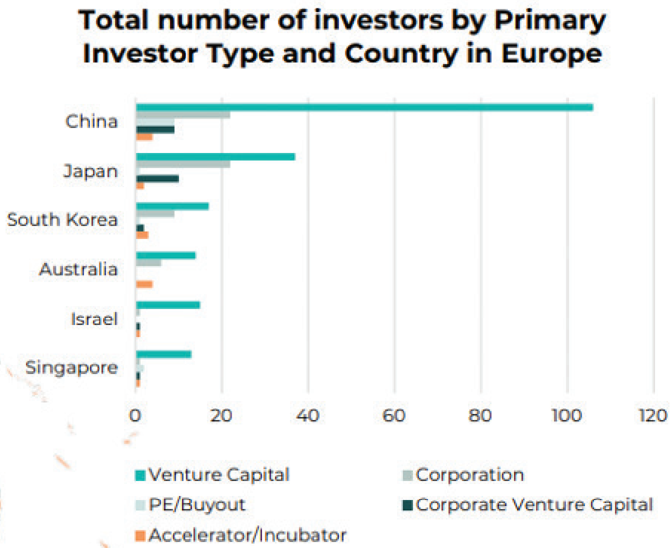
HQ Location (Country)	Number of Companies
China	54
Japan	23
Australia	22
Israel	12
India	12
South Korea	10
Singapore	10

HQ Location (City)	Number of Companies
Tokyo, Japan	14
Beijing, China	12
Shanghai, China	9
Singapore, Singapore	9
Sydney, Australia	6
Shenzhen, China	6
Suzhou, China	4
Hangzhou, China	4
Tel Aviv, Israel	4
Seoul, South Korea	3
Bengaluru, India	3

85. https://www.washingtontechnology.org/wp-content/uploads/2023/01/WTIA-Quantum-Information-Systems-Landscape_Final.pdf

Japan is second to China in terms of the number of companies involved in the Quantum information system. In terms of City, Tokyo is home to the most number of start-ups followed by Beijing in Asia.





HQ Country/Territory	Total number of Investors in QIS
China	177
Japan	76
South Korea	35
Australia	29
Israel	27
Singapore	22
Hong Kong	19

Japan has the most number of investors in QIS, second only to China. The start-up ecosystem is mainly focused on the software side with, for example, companies such as A*Quantum, Tokyo Quantum Computing or Sigma-I.

A*Quantum

Founded in 2020 by Sousa Sakura, A*Quantum defines itself as "a leader in quantum computing not only in Japan but also in the world by solving real-world business problems in logistics and advertising today". The company raised a $2.8M seed funding.

Tokyo Quantum Computing

Founded in 2017 in Tokyo by Dr. Chiaki Yamaguchi. TQC is providing a set of computer program source codes for massive simulations of quantum annealing.

Japanese investors are also increasingly interested in quantum technologies. For example, NTT DOCOMO Ventures, Inc (headquartered in Minato-ku, Tokyo, Japan; President and CEO, Takayuki Inagawa) has invested in Quantum Dots Laser which is an offshoot of Fujitsu Limited. The company is targeting the semiconductor industry but also the medical field (for patients with ametropia or corneal opacity and weak-sighted individuals).

QunaSys

QunaSys is a Tokyo-based quantum computing software company founded in 2018. In 2022, QunaSys raised $10M in series B funding stage the led by JIC Venture Growth Investments, with participation from ANRI, Fujitsu Ventures Fund LLC, Global Brain, HPC Systems Inc., JST SUCCESS Program, MUFJ Capital, Shinsei Corporate Investment Limited, and Zeon Corporation. In July 2020, QunaSys established QPARC, a Japanese consortium to study quantum computing applicability of quantum computers. QunaSys collaborated with the Pistoia Alliance in the development of quantum computing in the Pharma Industry and the Quantum Flagship program to re-train workers with quantum computing for chemistry learning programs. QunaSys also partnered with PsiQuantum on a joint research project to advance the use of quantum computing in the chemistry industry.

CORPORATE INTEREST

Mitsubishi Chemical

In 2019, Mitsubishi Chemical and IBM simulated the initial steps of the reaction mechanism between lithium and oxygen in lithium-air (Li-air) batteries on a quantum computer. Mitsubishi Chemical, in collaboration with IBM and IBM Q Hub at Keio University teams, is also exploring how to use quantum computers to create accurate simulations of a chemical reaction at a molecular level. Mitsubishi Chemical is also one of the founding members of Quantum Strategic Industry Alliance for Revolution (Q-STAR) established in 2021 to promote initiatives in quantum technologies.

Fujitsu

Fujitsu is engaged in gate-based quantum computing technology starting from quantum devices to software and applications. Fujitsu has developed a quantum computer simulator capable of handling 36 qubit quantum circuits on a cluster system. Fujitsu also conducted trials of its quantum simulator to assess vulnerability of RSA cryptosystem to potential quantum computer cryptography threat. In 2021, Fujitsu collaborated with Osaka University to establish Fujitsu Quantum Computing Joint Research Division for research and development on fault-tolerant quantum computers. Fujitsu has been working with Riken since 2021 through Riken RQC-Fujitsu Collaboration Center on superconducting quantum computers and plans to start selling quantum computers in 2023. Fujitsu will also offer a quantum computer to the Galician Supercomputing Center (Spain). Fujitsu also collaborated with QuTech and Element Six to demonstrate the fault-tolerant operation of a quantum bit using a quantum processor based on spin qubits in diamond.

NEC

NEC is working to establish practical applications for quantum annealers and is also developing annealing simulators that can handle large-scale combinatorial optimization problems. The New Energy and Industrial Technology Development Organization (NEDO) selected NEC to participate in the "Project for Innovative AI Chips and Next-Generation Computing Technology Development. In September 2022, NEC and NEC Fielding, Ltd., maintenance services provider for ICT equipment, introduced a delivery planning system for maintenance parts utilizing quantum computing in Tokyo that reduced planning next-day delivery of maintenance parts by 90%. NEC has also developed a four qubit unit cell of the LHZ scheme that facilitates scaling up to a fully-connected architecture using superconducting parametron and circuit coupling technology.

