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FRANCE NATIONAL QUANTUM STRATEGY

Annual report
March 2023

QUANTUM|FRANCE 2030

FRANCE 2030

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EDITORIAL

BY SYLVIE RETAILLEAU

Minister of higher education and research

Sylvie Retailleau
Ministre de l'Enseignement supérieur et de la Recherche

Science, technology and innovation made possible transformative capabilities across multiple sectors, form energy to health and communication. In this regard, quantum technologies revolutionizes both our understanding of fundamental phenomena and our ability to develop powerful computers, secure and rapid communication or new sensors. Mindful that the emergence of such robust technologies depends on the intensity of theoretical and practical understandings of quantum technologies, the French President announced the Quantum Technologies National Acceleration Strategy on February 21st, 2021. This strategy mobilizes massive investments to generate all the knowledge and to train and to attract all the talents we need to succeed in the quantum technology race.

The strategy has rapidly entered its operational phase. It relies on the excellence of the national quantum research ecosystem to support both fundamental research and application-oriented projects. This strategy ecosystem makes possible to respond to challenges such as quantum sensing, quantum computing, secure communications and to develop the requested enabling technologies. To this end, the French Ministry of Research and Higher Education mobilized the relevant French research organizations and a large number of Universities. In addition, we have given an impulse to education programs dedicated to quantum curricula in universities and engineering schools. The ambition is to train more than 5,000 talents at various levels, from technicians to PhDs.

This strategy strengthens today our international visibility in quantum technologies that also benefits from the Nobel Prize of Physics received last year by Alain Aspect. Two years after the launch of the strategy, we are seeing the first results. I want to thank and to congratulate all those who have worked toward this goal.

EDITORIAL

BY JEAN-NOEL BARROT

Minister of digital affairs

Jean-Noël Barrot
Ministre délégué chargé de la Transition numérique et des Télécommunications

Quantum computing has the potential to revolutionize the way we solve problems that are impossible to solve using classical computers. It is therefore expected to have a significant impact on a great number of fields, from cybersecurity and chemistry to finance and climate science.

France can rely on its existing strengths in this domain, such as the excellence of its scientific research, recently put into the spotlight by Alain Aspect's Nobel Prize. To foster France's vivid startup ecosystem, the Quantum Strategy has spearheaded public and private investment in the field.

In this first two years, the Quantum strategy has deployed significant funding especially for fundamental & applied research and skills: I expect the next two years to be dedicated to support our numerous start-ups to grow their activity, find new customers, raise funds and scale up!

EDITORIAL

BY BRUNO BONNELL

Secretary General for investments

Bruno Bonnel
Secrétaire Général
Pour l'Investissement

Quantum science has the potential to revolutionize a wide range of fields, from computing to communications to sensing and more.

The french quantum strategy established in 2021, and supported by France 2030 plan provides a roadmap for the government to coordinate and accelerate research and development in quantum science and technology.

Over the past year, the french quantum strategy has continued to make significant progress towards these goals. Significant investments have been made to support and accelerate quantum research and development and quantum-ready workforce development.

The first results are already there, major scientific breakthought had been realised by french research labs, french startups became between the post attractive ones by raising an historical amount of funds and a large amount of international quantum talents had chosen France as a destination for their career.

Based on these promising results, our ambition is to continue and accelerate the support of France 2030 plan, to the french quantum ecosystem.

EDITORIAL BY PATRICIA BARBIZET

Chair of Investments Supervisory Committee

Patricia Barbizet
Présidente du Comité de surveillance des investissements d'avenir (CSIA)

The second quantum revolution will transform our societies and carries a series of concrete and strategic applications. Some are expected, such as the optimization of industrial processes, satellite-free navigation or simulations of global warming. Others will be discovered as rapid progress is made in the fields of quantum sensors, communications, computers and cryptography.

In January 2021, the President of the Republic presented the French strategy on quantum technologies. This strategy aims for the mastery of quantum technologies and can count on the scientific excellence of our country in this field. In particular, it seeks to position France among the world leaders in the race for the scalable universal quantum computer.

Two years later, the first results of the national strategy are striking: the French quantum sector has strongly expanded. From Paris to Grenoble and Nice, research projects have intensified, start-ups have taken on a European and global scope and public-private collaborations have become widespread. The strategy has also developed engineering and doctoral training in the quantum sector. International cooperation are strengthened with the United States and other allies, particularly in terms of international standards.

The path to the quantum computer remains long and strewn with scientific, technological and industrial pitfalls. The French strategy could therefore be amplified over the next few years, in particular by enhancing support for start-ups in the quantum ecosystem. The roadmap would thus look beyond 2025, towards the industrialization of quantum technologies that will reach maturity. The second quantum revolution is underway, France has all the assets to be a pioneer player.

FOREWORD

BY NEIL ABROUG

Head of the French national quantum strategy

Neil Abroug
Coordinateur national de la stratégie quantique française

2022 was an extraordinary year for the French quantum ecosystem, marked by incredible scientific breakthroughs and unprecedented levels of funding for quantum startups. The government's investment of 350 million euros towards basic research, infrastructures, technology transfer, and education has been a game-changer. Even during a private equity shortage, a remarkable amount of 290 M€ has been raised, reflecting the confidence and enthusiasm of investors towards the French quantum industry. Moreover, our strengthened partnerships with European and international allies have positioned France as a leading player in the global quantum race.

FOREWORD

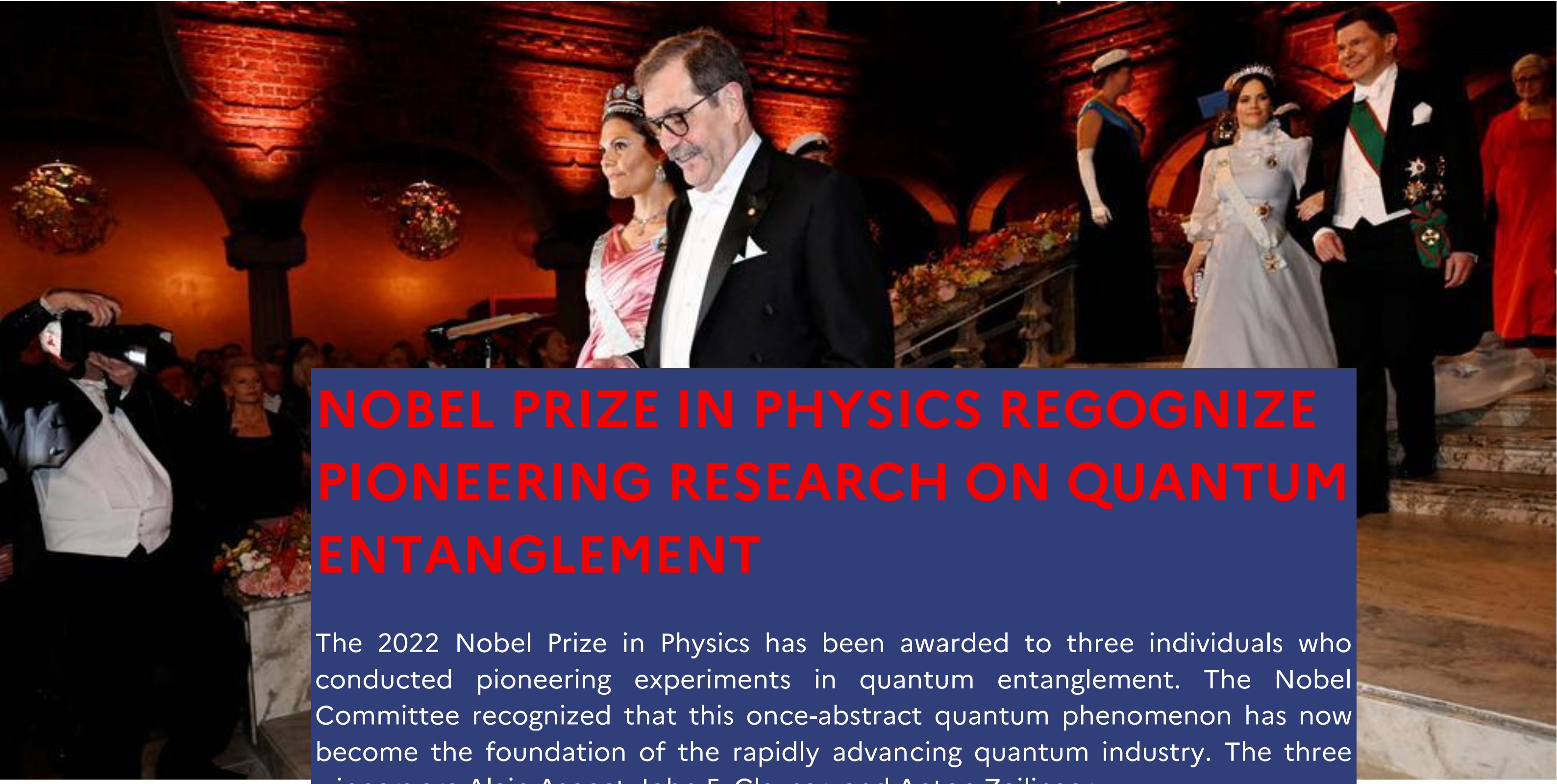
BY CATHERINE LAMBERT

Head of the scientific comity of the French national quantum strategy

Catherine Lambert
Présidente du CERFACS

The year 2022 revealed the capacity of the French scientific ecosystem to federate in strong interaction with industrials and start-ups. Structuring projects have been launched with a desire to synergize all the forces present in the national territory and with collaborations at the European level. A major training project involving 21 French universities also meets the need for skills in the field of quantum technologies, for engineers, researchers, teachers, technicians and managers.

The magic triangle of research, education and industry is well in place to accelerate innovation in the field of quantum technologies.



NOBEL PRIZE IN PHYSICS REGOGNIZE PIONEERING RESEARCH ON QUANTUM ENTANGLEMENT

The 2022 Nobel Prize in Physics has been awarded to three individuals who conducted pioneering experiments in quantum entanglement. The Nobel Committee recognized that this once-abstract quantum phenomenon has now become the foundation of the rapidly advancing quantum industry. The three winners are Alain Aspect, John F. Clauser, and Anton Zeilinger.

Entanglement refers to the behavior of two particles that can act as one, even when they are physically separated by a great distance. Clauser developed John Stewart Bell's concept of nonlocality, which came to be known as Bell's inequality. This idea led to practical experiments on entanglement, with Clauser's final measurement showing a preference for quantum mechanics, which made it impossible to use hidden variables to explain quantum mechanics.

Aspect addressed an important gap left after Clauser's experiments by changing the measurement settings as soon as the entangled pair left the source, so that the setting would not affect the results. Zeilinger and his team demonstrated quantum teleportation using entangled quantum states, which allowed them to transfer the quantum state from one quantum object to another.

Your Majesties, Your Royal Highnesses, Excellencies, Dear Laureates, Ladies and gentlemen:

On behalf of Dr John Clauser, Prof Anton Zeilinger and myself, we wish to thank The Royal Swedish Academy of Sciences and the Nobel Foundation for the invaluable honour of this prize. That recognition should go first to the late John Stuart Bell, without whom we would not be here today.

"Do you have a permanent position?" These were the first words of John Bell, in 1975, when I finished describing the scheme of the experiment I was planning. He explained that working on a test of the inequalities he had found would be considered a waste of time, as John Clauser knows well. But when I told him that I had a tenured position, he encouraged me to pursue a project that would address the core of Einstein's thinking.

Bell had demonstrated that one can settle experimentally a long-standing debate between Albert Einstein and Niels Bohr about the interpretation of the quantum formalism. The debate focused on a quantum situation described by Einstein, Podolsky and Rosen in 1935, where two particles are in a state that Schrödinger named "entangled" to emphasize the link between the particles even widely separated. It was, it appeared, merely a debate about how to interpret the results of a calculation on which there was no disagreement. But in 1964, John Bell discovered that adopting Einstein's point of view about the nature of physical reality would lead to a result in contradiction with the quantum predictions, in some situations. A seemingly philosophical debate about the nature of physical reality could be settled by an experiment! How could one not be amazed and attracted by such a discovery?

Beginning in 1972, the three of us successively developed realizations of such an experiment, with increasing sophistication. The conclusion is now clear: Einstein's view on physical reality cannot be upheld. Entanglement is confirmed in its strangest aspects. Nowadays entanglement is at the heart of a flourishing of quantum technologies, some based on experiments by Anton Zeilinger. We must thank Einstein, Bohr and Bell for pointing out that extraordinary property of the quantum world.

It took many decades to go from the first evidence of that extraordinary property of the quantum world to the second quantum revolution. That lesson should be recalled to governments and funding agencies.

ACHIEVEMENTS

300 PhDs

200 Post-docs

57 Startups

290 M€ raised

150 M€ invested in basic research

60 M€ invested in education

72 M€ invested in hybrid HPC-Quantum facility

80 M€ invested in critical supply-chain securing

NATIONAL PROGRAMS HIGHLIGHTS

350 M€

have been invested in 2022 to support research, innovation, education and ecosystem development

FRANCE LAUNCHES ITS **HYBRID HPC QUANTUM INITIATIVE**

HQI (France Hybrid HPC Quantum Initiative) is an academic and industry research program that relies on the acquisition of several quantum technologies. These systems will be coupled to GENCI's European-class supercomputer Joliot Curie hosted and operated by CEA, thus serving the interests of French and European researchers as well as international collaborations for research. This hybridization is an innovative and unique initiative that will benefit from the expertise of the CEA/TGCC teams in infrastructure operation, security and support to scientists. With a budget of €72.3 million, this program is managed by the CEA. The government has entrusted GENCI with the acquisition of simulators and quantum computers for an amount of €36,3 million, which should be supplemented by European and industry cofunding. The open and scalable platform will have a set of complementary French and European technologies to best address research needs and business use cases. The second part of the research program has a budget of €36 million. It is led by the CEA and Inria, with the support of the CNRS and France Universities, the IT manufacturer Atos, the cloud provider OVHcloud and startups. Together, they support the development of a programming and execution software layer on hybrid computing resources, including libraries for business verticals (health, chemistry, finance, etc.) or transversal needs (machine learning, optimization, etc.). GENCI is responsible to provide and promote the use of HQI's quantum computing resources as well as the dissemination to the quantum ecosystem (Le Lab Quantique, QuantX, Teratec, Systematic, etc.), local authorities and industry.

The first component of the HQI platform is already up and running since December 2021: it is based on the HPCQS project, co-funded by the EuroHPC Joint Undertaking (JU) and 6 member states of the consortium, including France and Germany. After the completion of a purchasing procedure called PPI (Public Procurement of Innovative Solutions), GENCI and Jülich Forschungszentrum (FZJ, Germany) acquired two 100 qubit cold-atom quantum simulators from Pasqal. This system will be installed at TGCC by the end of 2023 and will then be available for the HPCQS research program and HQI end-users. HQI-related research projects will benefit from a remote access to a Pasqal 100-qubit device from April 2023, until they can access the device hosted at TGCC.