Toshiba

Toshiba has been researching quantum cryptography since 2003 and offers QKD solutions. In April 2022, Toshiba, and BT along with EY launched the first commercial trial of a quantum-secured metro network for transmission of data between multiple physical locations in London over standard fibre optic links using QKD. In 2022, Toshiba, Tohoku University Tohoku Medical Megabank Organization, Tohoku University Hospital, and the National Institute of Information and Communications Technology (NICT) demonstrated a personalized healthcare system that stores genome data from many individuals in multiple locations secured on QKD link. Toshiba worked with Ciena and JPMorgan Chase demonstrated the viability of a 800 Gbps QKD-secured optical channel in mission-critical, metro-scale operational environments.

Mitsui

In October 2022, Mitsui and Quantinuum signed a strategic partnership agreement to collaborate in the delivery of quantum computing in Japan and the Asia-Pacific region. The companies will work on development of business use cases and business models utilizing quantum computing.

JSR Corporation

JSR and IBM are working on development of quantum chemical calculation technology focused on actual materials. In 2022, JSR also collaborated with Quantinuum to explore the application of quantum computing methods to model semiconducting materials, such as metal complexes and transition metal oxides.

Quantum Practical Application Research Consortium (QPARC)

QPARC is a community that offers a series of lecture courses and use-case development activity, targeting industrial engineers/ researchers involved in material development. Leading community members include JSR, Toyota, Bridgestone, AGC, Daikin, Fujifilm, Murata, and Panasonic among others. IBM research, Google, Microsoft, Rigetti, and IonQ are collaborative sponsors of QPARC.

Ministry of Economy, Trade and Industry (METI)

METI is working to drive the industrialization and social implementation of technologies such as quantum computers. METI is also assessing measures such as establishing a global-level base in National Institute of Advanced Industrial Science and Technology (AIST) for collaboration between industry, academia, and government, including support toward developing human resources and applications. In 2022, Quantum Technology Innovation Council formulated the Quantum Future Society Vision that includes increasing the production value by quantum technology to 50 trillion yen by 2030 and encouraging the development of made-in-Japan quantum computers.

India

India is witnessing a surge in interest in Quantum technology across industries, academia, government, and start-ups. According to NASSCOM, a not-for-profit industry association, Quantum technology has the potential to add $310B cumulative value to the Indian economy by 2030. India aims to build a quantum network and commercialize quantum security products for high-priority sectors. Government is the key sponsor of quantum initiatives in India. The Government of India has allocated nearly $1B for the National Mission on Quantum Technologies and Applications (NMQTA) for a period of five years that will act as a catalyst for growth of the quantum ecosystem in India. NMQTA further aims to create more than 25,000 quantum workforce in India over the next five to seven years. The Department of Science & Technology has also set up Quantum-Enabled Science & Technology (QuEST) and will invest a sum of $11.2M over the next three years to facilitate research in the Quantum field. AICTE Training and Learning (ATAL) Academy is offering various faculty development programs on quantum computing.

Indian Institute of Science launched its Quantum Technology Initiative (IQTI) in September 2020 to establish a strong foundation for quantum technologies and create a framework to encourage collaborations between physicists, material scientists, computer scientists, and engineers. Leading research institutes such as Tata Institute of Fundamental Research, and The Quantum Information, Control and Thermodynamics Group at IIT Bombay offer various summer projects and training opportunities to graduate and postgraduate students and researchers. Premier academic institutions in India have partnered with IBM to provide access to quantum systems, quantum learning resources, and quantum tools over the cloud for education and research purposes. Indian Institute of Technology (IIT) Madras collaborated with IBM Quantum Network to advance quantum computing skill development and research for the industries in India. Microsoft Garage India partnered with IIT Roorkee to conduct lectures on quantum computing for an entire semester.

India has the opportunity to create quantum-based products and services and offer them to customers globally along with transforming Indian industry by leveraging quantum technology. Major IT companies such as TCS, Infosys, Tech Mahindra, HCL, Mphasis are accelerating the development of practical, quantum-based use cases. Start-ups such as BosonQ Psi, Qulabs, and QNulabs are developing solutions based on Quantum technology.

QNu Labs

QNu Labs was incubated at IIT-Madras Research Park in 2016. The company offers QRNG, QKD, PQC solutions, and Entropy as a service that help mitigate data security risks across verticals such as defence, government, healthcare, financial services, and telecommunication. The company is building quantum technology to secure IoT devices, POS machines, and mobile devices. In 2022, QNu Labs raised an undisclosed amount of funding from deep tech venture firm Speciale Invest. In Dec 2022, Indian National Space Promotion and Authorisation Centre (IN-SPACe) signed a memorandum of understanding with QNu Labs to develop Indian Satellite QKD products.

BosonQ Psi

BosonQ Psi, a Bengaluru-based start-up founded in 2020, offers BQPhy, a Quantum-powered simulation-as-a-service (Q-SaaS) based software suite. BosonQ Psi has integrated BQ-Phy with Strangeworks' hardware ecosystem. The company provides structural mechanics, thermal sciences, and design optimization capabilities. The company is also exploring new ways to perform simulations for fault-tolerant quantum computers. In 2022, BosonQ Psi raised a pre-seed funding round of $525K led by 3to1 Capital.

Qulabs Software

Qulabs, a Hyderabad-based start-up founded in 2018, is working to provide quantum communication and quantum computing based solutions. Qulabs is developing solutions based on quantum principles in computing, communications, sensing, chemistry, cryptography, imaging, and mechanics.

Center for Development of Advanced Computing

Centre for Development of Advanced Computing (C-DAC) is a research and development organization of the Ministry of Electronics and Information Technology (MeitY) for carrying out R&D in IT, Electronics and associated areas. C-DAC has developed a Quantum Computing simulator Qsim capable of simulating the quantum gate model. C-DAC is also working on other quantum fields such as quantum communication, post-quantum cryptography algorithms, and quantum sensors. In 2022, C-DAC met a delegation from Finland to develop bilateral cooperation on quantum technologies.