The EuroQCS-France consortium, including CEA, FZ Jülish (Germany), Irish Centre for High-End Computing (ICHEC, Ireland), University Politehnica Bucharest (UPB, Romania), and led by GENCI, was selected in October 2022 by EuroHPC JU to host a photonic quantum computer. This second system will complement the technologies and environments exposed through HQI. It will be available early in 2024.

Today, even before the arrival of these two devices, HQI provides access to high-performance quantum emulation environments such as the Atos QLM, Pulser (Pasqal) and Perceval (Quandela). Other emulators and software environments will be added to the HQI platform over the next few months. Access to these services can be requested through the DARI platform.

France should capitalize on these programs and could couple its future Exascale supercomputer with quantum computing resources, paving the path to new computing architectures to address stakes linked to performance/eco-responsibility issues and support users in their journey towards the post-Exascale era.

Atos worked on integration of QLM in the TGCC infrastructure with CEA teams. The goal was to adapt the PowerAccess module, in order to fit the TGCC security rules and to modify the packaging of myQLM and its build chain. TGCC required building it by itself in its environment. This needed to provide the source code (under strict NDA), and to modify in-depth the build chain. The developments have started for a first HPC emulator, based on the linalg simulation algorithm. A MPI version of the linear algebra simulator is being developed from scratch. A development of a first proof of concept of a Large Scale Quantum Distributed Heterogeneous Programming was done. It is based on LLVM. Preliminary study tasks on Partial Differential Equation have started, in collaboration with LLJL lab.

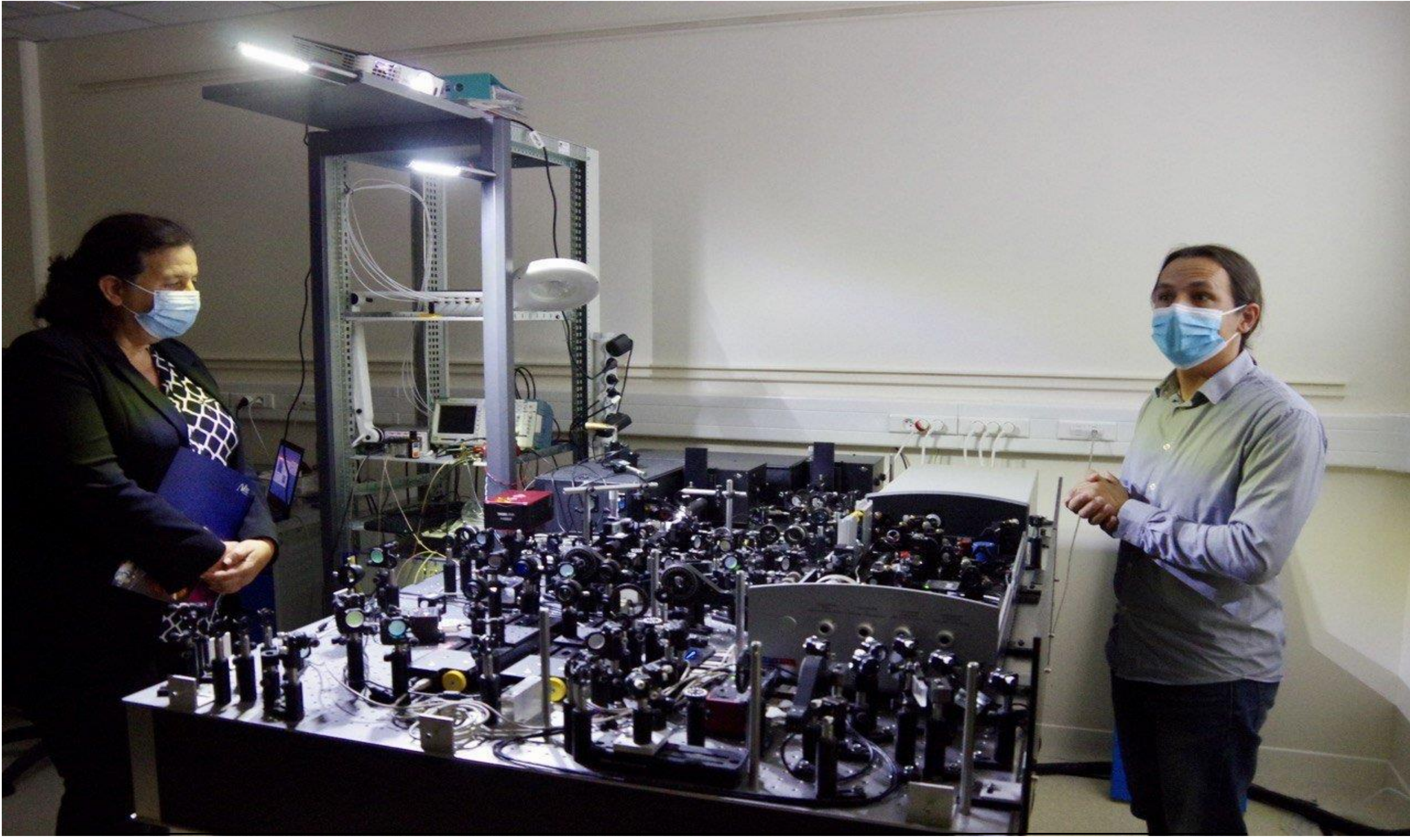
To support the adoption of quantum computing amongst industrial companies, GENCI, Le Lab Quantique and Teratec have teamed up with Région Ile-de-France since 2020. The regional authorities have then launched an initiative called "Pack Quantique", which aimed at co-funding 2-year proofs of concepts (PoC) that gathered Ile-de-France-based start-ups, academic laboratories and industrial players to explore the potential of quantum computing for a specific industrial use case. This co-funding scheme has allowed about 10 projects to emerge over the past 3 years, tackling various industries such as Aeronautics, Spatial and Defense (ASD) and is now exploring new grounds such as banking and insurance, or even luxury. Relying on the success of this pilot initiative, HQI offers to replicate this co-funding model in various regions to support the genesis of about 20 PoCs targeting a wider industrial spectrum. As local HPC-QC ecosystems emerge and seek connections with national and international organizations, HQI will also identify between 4 and 6 colocalization projects in different regions that will be supported financially and benefit from the label "Maison du Quantique". These initiatives will act as a network with a national governance and representation. The pilot initiative was already identified and should be announced in 2023.

HQI had a booth at the international Paris-based fair VivaTech, in June 2022. For four days, diverse players (start-ups, academia, industries, speakers) from the ecosystem gave talks on the booth to present their work. As it was the only booth fully dedicated to quantum computing in the whole event, it attracted several official delegations, who wished to learn more on this topic. The booth also hosted the signature of the purchasing agreement for the quantum simulator between GENCI and Pasqal, witnessed by SGPI and DGRI on June 17th.

To promote HPC-QC in various regions, as well as to potential international partners, HQI was presented at numerous events on hybrid quantum computing: ISC, TQCI, HPCQC, SC, to name a few. HQI partners also took part in initiatives that aimed at federating the ecosystem, such as FranceQuantum or le Lab Quantique. Teratec and EDF co-organized an event on hybrid HPC-QC in January 2023, where HQI was presented to a broad audience, including potential partners from the Quantum Innovation Zone in Sherbrooke (Canada). GENCI was invited to present the "Pack Quantique" initiative in front of an international audience during the EuroHPC Summit Week in Sweden in March 2023. They will also participate in a panel as a Hosting Entity for EuroQCS-France at ISC2023 in Hamburg, in June 2023.

These events gave rise to numerous discussions with international partners, in Europe and worldwide. The EuroQCS-France, -Spain and -Italy, respectively led by GENCI/CEA, BSC-CNS and CINECA, included a common part in their respective applications to the EuroHPC Call for Expression of Interest (CEI) in June 2022. This strengthened the relationships between these players around HPC-QC topics. They were also joined by the EuroQCS-Poland consortium, led by PSNC, who agreed to use the same EuroQCS prefix. GENCI and CEA also led discussions at SC22 in November 2022 with other potential international partners such as Travis Humble, from Oak Ridge National Laboratory (ORNL), who is currently in charge of the Quantum Computing User Program (QCUP) and would like to exchange on HPC-QC-related topics. CEA, GENCI and the RIKEN computing center (Japan) met in Paris in January 2023 and agreed they could collaborate on HPC-QC.

HQI also supported the organization of hackathons by quantum computing technology providers. The Minalogic, QuantX and Atos-led hackathon, hosted in Grenoble in October, was attended by around thirty participants and was sponsored by HQI. The initiative was presented by GENCI on this occasion. Quandela highlighted the release of its programming and emulation environment Perceval by organizing with Sorbonne University the LOQCathon (Linear Optical Quantum Computing hackathon) in November 2022, gathering more than 60 participants from 10 countries. As main sponsor, HQI was also presented. In March 2023, HQI will co-organize and sponsor the Big Quantum-AI-HPC Hack in Paris, along with QuantX and PRACE. This event aims at federating research communities on all three technological fields, to accelerate the generation of hybrid algorithms.

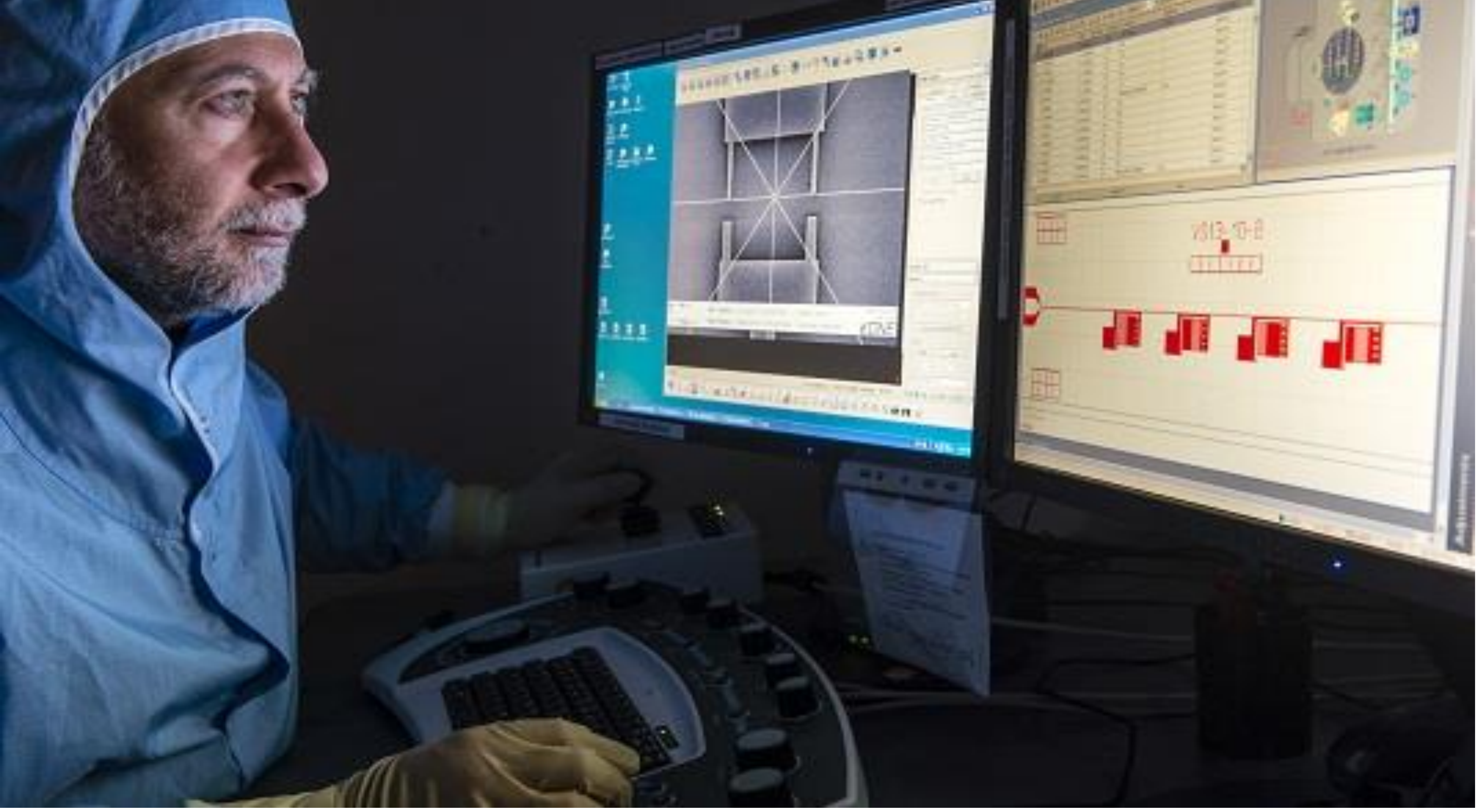


FRANCE GRANTS ELEVEN **PRIORITARY RESEARCH PROJECTS** AND THREE **PRIORITY RESEARCH INFRASTRUCTURES**

PRIORITY RESEARCH INFRASTRUCTURES

E-DIAMANT

The e-DIAMANT project aims to position France as a world leader in diamond sensor manufacturing and support current challenges in the field of quantum technologies. The laboratory of Process and Materials Sciences and the Sorbonne Paris Nord University are partners in this project and will receive funding for the acquisition of a diamond cutting laser guided by a water jet and a Raman spectrometer coupled with a measurement device for the coherence time of NV colored centers. The controlled introduction of impurities in its carbon network leads to the creation of colored centers that have revolutionized the field of quantum technologies. One of these defects, known by the acronym "NV" for Nitrogen-Vacancy, presents spin energy levels that are easily optically manipulable. The lifetimes of these states (coherence time) can reach a few milliseconds at room temperature, which may seem short, but allows for a large number of quantum functionalities to be implemented. The great sensitivity of this system to its environment can thus be used to create magnetic, electrical or thermal field sensors with unparalleled sensitivity compared to current classical systems. These unique properties among solid-state materials currently being studied would address areas of activity as diverse as communications, health, security, and fundamental sciences. However, developing such "perfectly imperfect" diamonds in a reproducible and adaptable manner for the development of these devices is a major challenge. The e-DIAMANT consortium aims to cover the entire value chain, from the base material synthesized by chemical vapor deposition (CVD) to the final component. Significant technological resources will be mobilized for laser cutting, defect creation by implantation, surface nanostructuring, evaluation of optical properties, and integration into magnetometers. Their performance will be put to the test in new areas of physics: spintronics, nanomagnetism,



high-pressure physics, and Earth sciences. Through industrial partnerships, the objective is to make France a world leader in diamond for quantum sensors with great autonomy in an extremely competitive landscape.