Center for Development of Advanced Computing

Singapore's quantum ecosystem is structured around the Center for Quantum Technologies (CQT) that benefits from an annual funding of about $15M. The CQT brings together about 60 research fellows and 60 PhD students covering all the fields of quantum technologies.

Six startups emerged from the CQT:

- Entropica Labs (quantum algorithms);
- Horizon Quantum Computing (software);
- Innovatus Q (hybrid algorithms);
- S-Fifteen Instruments (quantum cryptography);
- SpeQtral (satellite QKD).

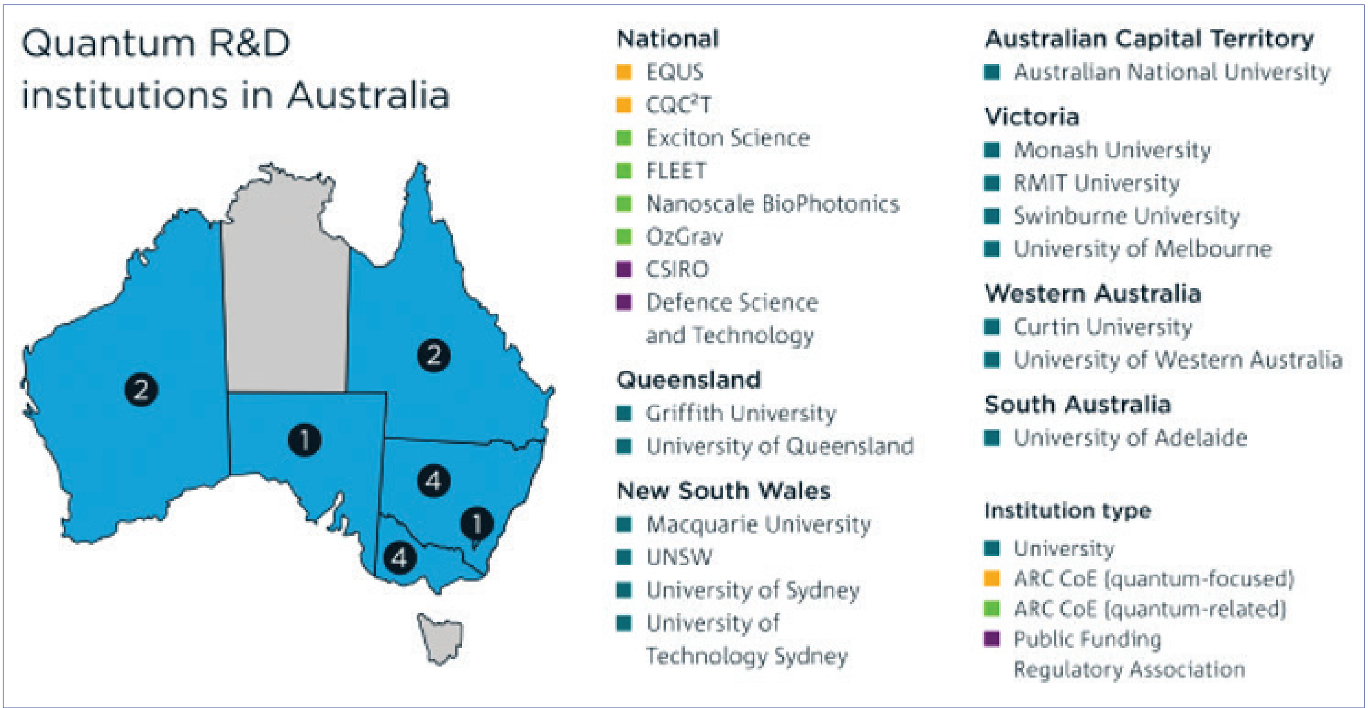
The Singapore government is also very active in the quantum sphere abroad through its sovereign fund Temasek which invested in Pasqal and PsiQuantum. Moreover, since 2021, The National University of Singapore (NUS) and Thales have started a two-year partnership to develop and test quantum technologies for commercial applications. This partnership is in line with Singapore's Quantum Engineering Programme (QEP) which has invested $121.6M to advance Singapore's quantum ecosystem. Quantum communication and security, as well as quantum sensing are two pillars of the programme. Thanks to those funding, NUS quantum research has been very advanced in some quantum topics such as magnetic skyrmions and spintronics. France also has its own research team in Singapore, the CNRS MajuLab, run by Alexia Auffèves since January 2023.