AQCESS

The aQCess project aims to create a unique computing platform based on quantum physics principles, which will be accessible to both academics and industry professionals in France and internationally. The project is led by the University of Strasbourg and involves a consortium of researchers from five institutes in Strasbourg, one institute in Nancy, and one institute in Montpellier. The platform will be housed in a state-of-the-art laboratory within the European Center for Quantum Sciences and will be called "Atomic quantum computing as a service - aQCess". The platform will use lasers to trap atoms and exploit the quantum effects in these systems to solve problems that are currently impossible to solve on classical computers, including those with the largest computing power. The aQCess platform will be widely used for research, interdisciplinary teaching, training, and by companies or start-ups investing in quantum technologies. The project includes international partners such as two institutes from the Karlsruhe Institute of Technology in Germany, the University of Vienna in Austria, BASF, a leading European chemical company, and two emerging quantum hubs: the Quantum Institute at the University of Sherbrooke in Canada and Forschungszentrum Jülich, a global leader in intensive computing.

QCOMMTESTBED-INFRA

This infrastructure aims to provide France with a national testbed for experimenting quantum communication applications in real-field condition, with performance benchmarks related to advanced protocols and associated use cases. The ultimate ambition of such an infrastructure is also to serve as foundational building block for connecting space and ground segments, thanks to the cooperation of academic and industrial partners such as Orange and Thales Alenia Space.

PRIORITY RESEARCH PROJECTS

PRESQUILE

Silicon-based spin qubits have demonstrated their potential at the individual level in several laboratories around the world. As early as 2016, CEA and CNRS demonstrated that industrial CMOS technology could be used to create a qubit. The challenge now is to assemble and control a large number of these qubits. In this context, the PRESQUILE project proposes a two-pronged strategy: i) the study and demonstration of qubit variants that can be integrated into the scalable architecture developed in parallel, and ii) the study of two key elements to consolidate the design of large-scale architectures (spin/spintronics interfaces and variability). This project will build on the results of the Quantum Silicon Grenoble

(QSG) program, which consists of teams from CEA, CNRS, and UGA, with the objective of identifying and overcoming scientific and technological barriers to demonstrate 100 silicon-based qubits in VLSI technology. It is led by a team that will bring together scientific expertise on Si spin qubits, quantum engineering, and VLSI technologies.

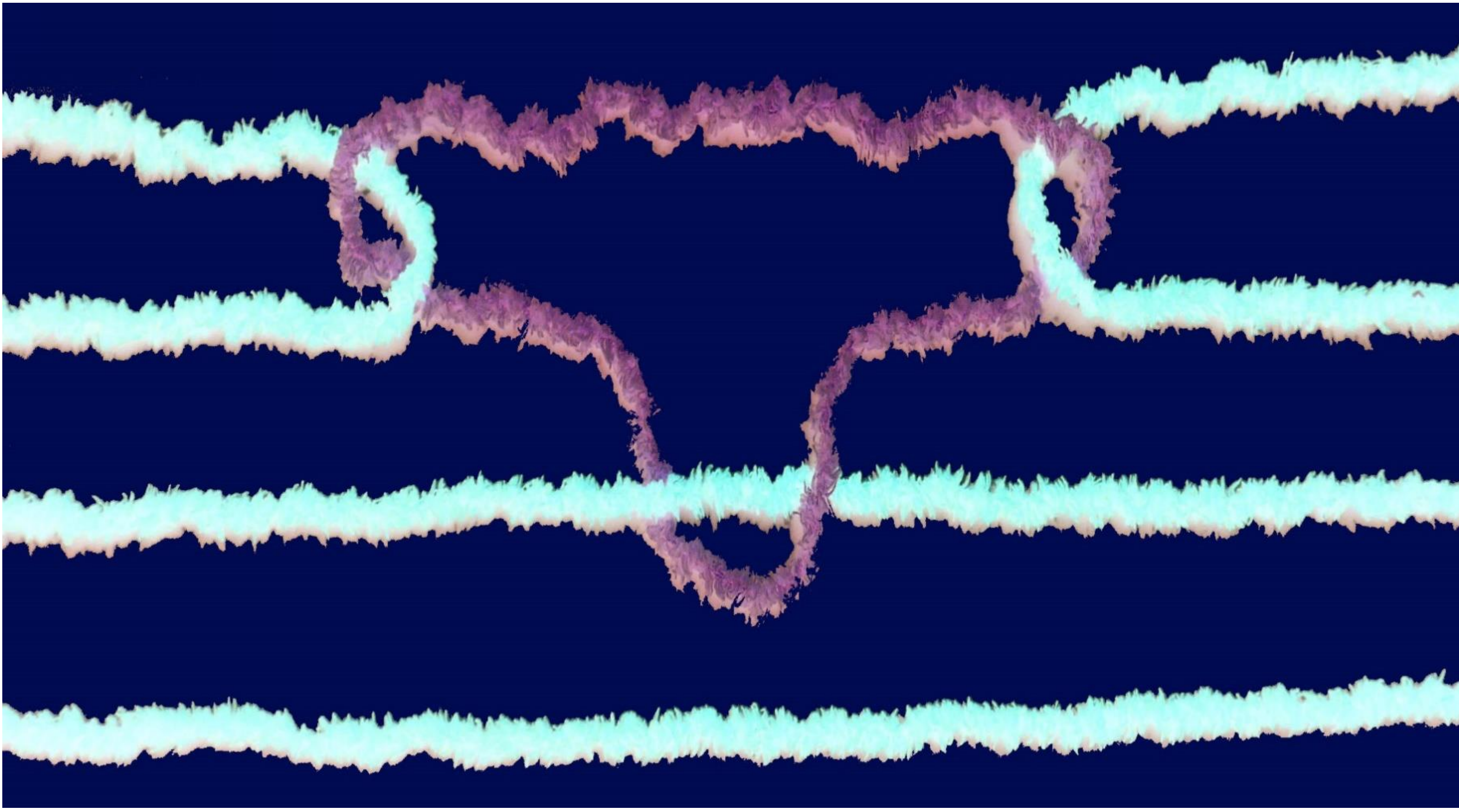
ROBUSTSUPERQ

The RobustSuperQ project aims to accelerate French R&D in by-design protected superconducting and hybrid qubits that are resilient against decoherence. It is part of a post-transmon strategy, and an alternative to surface code, in which French teams are at the forefront. The project brings together all of these teams around three complementary concepts: Cat-code architecture, spin qubits implanted on superconducting circuits, and topologically protected superconducting qubits. The 5-year goal is to demonstrate a high-fidelity, controllable, and measurable quantum processor, which does not exist on any platform yet (optical, atomic, or solid-state). The 3-year goal is to realize the first protected logical qubit based on one or a few physical qubits.

The acceleration of the development of these robust qubits is based on two pillars, platform and workforce. Regarding platform pillar, two technical poles, in Paris region and Grenoble, will undergo a qualitative leap in terms of resources through the creation of a new dedicated platform at CEA-Université Paris-Saclay and the acquisition of fabrication and characterization equipment in both poles. The resources will be shared and interoperable, and the knowledge and associated developments will be synergized. On the workforce side, involving three chairs surrounded by young researchers who can themselves recruit post-doctoral fellows and graduate students (approximately 40 equivalent post-doctoral years or 60 equivalent graduate student years).

QUBITAF

The goal of this project is to develop the potential of cold atom platforms that have already shown interest in quantum simulation: arrays of interacting atoms in optical tweezers and in optical networks. In order to approach the criteria of the quantum computer, the project focuses on three levers: (i) increase the number of manipulated atoms, (ii) characterize and certify the results of large-scale quantum simulators, and (iii) study the role of dissipation on the performance of these platforms. On Rydberg platforms, we will increase the number of manipulated atoms, the fidelity of operations, and the total duration of operations. In parallel, we will develop and experimentally demonstrate original methods for certifying platforms, particularly for entanglement with a large number of atoms, a central element in obtaining a quantum advantage. Finally, we will build two new types of quantum simulators to study the N-body problem in a dissipative regime with controlled dissipation. This project brings together 3 teams of experimentalists, a team of Pasqal developments, engineering of technological solutions, and exploration of applications,



from the most fundamental to the most applied.The QUBITAF project aims to improve cold atom platforms for quantum simulation, by increasing the number of atoms manipulated, certifying the results and specifying the performance of these platforms.

QAFCA

Cold atom sensors represent a major revolution for gravity field measurements, providing a unique reference system for analyzing climate change and a tool for anticipating natural disasters. Being both highly sensitive and inherently accurate, atomic sensors enable comparison of measurements separated in time and space at the highest level. These new sensors are expected to provide access to measurements that are inaccessible to traditional sensors by complementing ground gravity measurements and by making measurements at all spatial scales of the gravity field.
Among the many anticipated applications of these atomic sensors, this project focuses on the field of geophysics and will contribute to addressing the challenges of natural disaster management (volcanology, seismology...), climate change (to monitor sea level rise, ice melting, hydrological changes...) and civil engineering, thus providing decision makers with precise information.

The project's ambition is to (1) exploit the full potential of quantum measurement, (2) improve the form factor and transportability of these sensors, and (3) demonstrate new concrete use cases. The QAFCA project seeks to develop compact and transportable cold atom sensors to measure the gravity field, with applications in the analysis of climate change and the anticipation of natural disasters, or even civil engineering or CO_2 storage.

NISQ2LSQ

The aim of this project is to significantly accelerate research and development in the theory and design of effective error-correcting codes in hardware. The project, led by INRIA, is mainly focused on two of the most promising solutions in this direction, namely bosonic codes and LDPC (Low-Density Parity-Check) codes, and on two types of physical platforms, namely superconducting circuits and photonic circuits. The primary goal within 5 years is to demonstrate a prototype of a superconducting quantum processor based on cat qubits, which is fault-tolerant at order 1 and then at order 2, and to lay the groundwork for rapid scaling towards Large Scale Quantum (LSQ) at the end of the project. In the field of photonics, where scaling can take various forms, the goal is to define measurement-based computing architectures using these codes and to experimentally demonstrate the necessary elements for their construction. In the field of LDPC codes, the objective is to develop codes that are essentially optimal in terms of encoding rate and error correction, as well as efficient decoding algorithms and techniques for fault-tolerant logical operations specific to LDPC codes. Emphasis will be placed on

constructing small codes with a limited number of long-range interactions, in order to accelerate their integration into technologies based on photonic qubits or Rydberg atoms.

EPIQ

The EPIQ project is a French initiative focused on developing algorithmic techniques for quantum computing. It aims to understand the advantages and limitations of quantum computing and to develop techniques for both noisy quantum machines and fault-tolerant ones.

The project is divided into three work packages. The first WP focuses on algorithmic techniques and involves researching quantum complexity and enhancing algorithms. The second WP concentrates on computational models and languages, with the aim of facilitating quantum machine programming and optimizing code execution. The third WP concentrates on developing simulation techniques to anticipate algorithm performance on noisy quantum machines.

The project recognizes that algorithms are essential to quantum computing and the interface through which users will solve practical use cases, leading to economic gain. The French quantum computing research community's outstanding position forms the foundation of the EPIQ project.

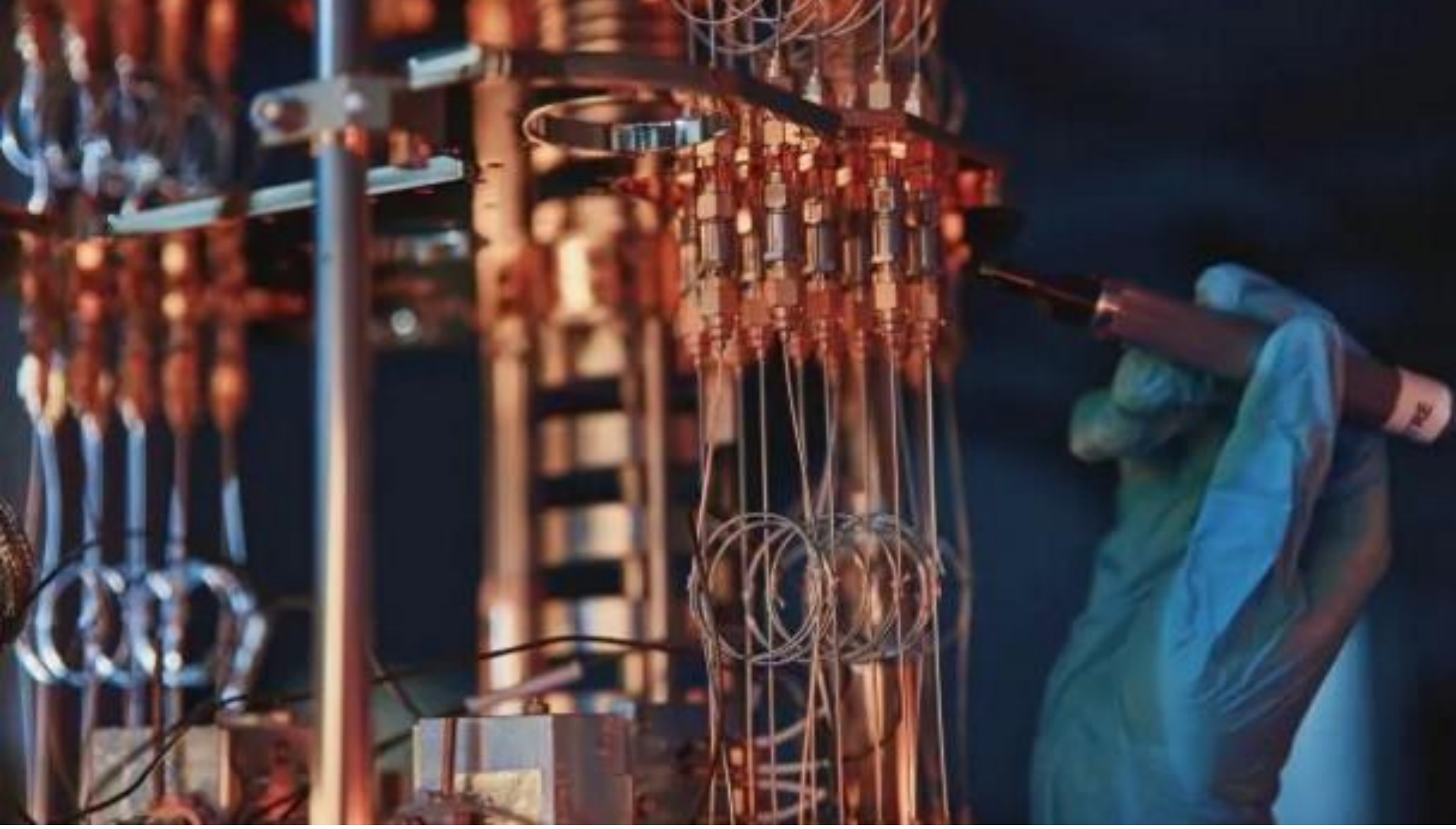
PQTLS

The PQ-TLS project aims to develop a post-quantum lock for web browsers that will replace the current cryptographic primitives used in the "https" protocol, which are vulnerable to quantum computing attacks. Over a period of five years, the project will develop post-quantum primitives that will be integrated into an open-source browser to create a prototype "post-quantum lock". The project will contribute to the evolution of cryptographic standards, ensuring that French actors in post-quantum cryptography are involved in the decision-making process.