2 REST OF THE WORLD

Australia

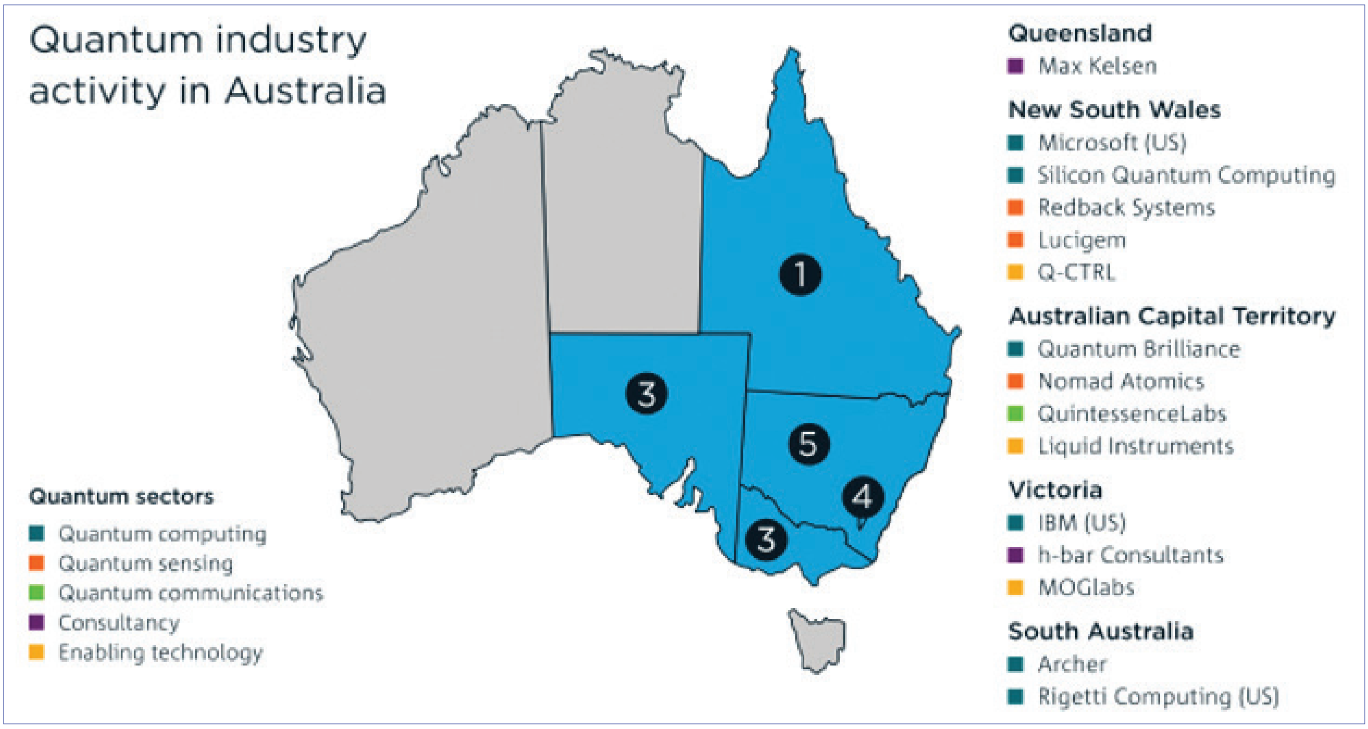
Australia is showing a growing interest in quantum technologies, as early as 2015 public money started to flow into the quantum sector with an allocation of $19M for the Center for Quantum Computation and Communication Technology.

In terms of research, Australia benefits from a structured and efficient system notably thanks to the establishment, in 2017, of the new quantum-focused centers of Excellence among which the FLEET (Future Low-Energy Electronics Technologies) located in Monash University and the Exciton Science Located in the University of Melbourne.



Overview of the Quantum R&D ecosystem in Australia

In May 2020, Australia launched the CSIRO plan, which aims to make the quantum industry a $4B market with 16,000 employees by 2040. To achieve these objectives, this plan is accompanied by a $175M public funding package (2022 figures).



Overview of the Quantum Industry activity in Australia

The start-up ecosystem has recently been marked by the emergence of some very promising companies:

Diraq

Diraq's ambition is to be the global leader in full-stack quantum computing using silicon based technologies. It was founded in 2022 by Andrew Dzurak and the company raised $13M in Series A funding.

SQC

Founded by Michelle Simons, Silicon Quantum Computing (SQC) is aimed to develop a silicon based quantum processor. As of today, the company is considered a pioneer in the field of silicon quantum computing.

Quantum Brilliance

Quantum Brilliance is a German-Australian manufacturer of quantum computing hardware providing diamond quantum accelerators supported by a full stack of software and application tools. In 2022, the company announced a joint research project with the Fraunhofer Institute for Applied Solid State Physics (IAF) and the University of Ulm to develop new techniques for the fabrication and control of diamond-based quantum microprocessors. The goal of this €19.9 million collaboration is to solve two key challenges surrounding diamond-based quantum computers by 2025. The project is 74% funded by the German Federal Ministry of Education and Research. Quantum Brilliance is among the pioneers in using NV Centers in the synthetically created diamonds for quantum computing.

Q-CTRL

Q-CTRL is the first Australian start-up coming from the Australia Research Council Centre of Excellence for Engineered Quantum Systems (EQuS). Its main product called Black Opal is a hardware-agnostic platform that can run on qubit processor quantum computers to reduce decoherence and errors at the physical layer. Quantum systems are very sensitive to decoherence, but Q-Ctrl's suite of controls can stabilize fragile systems, and effectively shift the decoherence back.The start-up has benefited from investment coming from Sequoia China, DCVC (Data Collective) and Horizon Ventures.

Analog quantum circuits

As solid-state quantum computers depend on high performance electronics to send and receive signals to the quantum bits, Analog Quantum Circuits is developing fabrication processes to integrate these devices "on-chip", so that the future generations of quantum technologies can scale. The company have released several papers:

- Passive superconducting circulator on a chip, 2022, arXiv
- Operating a passive on-chip superconducting circulator: Device control and quasiparticle effects, 2021, article, arXiv
- Nonreciprocity realized with quantum nonlinearity, 2018, article, arXiv
- Passive on-chip superconducting circulator using a ring of tunnel junctions, 2018, article, arXiv

QuintescenceLabs

In 2021, QuintescenceLabs has raised a $25M Series B to scale its quantum-safe cybersecurity solutions. The start-up uses quantum physics to build data security tools and has developed a quantum random number generator (QRNG). The start-up made the approved products list for a $2 billion program run by the US Department of Homeland Security, focused on strengthening data protection across participating agencies.

Canada

"Quantum technologies will shape the course of the future and Canada is at the forefront, leading the way. The National Quantum Strategy will support a resilient economy by strengthening our research, businesses and talent, giving Canada a competitive advantage for decades to come. I look forward to collaborating with businesses, researchers and academia as we build our quantum future."

Canada shows a real desire to establish itself as a leader in quantum. To support this ambition, they invested more than $1B on quantum technologies driven by these three pillars :

- Computing hardware and software: to make Canada a world leader in the continued development, deployment and use of these technologies
- Communications: to equip Canada with a national secure quantum communications network and post-quantum cryptography capabilities
- Sensors: to support Canadian developers and early adopters of new quantum sensing technologies

These investments led to an emerging start-up ecosystem, among which:

Nord Quantique

Nord Quantique is a spinoff from Sherbrooke University cofounded by Philippe Saint-Jean and Julien Camirand Lemyre. The Quebec-based start-up aims to develop superconducting circuits that can mitigate errors on every individual qubits paving the way for a fault-tolerant quantum computer.

Xanadu

Xanadu is a full-stack developer of quantum photonic processors and an open-source quantum software platform called Strawberry Fields. They have also developed Borealis, a programmable photonic quantum computer with 216 squeezed-state qubits that outperforms the best classical supercomputers at a specific task, available to people everywhere via Xanadu Cloud. The start-up raised a stunning $100B in a Series C funding round in late 2022.

D-Wave systems

D-Wave systems is a full stack technology provider. They provide cloud services, application development tools, and other services that support end to end quantum computing for enterprises and developers. The business focuses on superconducting qubits (both annealing and gate based implementations). In August 2022, D-Wave completed its planned merger with DPCM Capital, a SPAC (Special Purpose Acquisition Company), taking the company public on the New York Stock Exchange.

Israël

Israel started its quantum plan relatively late compared to other major countries and to the country's innovation-oriented culture.

In 2018, the country launched a 75M funding plan to better fund fundamental research in quantum physics. The following year, a special commission was tasked by the government to put in place a $350M plan over six years to accelerate quantum research, training and industrial and military applications. In 2021, Israël announced that it planned to build its own quantum computer, allocating a budget of $60M taken out of the six year plan.

Classiq

Classiq is developing a QAD (Quantum Algorithms Design) for the conception and optimization of quantum algorithms circuits. Their technology helps quantum teams to automate the process of converting high-level functional models into optimized quantum circuits. Users can combine embedded quantum modules with those they have defined, then specify constraints such as the number of gates, circuit depth and entanglement levels. The Classiq platform will then synthesize an optimized circuit that would have required weeks if built manually, its publisher says.

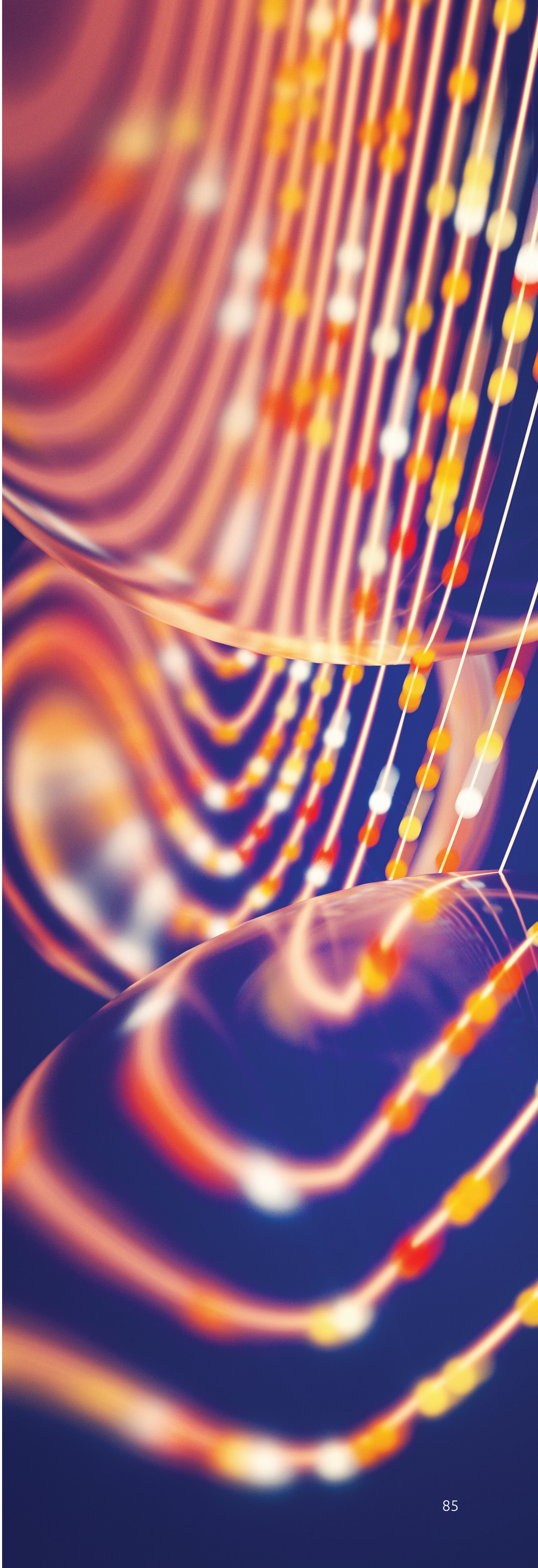
In February, the start-up raised a 33M$ Series B funding with the participation of HPE and Samsung through their respective funds (Hewlett Packard Pathfinder and Samsung Next) as leads. The round was also followed by Phoenix (insurance group), Spike Ventures and private investors (Lip-Bu Tan, ex-CEO of Cadence Design Systems, and Harvey Jones, ex-CEO of Synopsys).

Quantum Machines

Quantum Machines develops quantum control solutions that accelerate the realization of practical quantum computers. The start-up announced its $20m in funding, bringing the company's total funding of $100 millions. Moreover, Quantum machines was chosen last year to lead the establishment of the Israel Quantum Computing Center in conjunction with a consortium of international companies.

Quantum Source

Quantum source was founded in 2021 by Oded Melamed, Gil Semo, Dan Charash, and Professor Barak Dayan, intends to enable the scaling quantum computers to millions of qubits with its proprietary photonic technology. Currently, the company employs 25 physicists and engineers, 15 Ph.Ds. Quantum Source is the first funded Israeli company working on the qubit modality, which is touted to offer an alternative route to useful quantum computers. In 2022, the start-up raised a $15 million Seed funding round co-led by Grove Ventures, Pitango First and Eclipse Ventures.