The project will implement a post-quantum version of the security layer of network protocols, such as the Transport Layer Security (TLS) protocol used by web browsers. The selection of post-quantum primitives will comply with the standards set by normalizing agencies, while the project aims to contribute and even influence these choices through the demonstrators produced. The goal is to promote solutions from French academic and industrial research and pave the way for a secure post-quantum era of web communication.

The DIQKD project aims to develop the first prototype of a "device-independent" quantum key distribution (QKD) system using optical elements. QKD allows two users sharing a quantum channel to generate a secret key which can be used to encrypt their communications using a simple symmetric encryption algorithm. The security of QKD is based on the principles of information theory, assuming that a small number of well-identified hypotheses are satisfied, including the behavior of the quantum devices used to produce the key. However, recent "hacking" experiments have shown that the security guarantees can be compromised if these assumptions are not perfectly satisfied.

The device-independent approach aims to ensure security even when the devices are



only partially characterized. The project will develop new security proofs that reduce the detection efficiency constraint, increase tolerance to noise, and require a limited number of experiments. The project will also consider different uses of experimental resources through automated techniques, and comparative analyses will define the sim plest demonstrator to implement.
The demonstrator will be implemented in an experiment using linear and non-linear optics to perform a Bell test without post-selection.

QCOMMTESTBED-RESEARCH

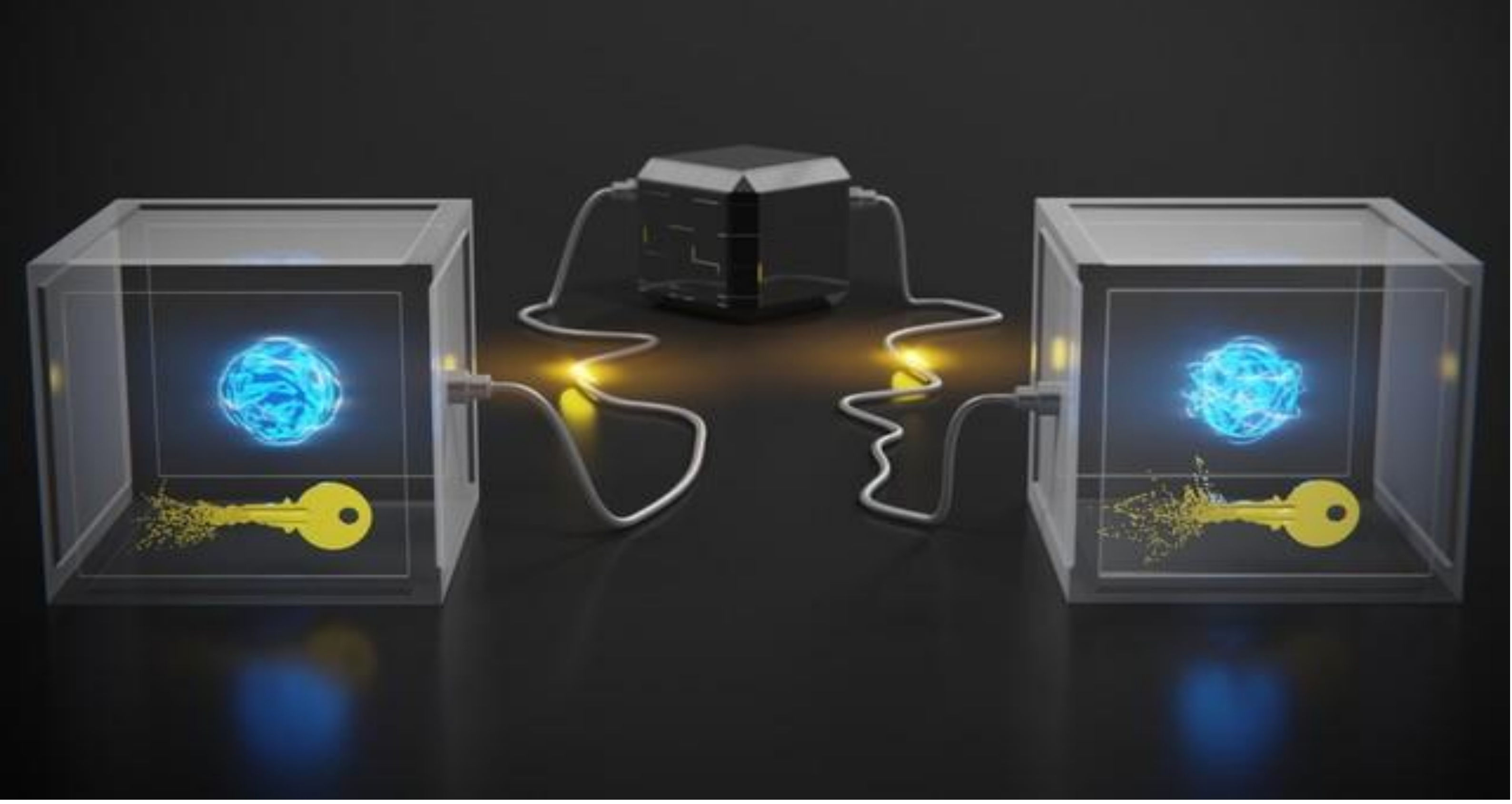
From the scientific side, QCommtestbed aims at exploiting the national infrastructure (see above) to experiment and assess advanced quantum communication protocols and applications, relying on quantum key distribution security levels. The ambition is to accelerate the development and transfer of technologies, from laboratory systems to commercial products. The project is based on an academic consortium bringing together proven and complementary expertise. It will consolidate and highlight these competences to position France at the forefront of this field in its global picture.

QMEMO

The QMEMO project aims to develop quantum memories with the required performance metrics for integration into future French and European experimental quantum networks. These memories will be crucial components in the deployment of quantum repeaters, which are necessary to extend quantum networks over long distances. Quantum repeaters divide the long distance into shorter segments, on which entanglement can be faithfully distributed. The adjacent segments are then connected. Quantum memories allow for asynchronous network preparation by storing entanglement on each segment before connecting them.
In addition to their role in quantum repeaters, quantum memories have numerous applications in quantum state engineering and optical quantum computing by enabling the synchronization of photon resources. The QMEMO project will optimize the storage and readout efficiency, storage time, and multiplexing of quantum memories. The project will rely on two complementary technologies: the first based on large ensembles of laser-cooled atoms and the second on rare-earth-ion-doped nanophotonic structures. The QMEMO project will bring together the entire French academic community working on quantum memories and stimulate the development of various enabling technologies. Quantum repeater deployment has become a central element of the roadmap for quantum networks in recent years, but it requires the development of extremely high-performance quantum memories.

OQULUS

This project aims to develop quantum computers using photons. The project brings integrated optics, quantum information, quantum computer science, and theory and experiment to build two optical noisy intermediate-scale quantum computers using



two different approaches: discrete variable and continuous variable.

Within the discrete variable framework, the team is developing an 8-qubit prototype using quantum dot sources of single and entangled photons coupled with ultra-low loss silicon nitride reconfigurable computing circuits. They are also working on generating photonic clusters and demonstrating first steps of measurement-based computing. The team is also working on improving key building blocks for next-generation processors, including the extension of quantum dot spin coherence time, the generation of indistinguishable photons, fast reconfigurable processing circuits, waveguide-integrated superconducting single photon detectors, and deterministic photon-photon gates.

In the continuous variables approach, the team is using time-frequency modes to create cluster states of between 10 and 10,000 nodes, which they are combining with mode-selective photon addition/subtraction to implement non-Gaussian operations. The team is also exploring alternative approaches, including color centers in silicon and nano-diamonds, ultra-compact III-V on SOI heralded single photon sources, and large clusters.

EQUBITFLY

This project aims to develop the first quantum nanoelectronics platform for generating, manipulating and detecting flying electrons on time scales down to picoseconds. Recent advances in the generation and manipulation of ultrafast electronic excitations indicate that on-fly coherent manipulation of such excitations is now poised to be addressed. The project is working to develop the last two of his technological building blocks necessary for the emergence of the first full-fledged electronic flying qubits.

On-demand generation of single electrons in the picosecond range and single-shot detection of such single flying electrons. The project is supported by state-of-the-art theoretical approaches such as quantum field theory, direct simulation at the microscopic level, and advanced machine learning. It culminates in the first demonstration of electronic flying qubits and, more generally, leads to important advances in the uncharted territory of quantum nanoelectronics at terahertz frequencies. Flying qubits have the potential to be a paradigm shift in quantum computing as they both solve the scalability problem (qubits are created on demand. a single circuit for many qubits, rather than a new circuit for each qubit) and connectivity problems (overcoming the nearest-neighbour interaction limitation)

FRANCE CONTINUE TO INVEST IN **DEFENSE RELATED QUANTUM TECHNOLOGIES**

DEFENSE TECHNOLOGY PROGRAMS

VALERIAN

This program aims to grow the technology readiness level (TRL) of a large band spectrum analyzer based spectral hole burning (SHB) effect inside doped non-linear crystals cooled down to 4K. Such a technology will serve in eletronic warfare applications (high range dynamic range). This program supports also the maturity rizing of SQIF technology (Superconducting Quantum Interference Filter).

EDAM

The EDAM program aims to develop ultra-compact clocks with an accuracy of "1 µs over the day", max volume of 25 cm3 and very low power consumption (< 200 mW).
The targeted applications are GNSS receivers, radio stations and tactical UAVs, and SCAF onboard carriers.

The level of precision of these micro-clocks, largely superior to the current quartz-based micro-clocks, will allow the integration of a resilient and robust time function.

CHRONOS

The CHRONOS program aims at developing very high performance airborne clocks with an accuracy of 10 ns over the day, max volume of 5 liters and power consumption of 30 W. These clocks are essential to meet the needs of the main SCAF platforms. The challenge is to have compact time sources that can withstand airborne environments and have the level of performance required to meet the needs of collaborative combat in GNSS denied conditions, which is impossible to achieve with current clocks (Cesium).

ASTRID EXPLORATORY PROJECTS

PARADIS

The project proposes the development of a quantum gas sensor using a hybrid PPLN/glass platform to generate and manipulate entangled photons on a photonic integrated circuit (PIC). The objective is a demonstration of CO_2 detection; leading to an increased sensitivity, (a factor 2 is announced). Defense interest: portable chemical analyzer

FRANCE GRANTS AN AMBITIOUS PROGRAM OF **TECHNOLOGY TRANSFER FROM LABS TO INDUSTRY**

In order to intensify and consolidate the chain of support for high-potential innovation projects, in terms of pre-maturation and maturation activities, a co-financing and support program has been set up to support the national quantum technology acceleration strategy.
The objective of this consortium, composed of 17 partners (National Research Labs, higher education and research establishments, and SATTs) who have demonstrated their experience in financing and supporting projects in this field, is to accelerate the transfer of these projects to the socio-economic world. It articulates the various tools proposed by France 2030, in particular the PEPR quantum technologies.
Winner of a France 2030 grant amounting to 15 M€, the program coordinated by CNRS and SATT AxLR is scheduled to begin in 2023. This program will build up on a successful expertise in terms of start-up creation. As an example, three projects that were recently supported in the CNRS RISE program resulted in the creation of start-ups, namely Silent Waves, WeLinq, and HiQute Diamond in 2022.
Furthermore, CEA and CNRS supported the creation of start-up Siquance by entering into its capital in November 2022.
The projects supported by CNRS-Innovation have also performed well in terms of fundraising, with several projects raising substantial amounts, such as Alice & Bob, which raised 27 million Euros; Qubit Pharmaceuticals, which raised 16 million Euros; Aqemia, which raised 30 million Euros; Pasqal, which raised 100 million Euros, and Welinq, which recently raised 5 million Euros.
Apart from these individual successes, exciting cross-cutting projects are also underway, such as for example the collaboration between CNRS and CEA on the pre-industrialization of C12's carbon nanotube-based quantum processor, and the support for the QRYOLink project under the I-DEMO program, which aims to develop new generations of cryogenic microwave cabling systems for quantum computers. The consortium of this project covers the entire value chain and includes Alice & Bob, Atem, C12, CEA, CNRS, Cryoconcept, and Radiall.

FRANCE GRANTS FOUR R&D PROJECTS IN HARDWARE INTENSIVE **POST QUANTUM CRYPTOGRAPHY** SOLUTIONS

HYPERFORM

The Hyperform project is an industrial research project to develop software and hardware components for post-quantum cryptography. This is a response to the growing cybersecurity threat posed by quantum computing. Led by IDEMIA, the project involves two of his Hexatrust SMEs and three specialized laboratories. ANSSI and two CESTIs, including the rapidly growing SMEs, are also involved.

This project aims to develop post-quantum cryptography components for five industrial use cases, establish a reference platform for evaluating performance and vulnerability, and support standardization of cryptographic algorithms and business protocols. increase. Significant R&D activities include hiring 29 new R&D personnel, including 3 PhDs and 4 postdocs, and developing 12 patents.

The aim of the project is to put France at the forefront of global industrial research in post-quantum cryptography and serve as a core for broader expansion to other French and European players.

RESQUE

RESQUE is a collaborative project that aims to address the growing threat to current cryptography algorithms posed by emerging quantum computers. It brings together various stakeholders, including industry leaders, academics, and institutional actors, to improve the robustness of these algorithms and develop a user-oriented secure solution. The project focuses on developing a hybrid and agile Virtual Private Network (VPN) and a robust and efficient Hardware Security Module (HSM) that can protect communications, infrastructures, and networks. Regular updates of security algorithms are planned to provide an edge against external attacks, especially quantum ones. The consortium involves Thales SIX GTS France, CryptoExperts, CryptoNext, TheGreenBow, ANSSI, and INRIA.

µPQRS

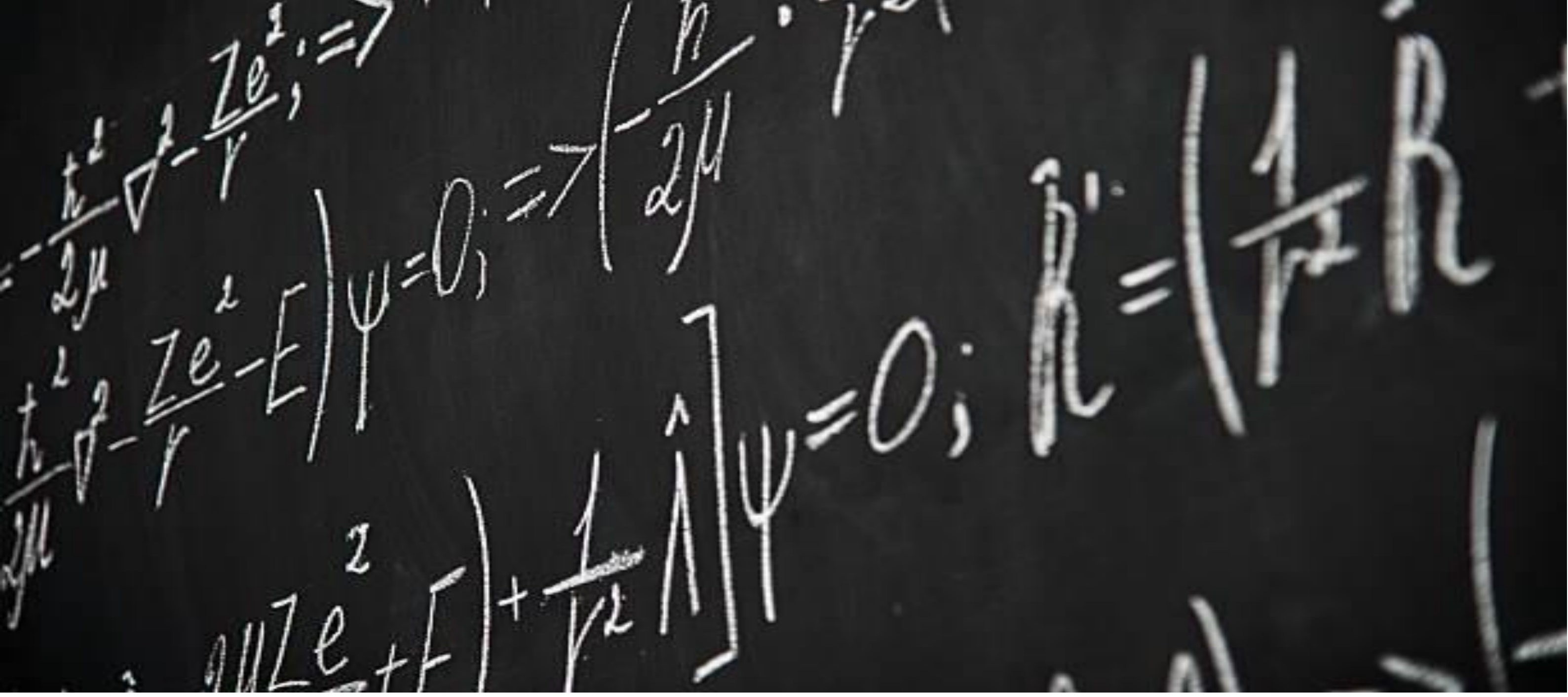
The µPQRS project aims to develop a secure microcontroller that will provide a long-term solution for the protection of sensitive data of French and European industries. The partners involved in the project, including Tiempo, Atos, Synacktiv, Menta, LIRMM, Institut Fourier, and Fondazione Bruno Kessler, will work together to design and prototype a microprocessor that will protect critical systems against cyberattacks, including quantum threats.

The secure microprocessor will have a certified architecture that will include cryptographic processors, programmable accelerators, peripherals, memories, and sensors necessary for developing security software applications. The microprocessor will be designed with the potential for future evolution, making it secure, multi-application, and suitable for a variety of deployment contexts, both civil and military.

Overall, the project aims to provide an innovative and secure solution that will help French and European industries address the growing cybersecurity threats, ultimately contributing to a safer and more resilient digital world.

X7PQC

The X7-PQC project aims to develop a innovative post-quantum cryptography to ensure France's digital sovereignty in securing tactical data links and IT infrastructure. Hensoldt France SAS has decided to develop this technology in partnership with SECURE-IC and the XLIM and TELCOM PARIS research laboratories. Essentially, the project is focused on developing a new kind of technology that will help protect important digital communications and infrastructure from future quantum computing threat.



FRANCE GRANTS A CONSORTIUM OF TWENTY-ONE UNIVERISTIES TO ENFORCE **EDUCATION AND WORKFORCE DEVELOPMENT**

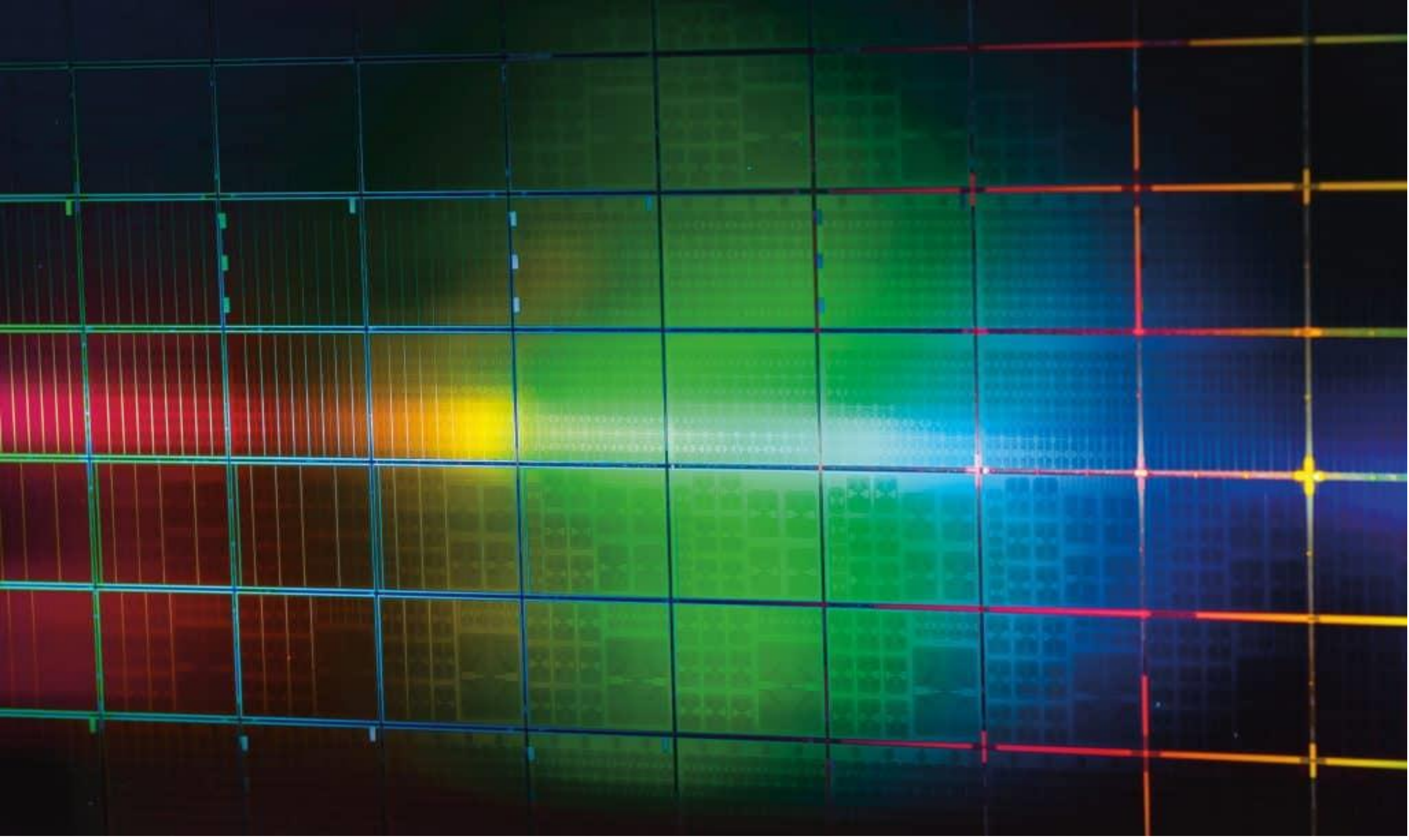
The QuanTEdu-France project, led by the University of Grenoble Alpes and supported by a consortium of 21 academic institutions, brings together professionals in initial and continuous education, with the participation of major industrial and innovation actors in quantum technology, as well as support from the Occitan Region, with the ambition of meeting the objectives set by the national strategy for quantum technology as part of the acceleration of the development of skills and human capital. The central objective of QuantEdu-France is to implement concrete actions from pre-university training to doctoral training, in initial and continuous education, in partnership with professional training and industrial players, while actively participating in the digital transition of training in higher education institutions, in order to meet the growing need for skills in quantum technologies in engineers, researchers, assistant professors and professors, technicians and managers. Indeed, the emergence of new professions encouraged by the national acceleration strategy, such as quantum engineer-doctors, calls for in-depth reflection on the education methods to be adopted. These methods must preserve the generalist character of disciplinary and fundamental teachings, while promoting interdisciplinarity, the spirit of innovation, and absorption by the job market. The objective of the QuanTEdu-France project is to consolidate interactions between academics of all disciplines, researchers, and local and national economic actors. It is also essential that fundamental research and industrial actors be able to rely on increased and improved strategic skills. Thus, the QuanTEdu-France project proposes an ambitious program to finance doctoral contracts, including the managerial and entrepreneurial component. In addition to these initial training initiatives, the development of human capital and future talent must be supported by an ambitious continiuous education program in order to double the pool of experts in quantum technologies by 2027. Quantum technologies also create a renewed need for lifelong learning, as engineers need to be (re)trained in the fundamental concepts of quantum physics or in the constant evolution of quantum technologies. Thus, beyond the strengthening of links, exchanges and interactions between the main academic, industrial and innovation players in quantum technologies, the capitalization of the actions deployed will take the form of a considerable reinforcement of the initial and continuing training offers, while actively participating in the digital transition of training in higher education institutions.

OUTSTANDING SCIENTIFIC RESULTS

More than

1000

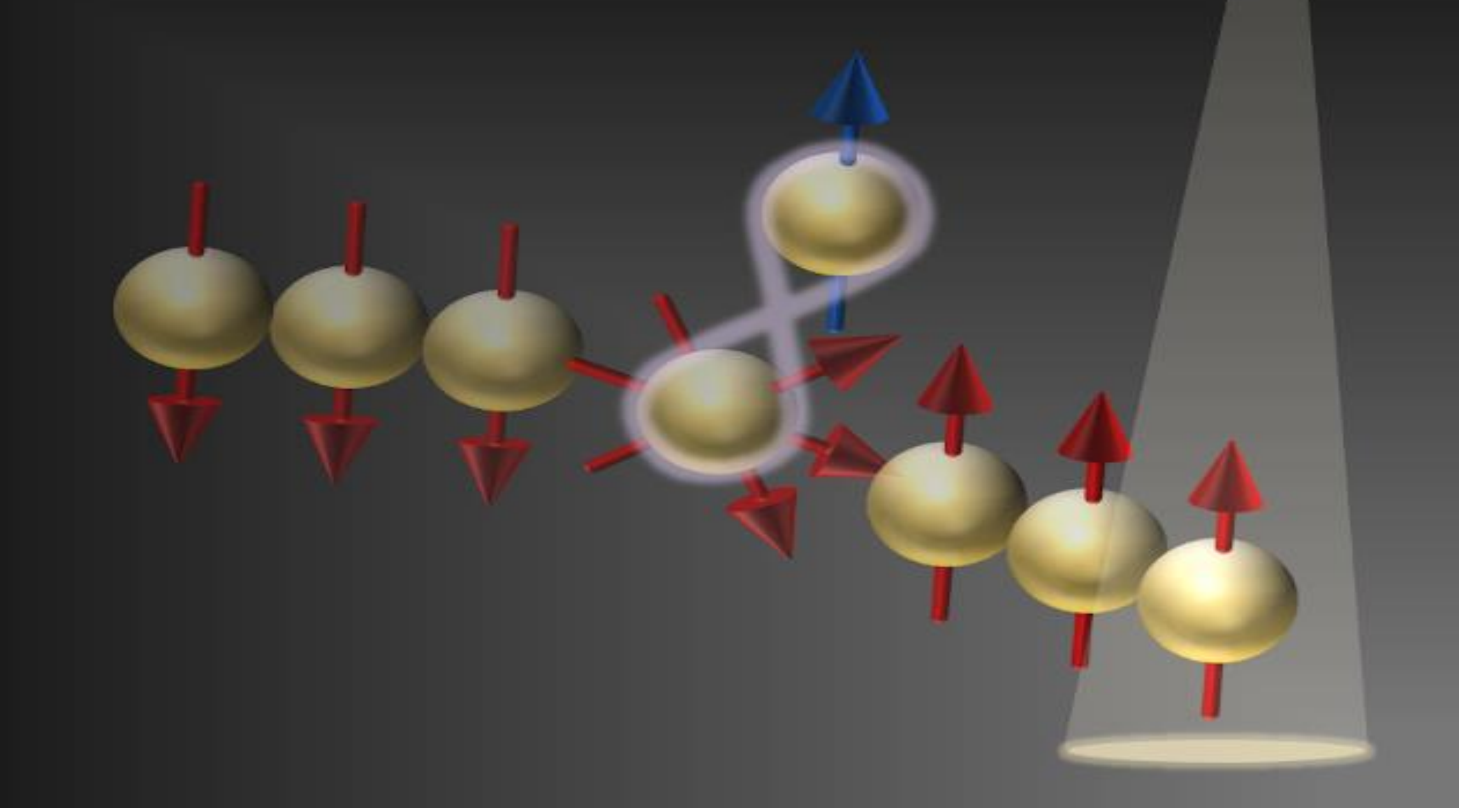
Scientific articles have been published between 2021 and 2022



A SINGLE HOLE SPIN WITH ENHANCED COHERENCE IN NATURAL SILICON

Semiconductor spin qubits based on spin-orbit states are sensitive to electric field excitations, allowing convenient, fast, and potentially scalable control of qubits. However, the electrical susceptibility of spin makes these qubits generally vulnerable to electrical noise, which limits their coherence time. We report here our work on the realization of a spin-orbit consisting of a single hole electrostatically confined in a natural (non-isotopically purified) silicon metal oxide semiconductor device. By varying the orientation of the magnetic field, we reveal the existence of optimal operating points where the impact of charge noise is minimized while preserving an efficient spin control of the electric dipole. As a consequence, we observe an extension of the Hahn-echo coherence time up to 88 mu s, exceeding by an order of magnitude the existing values reported for hole spin qubits, and approaching the state of the art for electron spin qubits with spin-orbit coupling synthesis in isotopically purified silicon. Our discovery improves the prospects of silicon-based hole spin qubits for scalable quantum information processing.