D | QUANTUM AND COOPERATION: STATE OF THE ART OF STRATEGIC PARTNERSHIPS

1 INTRA EUROPEAN PARTNERSHIPS

France and The Netherlands[86]

In August 2021, The Dutch and French governments signed a memorandum of Understanding (MoU) to strengthen their bilateral cooperation in quantum technologies. Both governments committed significant sums to the quantum field, which amounted to respectively €615M and €1.8B. This partnership shows that both countries recognize that the required ecosystem and workforce are larger than any country could build on its own, and therefore that a partnership and collaboration is more than necessary in order to keep the pace in the quantum field. Europe is certainly conducive to large scale development. However certain topics could go faster with smaller scale partnerships. On the one hand, the Netherlands expertise lies in building complex equipment, like lithography equipment for the semiconductor industry. On the other hand, France is skilled at computing technology and optics, making it complementary to the Dutch expertise on equipment development. Moreover, both of them are conducting research projects on spin based quantum bits. Finally, besides the scientific aspects, the manufacturing infrastructure in France and the Netherlands are complementary, which makes this partnership naturally sensible.

In Dec. 2022, The Dutch, French and German national governments have signed a joint statement[87] on their intent to strengthen collaboration on quantum technology. This effort to increase synergies will not only include the research field but other areas including education, policy, implementation and use case development.

2 INTERNATIONAL PARTNERSHIPS

France & USA

In December 2022, the US and France agreed to deepen collaboration on quantum technologies as both countries were interested in increasing technical and scientific exchange around what they consider a shared priority. White House Office of Science and Technology Policy Director Arati Prabhakar signed a joint statement on cooperation in quantum information science (QIS) and technology on behalf of the US together with France's minister for higher education and research, Sylvie Retailleau.

The statement comes as French President Emmanuel Macron visits the US and builds on the Agreement on Science and Technology Cooperation signed in 2018 and the Joint Statement on Science and Technology Cooperation signed in 2021 by both countries - the latter identifying as a focus. This statement covers the development of quantum computers, quantum networks, quantum sensors, as well as the post-quantum cryptography.

86. https://www.institutmontaigne.org/en/analysis/dutch-and-french-cooperation-quantum-innovation
87. Quantum Delta, The Netherlands, France and Germany intend to join forces to put Europe ahead in the quantum tech race, 19 Dec, 2022

Pasqal and the University of Chicago also announced[88] their collaboration on neutral atom quantum computing to enable high-fidelity qubit control, as foreign companies are increasingly working with US institutions on QIS. The collaboration is done with the lab of Hannes Bernien, professor of molecular engineering at the Pritzker School of Molecular Engineering at the University of Chicago and world expert in quantum many-body physics and quantum information processing. Bernien was postdoc in the Lukin group at Harvard, working on the experiment that led to Quera. As the Quera and Pasqal teams have always been synchronized, the partnership with Hannes should not come as a surprise.

US President Joe Biden's administration has established several bilateral alliances with allies focused on advancing quantum technology and previously made similar agreements with Switzerland and Australia.

In December 2022, the French embassy in Washington transmitted the first diplomatic letter encrypted[89] to withstand future quantum computers. The transmission was part of President Emmanuel Macron's Quantum Plan, unveiled in January 2021. The action is in line with the G7 forum's call for cooperation on key matters relating to the growth of the quantum industry and the development of post-quantum cryptography solutions during its Munich meeting in 2022.

According to a statement from the Paris foreign ministry, the embassy sent the encrypted message using software developed by startup CryptoNext. CryptoNext is creating post-quantum cryptography solutions as a result of research by the French National Institute for Research in Digital Science and Technology (INRIA), the French National Centre for Scientific Research and Sorbonne University (CNRS).

France & Canada

CNRS and Canadian universities have begun to build an international network in quantum science and technology. Announced in 2021 with a budget of $360M over seven years - and building on the already substantial investments made between 2009 and 2020 - the Canadian strategy received additional funding from the government to invest in the same scientific and technological focus areas. The creation of a French-Canadian network is an example of the large-scale research synergies possible between the two countries. In 2022, the CNRS has strengthened its presence in Canada. After opening its ninth office abroad in Canada at the beginning of the year, just before inaugurating its tenth in Australia, the CNRS is now strengthening its presence there with the creation of two International Research Laboratories (IRL)

The quantum network is a natural evolution in the collaboration between the two countries, which are already numerous and win-win. This is demonstrated by the undeniable success of the Quantum Frontiers Laboratory, an International Research Laboratory (IRL) based at Sherbrooke. There is expertise in Canada that does not exist in France, as well as the other way around.

With an official launch planned in January 2023, the network is led by the CNRS, and currently involves 16 universities, eight in each country, all of which are, like the CNRS, major actors in the quantum field. In addition to the four scientific coordinators with their respective national vision, representatives for local scientists have been designated on each campus to establish ties with the communities of each member institution. The IRN is also open toward the business world, and is designed to include all willing French and Canadian actors who are collaborating or hope to collaborate on the subject.

With the support of the Quebec government, Quantum innovation zones have been created which call on various socio-economic players including businesses, economic organizations, research and educational institutions and municipalities. The Zone relies on an ecosystem established by world-renowned leadership in quantum research at the University of Sherbrooke and the Quantum Institute, where high quality fundamental research is conducted to develop the quantum technologies. The objective of these zones of innovation is to collaborate around promising technological sectors, to attract talent, entrepreneurs, major contractors and researchers from Quebec and elsewhere, in defined geographical areas where industrial, entrepreneurial, knowledge-based, connected and collaborative activities.