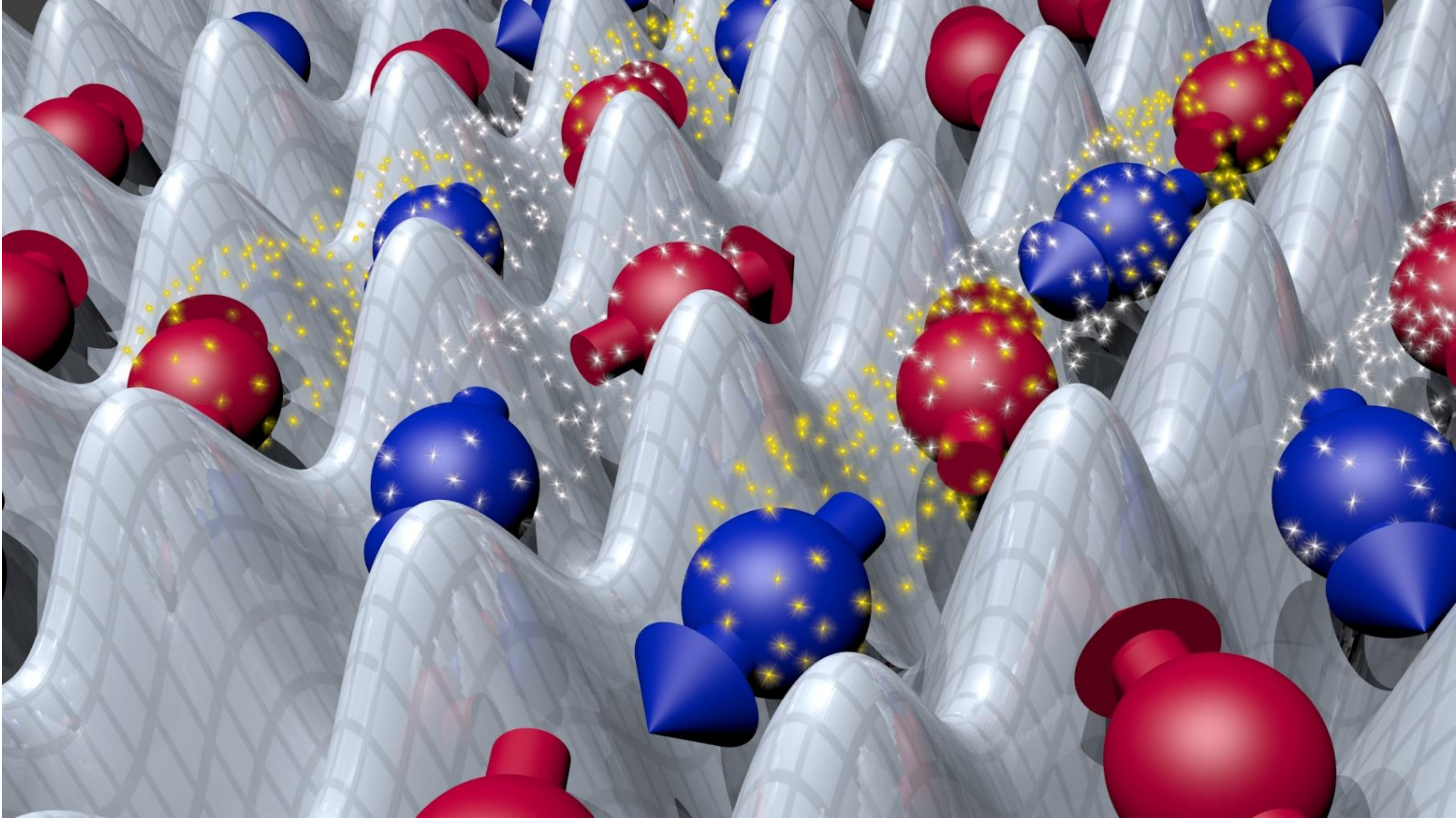
Work published in Nature Nanotechnology, October 2022.



CONTROL AND MEASUREMENT OF MULTIPLE INDIVIDUAL ELECTRON SPIN QUBITS

A team from RobustSuperQ has just achieved a major milestone in the control and readout of electron spins that can serve as decoh erence-robust quantum bits (qubits). The researchers have fabricated a simple superconducting microwave resonator on the surface of a crystal ($CaWO_4$) containing a low concentration of Er^{3+} ions. At low temperature (~10 mK) and under a moderate magnetic field B_0 (~ 0.4T), these ions behave as ½ spins initialized in their lowest energy state, and thus qubits in the |0> state. The resonator being well coupled to only a hundred of these spins, and the latter each having slightly different frequencies that vary with the amplitude of the B_0 field, it is sufficient to compensate for this amplitude to bring each spin to the resonator frequency. Once at resonance, the qubit is driven by microwave pulses. Measuring the state of the qubit is a bit more challenging! It uses a microwave photon counter developed in the same team, and based on another superconducting quantum circuit.

The counter detects the single photon emitted by the qubit when it is in its excited state |1>. In this experiment, the coherence time of each spin is greater than a millisecond, and is simply limited by the characteristic emission time of the photon (deliberately chosen to be low so that the experiment is fast). Promising in terms of quantum information processing with spins, these results also bring to a single spin the sensitivity of the electron paramagnetic resonance (EPR), a method widely used to characterize matter, and which will now be able to tackle the analysis of nano-objects.
Work to appear in Nature (2023), Z. Wang et al., Single electron-spin-resonance detection by microwave photon counting.

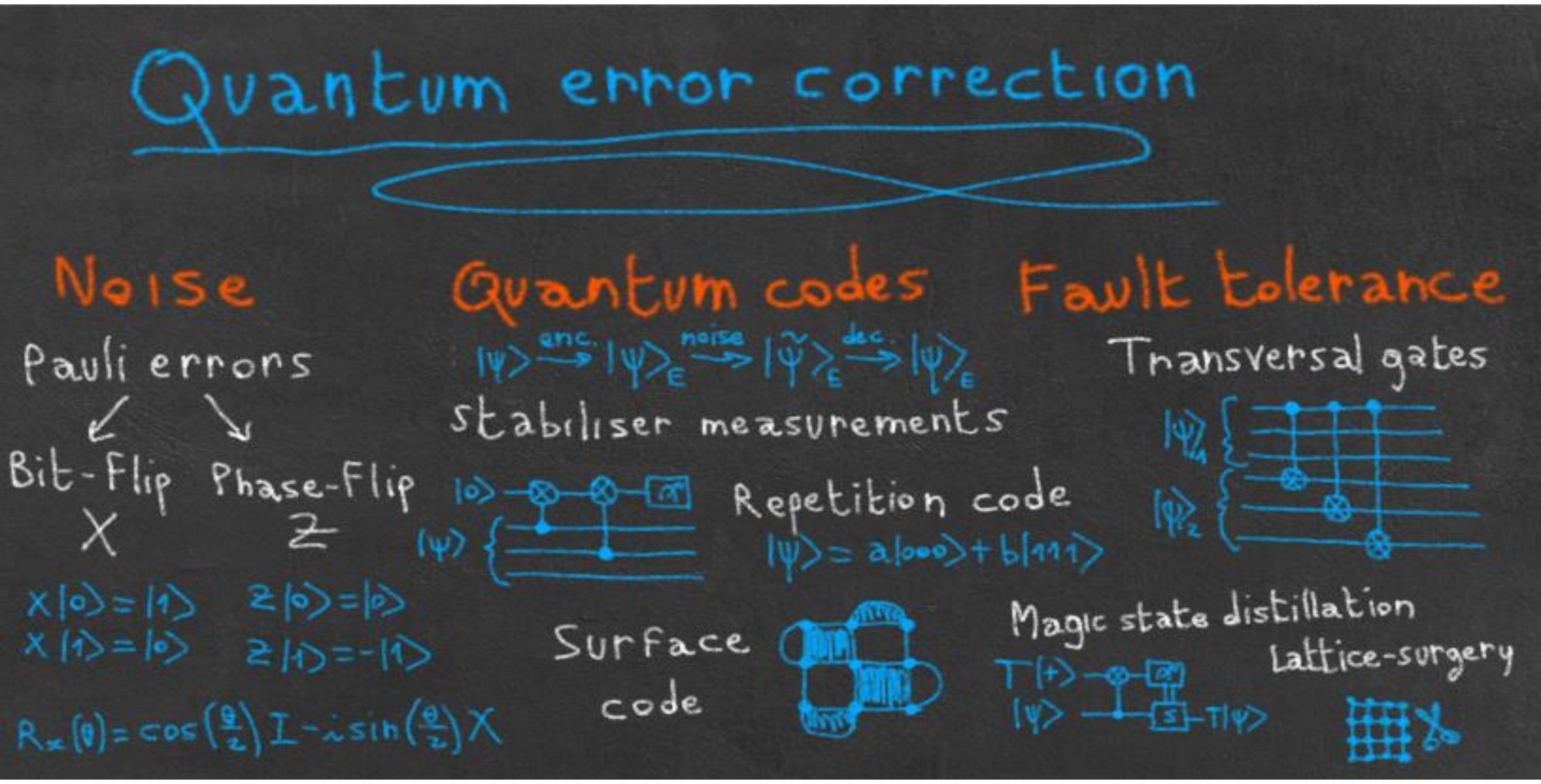


OBSERVATION OF LONG RANGE MAGNETIC ORDER IN ARTIFICIAL QUANTUM MAGNETS

Spontaneous symmetry breaking underlies much of the classification of phases of matter and their associated transitions. The nature of the underlying symmetry being broken determines many of the qualitative properties of the phase; this is illustrated by the case of discrete versus continuous symmetry breaking. Indeed, in contrast to the discrete case, the breaking of a continuous symmetry leads to the emergence of gapless Goldstone modes controlling, for instance, the thermodynamic stability of the ordered phase.

In this context, a team from the QubitAF project has experimentally realized new magnetic phases of matter. These phases have been obtained using a programable quantum simulator using a hundred of cold atoms, individually controlled, being trapped in a two-dimensional square lattice. After excitation of these atoms into well-chosen Rydberg states, their internal state can be represented by a "spin". These spins interact very strongly with each other. The team has thus realized an artificial system, described by an emblematic model in condensed matter physics, called "XY model", whose particularity lies in the fact that the interactions between spins decrease relatively slowly with distance.

This work and related results have been published by C. Cheng et al., Nature, February 2023.



THE DISCOVERY OF QUANTUM LDPC CODES WITH OPTIMAL PARAMETERS AND AN EFFICIENT DECODER

For more than 20 years, a big open question for quantum codes was to understand whether quantum LDPC codes could guarantee better protection than the surface code. In late 2021, two researchers, Panteleev and Kalachev, gave an initial construction of such codes, but without saying whether they could be decoded efficiently. In a work conducted within the framework of the NISQ2LSQ project, a simpler variant of this construction, quantum Tanner codes, was proposed by a team of researchers from INRIA and the university of Bordeaux, which indeed allows for efficient error correction, a prerequisite for using such codes for fault-tolerant computing.

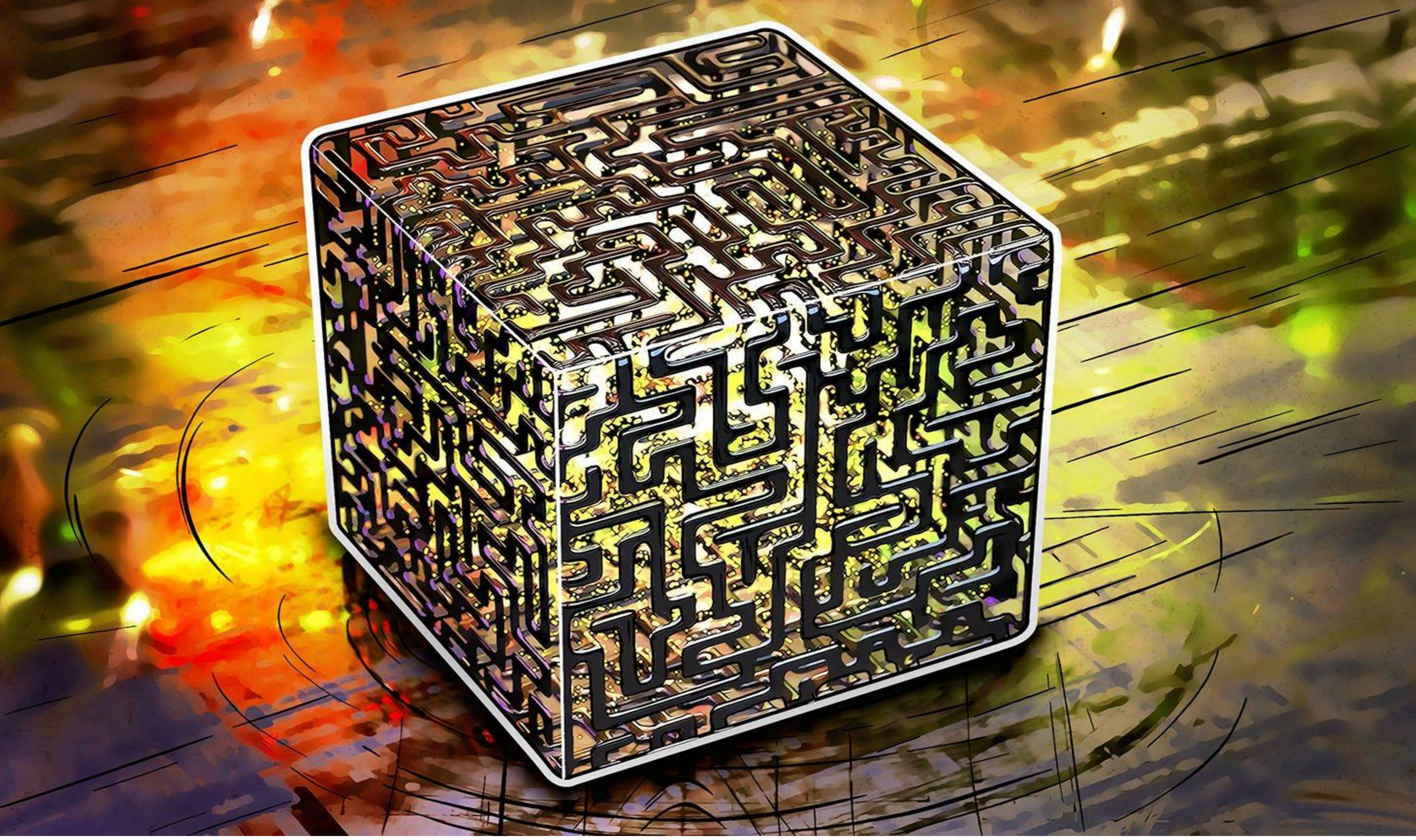
These results have greatly increased the interest of LDPC codes for quantum computing.

Those results are the object of 3 scientific papers:

- Leverrier and Gilles Zémor, "Quantum tanner codes." 2022 IEEE 63rd Annual Symposium on Foundations of Computer Science (FOCS). IEEE, 2022.

- A. Leverrier and Gilles Zémor, "Efficient decoding up to a constant fraction of the code length for asymptotically good quantum codes." Proceedings of the Annual ACM-SIAM Symposium on Discrete Algorithms (SODA), Society for Industrial and Applied Mathematics, 2023.

- A. Leverrier and Gilles Zémor, "Decoding quantum Tanner codes", arXiv preprint arXiv:2208.05537, 2022.



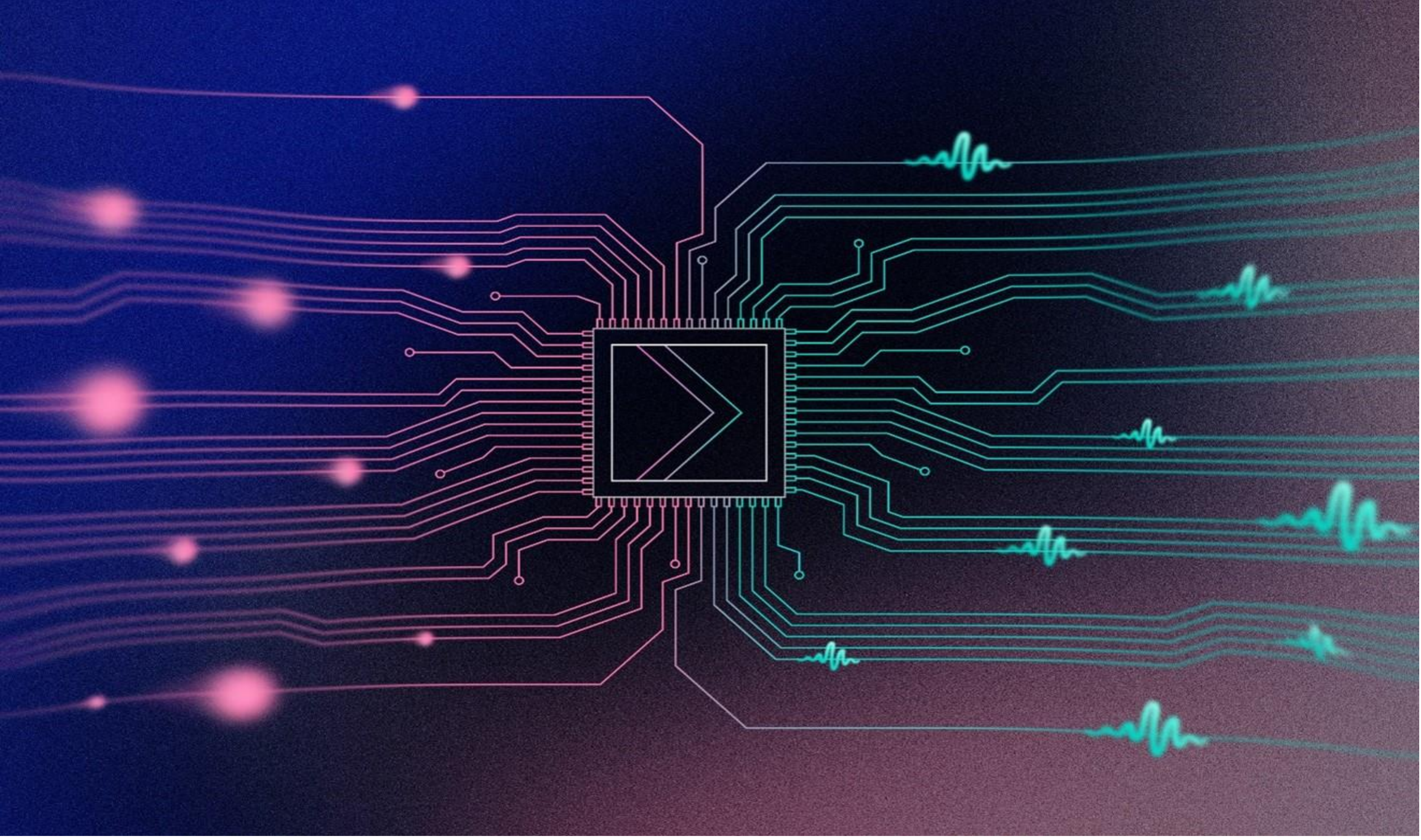
QUANTUM SUPREMACY BENCHMARK FROM GOOGLE BROKEN BY CLASSICAL COMPUTING

This work introduces a new algorithm for the simulation of quantum circuits. For the most difficult possible circuits for this technique, the so-called "quantum supremacy" benchmark of Google Inc., this new algorithm can generate bit strings of the same quality as the seminal Google experiment on a single computing core.

The algorithm is even more efficient on structured circuits used for combinatorial optimization (Quantum Approximate Optimization Algorithm or QAOA), with error rates dropping by a factor of 100 compared with random quantum circuits.

These results suggest that the current bottleneck of quantum computers is their fidelities rather than the number of qubits.

This work has been published by T. Ayral et al., PRW Quantum, February 2023.



A QUANTUM BIT ENCODING CONVERTER

Researchers at the Kastler Brossel Laboratory in Paris have succeeded in building the first converter between the two different types of quantum-bit encodings an equivalent to converters for classical information, but targeted to different types of quantum data.

This high-quality rewriting of information shows the way towards bridging the gap between the many different platforms competing in the race for quantum computing and may enable the interconnectivity of future networks.

This work has been published by T. Darras et al., Nature Photonics, January 2023, with associated press release as a News in Phys.org, and associated patent pending.

NOTABLE BUSINESS ACHIEVEMENTS

290 M€

have been raised until 2022 by

57

startups

PASQAL RAISES **€100 MILLION SERIES B FUNDING**

PASQAL, a world leader in neutral atoms quantum computing, announced today that it has secured a €100 million equity Series B raise led by Temasek, a global investment company headquartered in Singapore. This latest round of funding, which is **the most important in europe ever in quantum technologies**, includes participation from other new investors, including the European Innovation Council (EIC) Fund, Wa'ed Ventures, and Bpifrance, through its Large Venture Fund, as well as continuing investors Quantonation, the Defense Innovation Fund, Daphni, and Eni Next.

PASQAL's technology is built upon the Nobel Prize-winning research of company co-founder Alain Aspect. The company believes that its neutral atoms quantum computing platform will deliver major commercial advantages over classical computers by 2024. With the new funding, PASQAL plans to accelerate its research and development efforts to build a 1,000-qubit quantum computer in the short term and fault-tolerant architectures in the long term. The company also plans to double its current team of 100 employees this year.

The new funding will also allow PASQAL to expand its global footprint. The company plans to open offices in the Middle East and Asia this year, in addition to growing its existing operations in Europe and North America.

SIQUANCE: A NEW BORN IN THE PROMISING RACE TO **SILICON QUANTUM COMPUTING**

Siquance, a start-up founded by the French Atomic Energy Commission (CEA) and the National Centre for Scientific Research (CNRS), was launched on November 29, 2022, in Grenoble. Led by co-founder and CEO Maud Vinet, Siquance aims to develop and eventually commercialize a quantum computer based on microelectronics technology and using the capabilities of European semiconductor producers. The start-up aspires to be at the forefront of French and European sovereignty in the field of quantum computing and to become a global technological leader in the field.

Siquance's goal is to develop and market a silicon-based quantum computer using the same technologies as standard integrated circuits.

The main technological breakthrough involves transforming a transistor, the basic unit of classical computing, into a quantum bit, the basic unit of quantum computing. When assembled, these quantum bits will form a new type of computer capable of solving many problems that are currently inaccessible to classical computers.

The semiconductor-based approach is expected to be the most rapidly industrializable on a large scale, and Siquance is leveraging existing production capacities, particularly French and European semiconductor factories. Quantum computing is expected to solve complex equations that are currently beyond the reach of conventional computers. It addresses a variety of strategic and cutting-edge industrial sectors such as health, engineering, meteorology, finance, and more. Disruptive, it offers an opportunity for Europe to restore the balance of power with the US and Asia in the digital field.

Siquance was founded by Maud Vinet (CEO, from CEA, ERC laureate), Tristan Meunier (CTO, from CNRS, ERC laureate), and François Perruchot (COO, from CEA), international experts in silicon technologies, quantum engineering, and strategic marketing. Siquance is built on 15 years of research at CEA and CNRS, and its founders have been working together in their facilities for six years.

The company is strongly supported by CEA and CNRS, which are shareholders of Siquance and have provided the company with their expertise and R&D capabilities, intellectual property, technological means, and strong ecosystems covering all quantum technology issues from fundamental research to industrialization.

An R&D program with CEA and CNRS is expected to lead to the establishment of two joint laboratories, forms of collaboration between public research and companies. It will extend the support provided by CEA and CNRS.

FOUR **NEW QUANTUM ENABLING TECHNOLOGIES STARTUPS**

In 2022, France has seen a surge in the creation of startups focused on enabling technologies for quantum computing, communications and sensing.
One such startup is Welinq, which has recently raised 5 M€ to fund the development of its solution for interconnecting quantum processors. Welink's technology relies on a quantum memory that synchronizes the operations of multiple processors to increase the available computing power. This same technology also allows for the creation of quantum repeaters, which enable reliable information transfer over long distances. The company has filed several patents to protect its technology, which offers record efficiency in storing and reading information.

Another startup founded in 2022, Viqthor, is applying its expertise in RF, microwaves, and photonics to the world of quantum physics. The company's experience with these technologies allows it to provide advanced solutions for quantum processing, where qubits are controlled and read by microwave pulsed signals. Viqthor's background in developing solutions for radar, telecommunications, and atomic clocks has led to worldwide partnerships with companies such as Northtop Grumman Corporation, Raytheon, Thalès, ISRO, Boeing, and NASA.
HiQuTe Diamond, founded by researchers from Laboratoire des sciences des procédés et des matériaux and the Institut de Recherche de Chimie Paris, aims to address the shortage of high-quality, large-dimensioned single-crystal diamonds required for the development of quantum technologies based on diamond. The access to this material with reproducible and well-controlled properties is of strategic importance and raises issues of national independence.

Silent Waves, a spin-out of Néel Institute, is focused on providing advanced readout solutions. The company, co-founded by Luca Planat, Nicolas Roch, and Baptiste Planat, has developed its first product, the Argo, which is a traveling-wave parametric amplifier based on Josephson junctions. The Argo offers near quantum-limited amplification with ultra-low noise, wideband capabilities, flux-noise immunity, and high-saturation power.
With the support of academic institutions such as CNRS, these startups are well-positioned to make a significant impact in the field of quantum computing in the years to come.

THE FIRST EUROPEAN QUANTUM COMPUTER IN THE CLOUD DEVELOPED BY QUANDELA

Quandela, a quantum photonics company based in Massy, France, has launched the first European online service that provides access to its quantum computers through the infrastructures of the French cloud provider OVHcloud. This new offering allows scientists, industry players, and companies to access several photonic processors for calculations of up to 5 photonic qubits. The company plans to have 12 qubits available online by the end of 2023, with each additional photonic qubit doubling the computing power of the quantum computer.

This marks a major milestone in the medium-term development of a full-stack, fault-tolerant photonic quantum computer, as planned by Quandela a year ago. Using Quandela's Perceval software suite, users can now develop and run algorithms on a real photonic quantum processor (QPU), in addition to the simulators already available.

This allows researchers to validate their algorithms on a real architecture, thus moving one step closer to commercial applications.
The new online quantum computing service was used for the first time by researchers and students from all over Europe participating in a quantum hackathon organized by Quandela at the Sorbonne in early November. More than sixty participants were able to propose solutions to concrete use cases, proposed by industrial partners such as Thales, and ran them on photonic processors.
This new European offering joins those already proposed by some suppliers, notably American and Canadian, such as IBM, of "Quantum as a Service" allowing industrial players to discover and develop applications specific to their industry.

While quantum computing is still in its infancy, it has the potential to revolutionize industries such as finance, healthcare, and logistics. Quantum computers operate on the principles of quantum mechanics, which allow them to perform certain tasks much faster than classical computers. For example, quantum computers could break encryption methods that are currently considered secure, leading to new security challenges and opportunities.

Quandela's new offering is a significant step forward for European quantum computing, and it will be interesting to see how companies and researchers take advantage of this new service. With the promise of faster and more efficient computing power, the future of quantum computing is an exciting one, and it will be fascinating to see how this technology develops in the years to come.

PASQAL, CACIB AND MULTIVERSE COMPUTING CLOSE THE GAP TO **BUSINESS RELEVANT QUANTUM ADVANTAGE**

Crédit Agricole CIB and two European quantum computing leaders, Pasqal and Multiverse Computing, have announced conclusive results from two proof of concept (PoC) experiments using quantum computing in finance. The aim of the PoCs, launched in June 2021 by Crédit Agricole CIB, was to assess the use of an algorithmic approach inspired by quantum computing and the potential of quantum computers in finance.

The first experiment was to test the performance gain of a quantum-inspired calculation method in the valuation of derivative products, while the second was to measure the ability of a quantum computer to solve the problem of predicting the credit rating degradation of counterparties. The PoCs were successful, with a significant acceleration in calculation time and lower memory footprint, opening the door to using quantum computing in production for derivative valuations. Meanwhile, the use of the Pasqal quantum computer showed promising results, with projections indicating that this performance could be exceeded with 300 qubits, which should be available industrially in 2024.

The potential for a technological breakthrough in quantum computing is evident, and financial institutions must prepare to adapt to this disruption. The possibility of a quantum computing revolution in the finance industry is exciting, and these successful experiments demonstrate that we are one step closer to this reality.

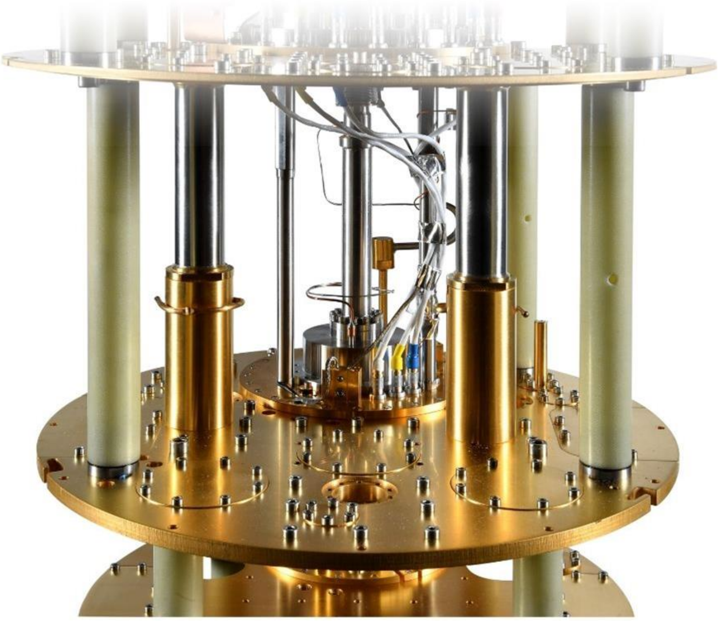
ORANO PROVIDES A NEW SOURCE OF ISOTOPICALLY **PURIFIED ^{28}Si**

After unveiling its new stable isotopes facility by the end of 2021, the French nuclear supplier ORANO will become in 2023 a reliable alternative in a market dominated by Russia as a provider of 28Si, a key material used in the production of silicon qubits.