On 15th Nov, 2022, EDF, Exaion Inc (based in Sherbrooke), PASQAL, and the Quantum Innovation Zone of Sherbrooke have built a partnership to create the first open algorithms center of excellence to develop solutions for the energy industry using the combined capabilities of high-performance computing and quantum computing. As the world faces unprecedented energy challenges, the goal of the partnership is to provide the energy industry with real-world solutions based on quantum computing in 2024. This center of excellence is called QuaTERA (Quantum Technologies Energy Result Accelerator), aims to form an ecosystem of partnerships at the intersection of the energy industry, classical/quantum technologies, and hybrid algorithms to design and develop solutions to solve these challenges.

88. InsideHPC, PASQAL and University of Chicago Anounce Neutral Atoms Quantum Computing Collaboration, Nov 30, 2022
89. LeMonde, Post-Quantum cryptography: What is Emmanuel Macron talking about ?, 4 Dec, 2022

The synergies between France and Canada should thrive in the coming years and serve as a base for quantum research and excellence. Indeed, Pasqal has recently opened an office at Sherbrooke which demonstrates Canada's interest in French expertise, and vice versa. Vincent Aimez, who is responsible for Sherbrooke university partnerships, has paved the way in the past few years for many strategic industrial partnerships in the field of micro-nanotechnology, including the establishment of the first two innovation zones in Quebec, Sherbrooke Quantum and the Technum Quebec innovation zone in Bromont.

France, Japan and Singapore joint laboratories, In addition to China, Australia, the US and Canada.[90]

Partnerships between France and Asia are more scarce in quantum technologies, which remains a weak point and an improvement axis for the French Quantum strategy.

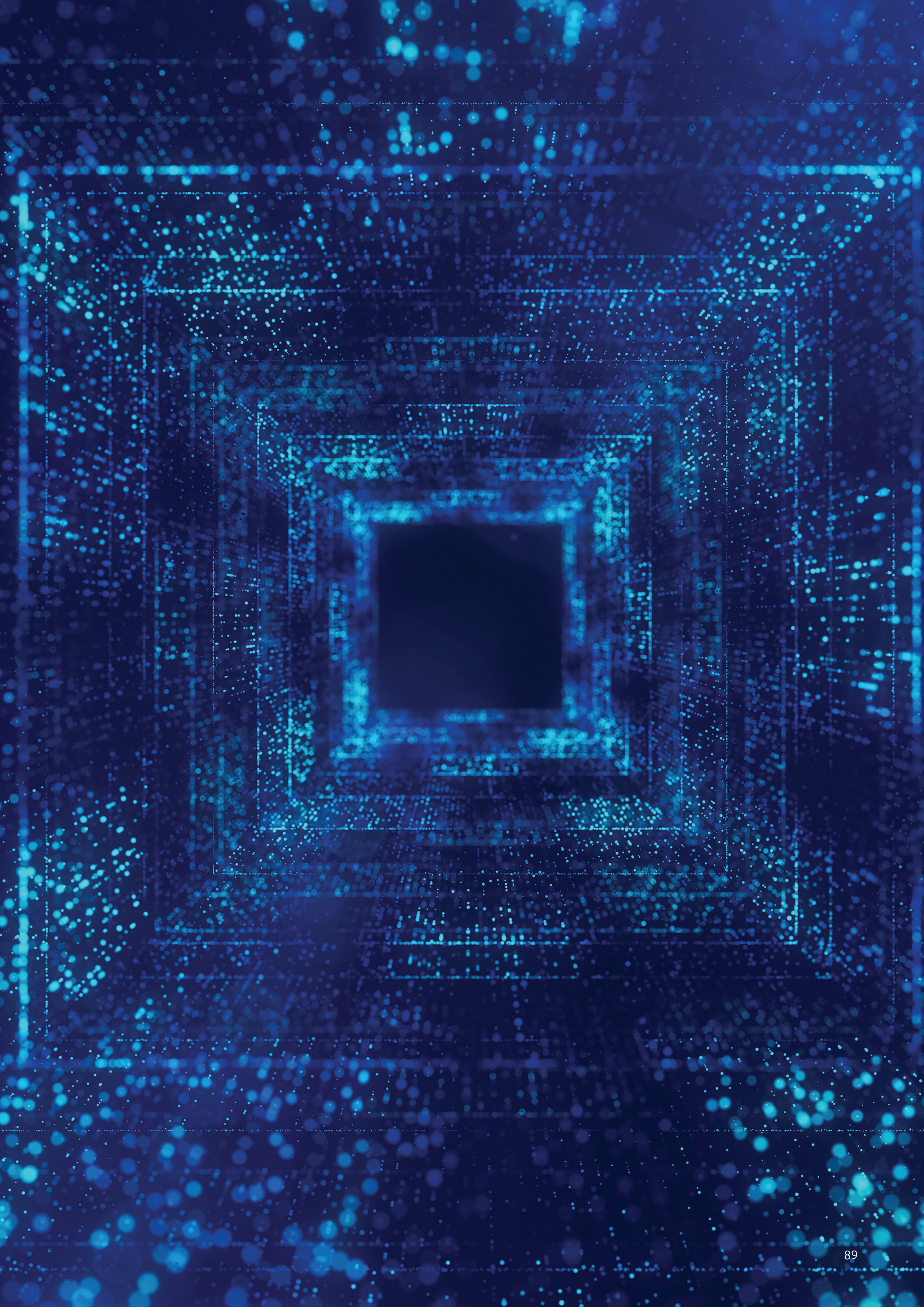
However, some academic partnerships serve as small bridges between the two ecosystems. Indeed, the Japanese-French Laboratory for Informatics (JFLI) was created in 2009 and is based in Tokyo and hosted at both the NUU and the University of Tokyo. It brings together researchers from the University of Tokyo. This joint laboratory brings together researchers from the Universities of Tokyo, Keio, NII, CNRS, Sorbonne University, Inria and Université Paris-Sud. This multidisciplinary team ranges from fundamental physics to algorithms and studies the feasibility of large-scale quantum computing as well as quantum cryptography. In 2018, the France-Singapore collaboration in quantum physics and quantum information was renewed for five years on 23 January 2018 in the presence of the French Minister for Higher Education, Research and Innovation and the Ambassador of France to Singapore. This partnership called IMU Majulab was established in 2014 as a joint research unit of the National University of Singapore, the Nanyang Technological University, the CNRS and the University of Nice Sophia Antipolis.

As several Asian countries are racing to get quantum computers fully operational. Technological development has been very US-centric, but now Asian nations don't want to be left behind on quantum computing. Thus, Nation states like India, Japan and China don't want to see the kind of hegemony that's arisen where the large cloud aggregators are mostly American. Quantum computing was already gathering pace in Japan and elsewhere in Asia when the University of Tokyo and IBM launched their new quantum computer last year. The computer was the second such system built outside the United States by IBM. The university and IBM have led the Quantum Innovation Initiative Consortium alongside heavyweights of Japanese industry like Toyota and Sony. China has committed a a lot of ressources to the quantum race. Researchers have touted breakthroughs and debates on whether China has surpassed the US on some fronts. India, for its part, announced plans earlier this year to invest $1B in a five-year plan to develop a quantum computer in the country.

There are two major areas where quantum's breakthrough will be felt : industry and defense. Magda Lilia Chelly, chief information security officer at Singaporean Cybersecurity firm Responsible Cyber, told CNBC that there needs to be a twin track of encryption and quantum research and development so that security isn't outpaced.

Moreover, China, South Korea and Japan have deployed among the largest Quantum Communication Networks. Thus, France could be more looking towards Asia which offers plenty of business and collaboration research opportunities. Besides, many french start-ups have already benefited from asian companies and funds investments coming from Temasek and Tencent. Those efforts should be pushed by the French government's bilateral cooperation and business opportunities.

90. https://www.inria.fr/en/quantum-computing-main-players



CONCLUSIONS

In conclusion, the annual report on quantum technologies in France highlights the significant progress made in the country in the field of quantum computing, sensing and communications. The quantum communications sector is structuring itself to address the cryptographic challenges raised by the quantum threat, and the sensor ecosystem is offering the first commercially valuable use cases, already useful in many industries. On the quantum computing side, the development of stable and reliable qubits, which are the fundamental building blocks of quantum computers, has been a crucial technical challenge addressed by French actors. Indeed, France has made significant strides in this area with leading groups and young startups investing heavily in improving the quality and scalability of qubits. The French government and research institutions have also invested heavily in exploring new experimental technologies to compete for the future commercialization of quantum computers.

Despite the progress made in France, the lack of standardization and interoperability among different quantum systems still poses a challenge. Application-based benchmarks will allow for better interpretation of the performance and applicability of quantum computers, and the creation of a robust ecosystem and a workforce of talents to design, build, and operate quantum computers, sensors, and networks will be crucial for the successful growth of quantum technology and its future commercialization. The quantum ecosystem is at a singular stage of development. Young start-ups created a few months ago rub shoulders with established players, world leaders in their technologies. The innovations, almost exclusively coming out of research laboratories, are side by side without it being possible yet to distinguish the technology that will impose itself as a standard or the first use case that will offer a commercial advantage.

Efforts to support the ecosystem will thus be central, to develop collaborations between eclectic players (large groups, public institutions, academics, and startups) and exchanges beyond purely commercial logics, to make the greatest number of people aware of the issues raised by the second quantum revolution, and to multiply the federating places. These efforts, which are central to the national strategies of many countries, have borne fruit in Canada, the Netherlands, the United States and Germany, and will serve as an inspiration in France.

This first annual report, written in a collaborative way and the first of several, is in line with the missions of Le Lab Quantique and its partners. Offering a platform for exchange, expression and highlighting of initiatives related to quantum technologies in France is essential to better connect its actors and raise awareness of the issues it will be brought to cross. This report was not intended to be absolutely exhaustive, but to provide a first overview of the forces that are pushing the ecosystem towards maturation. To this end, Le Lab Quantique will open a first collaborative space in 2023, which will host some twenty organizations, and will open the first Maison du Quantique in 2025.

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GLOSSARY

Term	Definition
Qubits	The most fundamental unit of quantum information, analogous to “bits” in classical computers.
Quantum entanglement	A quantum-physical phenomenon in which the quantum states of two particles (e.g., electrons, photons) are linked together regardless of their physical separation.
Quantum superposition	A property of a quantum system to exist in multiple states until measured. For instance, a qubit can exhibit two quantum states at the same time.
Available for use	Ready to be deployed in a limited way to at least one commercial application.
Emerging	Several proofs of concept developed, but not ready for c ommercial deployment.
On the horizon	At proof-of-principle stage; requires several technical breakthroughs to advance to the next stage.
Quantum decoherence	The phenomenon by which quantum particles lose their quantum behavior, for instance, when exposed to an environment
NISQ or Noisy Intermediate-Scale Quantum Era	The current state of quantum processors in which the qubits are ‘noisy’ – very sensitive to environment and lose their quantum state easily. Due to this the quantum processor is impacted by decoherence and requires ‘error correction’ in its output.
PQC or Post-Quantum Cryptography	NIST defines PQC systems as cryptographic systems that are secure against both quantum and classical computers, and can interoperate with existing communications protocols and networks.
QKD or Quantum Key Distribution	A key distribution protocol to generate “quantum” keys that can be used for secure information exchange over a classical channel with classical cryptographytechniques. The keys are distributed using rules of quantum mechanics where any act of listening in leaves a detectable sign of snooping.

le lab quantique

Le Lab Quantique is an association under the French law of 1901 whose mission is to promote quantum technologies in France and internationally. It currently has more than 50 member organizations. In order to create synergies between public and academic actors, large groups and startups, Le Lab Quantique organizes events (workshops, hackathons, scientific and artistic exhibitions) bringing together all the actors of the ecosystem. It produces content to promote quantum technologies and help identify use cases, coordinates regional and national funding initiatives, and supports workforce development by connecting innovation and talent. Le Lab Quantique also works with its partners to create Les Maisons du Quantiques, a physical space for the development and federation of French quantum players.