Orano Stable Isotopes has developed an isotope separation line using gas centrifugation that allows to enrich Silicon-28 up to 99,99%. This process ensures high isotopic purity and a stable supply chain located in France, making Orano a reliable and efficient provider of 28Si.

With this capability, France will become a viable supplier in the production of 28Si, providing worldwide companies and labs with a secure and stable source of this essential material.

As the field of quantum technologies continues to grow, France's ability to supply high-quality 28Si will be increasingly important, and Orano's expertise in isotopic separation and its dedicated production capability will be a key factor in ensuring the success of this field.



AIRLIQUIDE PROVIDES A NEW SOURCE OF ^{3}He

Air Liquide, with its long track record of mastering very low temperatures at industrial scale, is a key partner for the scaling-up of quantum computing. Cooling power at very low temperatures will become critical to ensure an adequate thermal environment for several promising qubits technologies and their associated electronics.

Air Liquide ambitions to play a key role in quantum computing focusing on two main objectives: (i) anticipate the needs for industrial cryogenic systems operating from room temperature down to 20 millikelvin and (ii) develop robust cryogenics systems to support the ever growing requirements of quantum chips manufacturing and quantum stacks integrators. This includes the supply of critical raw materials such as Silicon-28 or Helium-3, a stable isotope of helium that offers access to extremely cold temperatures under 1 Kelvin.

In 2022, the Air Liquide Cryoconcept team passed a major milestone while delivering cooling power at 7 mK with their dilution refrigeration technology.

For Helium-3, Air Liquide has set up a new source from the Canadian civil nuclear power sector through a partnership with Laurentis Energy Partners to produce and deliver this rare and paramount gas to its customers.

Since the end of 2021, Laurentis Energy Partners has launched the Helium-3 production phase with the extraction, pre-purification and filling of a first crude Helium-3 cylinder. Air Liquide Rare Gases then purifies the molecule and packages it for distribution to end-users worldwide. This step marks an important milestone in setting up the supply chain in France. The ambition remains high and Air Liquide is working together with the major stakeholders of the worldwide ecosystem to provide them with a reliable Helium-3 source in short to medium term and then contributes to quantum computing technologies development.

QUANTUM RELATED POLICIES

- ✓ International cooperation
- ✓ Standardization
- ✓ National Security

FRANCE ESTABLISHES A NATIONAL PROGRAM ON **MEASUREMENT, EVALUATION AND STANDARDIZATION** OF QUANTUM TECHNOLOGIES

With the ambition to support innovation and establishment of a thriving and sustainable quantum industry, MetriQs-France program aims at developing, exploiting and promoting reference measurement means for reliable, comparable, and impartial characterizations and performance evaluations of these emerging technologies. Such information is required to demonstrate indisputably the possible advantage of the quantum technologies over existing ones and to enable their adoption by industry and market. This is all the more important in the context of the strong international competition resulting from the high promises and potential of quantum technologies regarding socio-economical and sovereignty impacts.

The program has three specific objectives: (1) Develop reference methods and technical capabilities, well-established, validated, harmonized, for reliable, comparable and objective measurements of device characteristics and performance on the same basis; (2) Test and evaluate the technologies using the above mentioned methods and capabilities; (3) Promote the outcomes and results through standardization, good practice guides, metrology services, scientific papers…

The program will address the measurement needs on the priority topics of the National Quantum Strategy: quantum computing (from hardware to applications, passing through algorithms, and programing languages), quantum sensing, quantum communication and importantly the enabling technologies (electronics, cryogenics, lasers…). MetriQs-France is coordinated by LNE, the French national metrology and testing laboratory, which will take advantage of its expertise of measurements, including its ability to deliver high-level measurement services, of its competences in quantum metrology, and of its status of independent and trustable third party.

Practically, the program comprises two complementary parts: (1) a main operating part dedicated to R&D on the measurement means, to evaluation, to promotion and coordination actions; (2) a second part for the deployment of a quantum metrology infrastructure based on the French national metrology network led by LNE.

The first part mixes thematic collaborative projects on the topics where needs have been expressed and transversal actions about coordination and promotion. Application-oriented performance benchmarks for quantum computing, characterization of hardware components, of electronics, cryogenics and lasers are among the topics the program plans to address.

In 2022, with the support of MetriQs-France, the French national standardization committee on quantum technologies has been created at AFNOR. The establishment of the committee is a crucial step towards ensuring the success of the French quantum ecosystem. With already more than twenty active members at the end of 2022, the committee brings together experts from academia, industry, and government to develop and promote standards that will guide the development, deployment, and use of quantum technologies worldwide, and in France first. The AFNOR committee thus enables the French participation in European and international standardization projects and committees related to quantum technologies, like at ISO/IEC JTC1 on "Information Technology" led by the USA.
Importantly, France has just taken the leadership of the working group on "Quantum Computing and Simulation" in the newly created European committee CEN-CENELEC JTC22 on "Quantum Technologies" led by Germany and the Netherlands. In parallel to roadmapping activities, the first standardization projects concern terminology, characterization or interoperability, depending on the field of quantum technologies, all targeting best common practices and harmonization.

MetriQs-France, with AFNOR as first actor, also promotes awareness and understanding of the importance of standards in the development of quantum technologies, and encourage participation and contributions from all stakeholders in the French quantum ecosystem, with the vision of standards that must be industry driven and science based. MetriQs-France also coordinates the French efforts in the different standardization channels, be there in the above mentioned standard development organizations or private consortia like IEEE (US), as well as pre-standardization initiatives.

Regarding the quantum metrology platform led by LNE, the ambition is to have a national infrastructure, expert, independent, open to academic and industrial users and with state-of-the art equipment for metrology R&D and services to support quantum technologies development (high-level characterization, calibration, test and evaluation, validation…).
The platform will gather expertise available in the French national metrology network, about engineering and measurement of quantum systems (cold atoms to condensed matters and nanodevices), experimental facilities with best-controlled environment, and well-mastered equipment. Installation of new state-of-the-art equipment will complete the existing ones and reinforce the capabilities of the network to address the measurement needs emerging in the National Quantum Strategy within projects unfolded in the first part of the program.

The platform will cover the characterization of solid-state qubits and the corresponding enabling technologies, thermometry at very low temperature (~10 mK) with quantum optomechanical techniques in particular, and services for the characterization of atomic clocks and gravimeters at the best level. The platform will be deployed within the perspective of building a national network of trusted characterization facilities for quantum technologies. Another important objective is to strongly position the platform in Europe and at international, with participation in initiatives like the European Metrology Network for Quantum Technologies (EMN-Q) under the auspices of EURAMET and Qu-Test, the European infrastructure for test and experimentation of quantum technologies under development.

NIST, CNRS AND UNIVERSITY OF LIMOGES SIGN LICENSE AGREEMENT TO PROMOTE WIDESPREAD ADOPTION OF **PQC STANDARDS**

In 2022, the National Institute of Standards and Technology (NIST), the French National Centre for Scientific Research (CNRS) and the University of Limoges signed a license agreement to promote timely and large adoption of post-quantum cryptographic (PQC) standards derived from selected algorithms.

As the development of quantum computers poses a security threat to the communication and authentication systems widely used in our everyday lives, the NIST launched an international call for contributions in July 2016 to identify the best candidates for future post-quantum cryptography standards capable of resisting the quantum computers of the future.

After analyzing the security level and performance of the candidates, the NIST selected four of them for a final phase. Two of the finalist solutions were found to be based on patent families submitted in 2010 by researchers from the joint research unit CNRS Xlim, which are jointly held by the CNRS and the University of Limoges.

In light of the general interest of a global standardization process, the CNRS and the University of Limoges agreed, with the support of France Brevets, to a license agreement that promotes an intellectual property that emerged from results achieved by French public research.

As a result of the license agreement, implementers and end users of cryptographic standards derived from the selected PQC algorithms do not require a separate license under the CNRS patent family. This will facilitate the timely and widespread adoption of these cryptographic standards, a common goal of NIST and CNRS.

License agreements are a testimony to the value of international cooperation in fostering innovation and promoting common good. NIST, CNRS, and the University of Limoges have committed to continue working together to advance the field of post-quantum cryptography and promote widespread adoption of secure cryptographic standards.

THE FRENCH LANGUAGE ENRICHMENT COMMISSION OFFICIALLY INTEGRATES **QUANTUM TECHNOLOGIES VOCABULARY**

The Commission for the Enrichment of French Language (CELF) has been very active in the year 2022, particularly in the field of quantum computing. The commission, which is an inter-ministerial device under the authority of the Prime Minister, has a mission to promote and define French equivalents of foreign words used in various domains.

The inclusion of quantum vocabulary to the French language is an important milestone achieved in 2022. The CELF recognized the growing significance of quantum computing and its potential impact on various sectors, and thus took the initiative to address this technical domain.
As the subject of quantum computing is relatively new, there is a lack of established French vocabulary to describe its terms and concepts. The CELF aims to overcome this issue by introducing new French words that accurately describe the technical terminology of quantum computing.

The commission had a team of experts, including Hervé Arribart, Alain Aspect, Alexia Auffèves, Éric-Marc Mahé, Olivier Ezratty, Jean-Pierre Grandjean, and Philippe Grangier, who worked together to identify and promote French equivalents of the technical terms related to quantum computing. They analyzed and interpreted the complex concepts and technical vocabulary to create words that are precise and understandable to the public.

The commission's efforts have resulted in the creation of several new French words, such as "accélérateur quantique" (quantum accelerator), "cryptographie postquantique" (post-quantum cryptography), and "dualité onde-corpuscule" (wave-particle duality), to name a few. These new words help French speakers to have access to a precise and accurate vocabulary to describe quantum computing concepts.

Lean more :
https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000046761612

#QEI

the quantum energy initiative

FRANCE SUPPORTS **A QUANTUM ENERGY INITIATIVE**

The Quantum Energy Initiative is an international community of researchers and industry vendors launched in August 2022. It gathers experts from various origins, from fundamental quantum physics to technology, from hardware to software, from research to industry, caring for the physical resource cost of emerging quantum technologies and willing to address the question in a scientific way. This requires building new methodologies, language, and roadmaps.

The launch of the initiative followed the publication of the "Quantum Technologies Need an Energy Initiative" perspective in PRX Quantum in June 2022 authored by Alexia Auffèves, then at Institut Néel in Grenoble. Its founders are Alexia Auffèves (now, Director of the CNRS International Research Lab MajuLab in Singapore, author of the perspective), Robert Whitney (CNRS LPMMC Grenoble), Janine Splettstoesser (Chalmers University, Sweden) and Olivier Ezratty (quantum technology expert and author of the reference "Understanding Quantum Technologies" open source book).
It has an international board with scientists from five continents (North and South America, Europe, Asia and Australia). As of March 2023, the Quantum Energy Initiative gathered the support of more than 290 participants from over 40 countries, as well as 24 research, industry vendors, HPC providers partners and quantum ecosystems participants.
This international initiative is supported by France National Quantum Strategy, HQI-GENCI, Pasqal, Quandela, Alice&Bob, Siquance, Atos, Le Lab Quantique, Quantonation as well as by CSC (Finland), aQuantum (Spain), Qilimanjaro (Spain), IQM (Finland), ParityQC (Austria), Kipu Quantum (Germany) and Qnami (Switzerland).

It will contribute to establish news standards and benchmarks on the energetics of quantum technologies and establish the basis of responsible innovation practices for quantum technologies.

The Quantum Energy Initiative is organizing its first international workshop in Singapore in November 20th-24th, 2023 with confirmed talks from Michel Devoret (Yale University), Peter Zoller (ICOQI, Innsbruck), Giulia Ferrini (Chalmers University), Masahito Ueda (University of Tokyo), Janet Anders (Exeter University) and Benjamin Huard (ENS Lyon) among other speakers.

Lean more :
https://quantum-energy-initiative.org/

FRANCE, THE NETHERLANDS AND GERMANY SIGN AN AGREEMENT TO ENFORCE **TRILATERAL QUANTUM COOPERATION**

The French, the German and Dutch quantum strategies and the European framework program constitute opportunities to position Europe in the race to lead the development of quantum technologies and contribute to solve the major challenges of the coming decades: climate changes, drug design, cyber security...

To meet the challenge of European strategic autonomy in this technology area and create the basis for future European leaders in quantum, Bruno Bonnel, the French Secretary General for Investments, Ina Schieferdecker, the German Director General for Research for Technological Severeignty and Innovation, and Guido Biessen, Dutch Acting Director-General for Enterprises and Innovation, signed on November the 17th 2022, a Joint Statement On Cooperation in Quantum Technologies. Its aim: to increase the synergies between the French, the German and Dutch ecosystems and achieve the critical mass needed to help develop European leaders and attract the best international talents.

” Quantum technologies are among the few key digital technologies that have emerged in Europe and on which we must collectively give ourselves the means to be the leaders of tomorrow. Through the signing of the joint statement between Germany, the Netherlands and France, three global leading countries in quantum technologies, we wish to consolidate our trilateral cooperation in academic research and accelerate private synergies that will lay the foundations for European quantum unicorns, especially in universal quantum computers. Thru our respective national quantum initiatives, and the programs of the European Commission, Europe is by far the world's leading investor in quantum. Cooperation between member states is the key to our collective success.

Neil ABROUG

FRANCE AND THE UNITED STATES SIGN AN AGREEMENT TO ENFORCE **BILATERAL QUANTUM COOPERATION**

On November 30th, 2022, the United States and France signed a Joint Statement on Cooperation in Quantum Information Science and Technology (QIST) in Washington, DC.

The agreement builds upon previous agreements, including an Agreement on Science and Technology Cooperation signed in 2018 and a 2021 Joint Statement on Science and Technology Cooperation, which focused on quantum information science. Dr. Arati Prabhakar, Director of the White House Office of Science and Technology Policy, signed the joint statement for the United States, while Dr. Sylvie Retailleau, Minister for Higher Education and Research, signed for France. The statement recognizes the potential for QIST to transform science and technology through the development of quantum computers, networks, and sensors, but also acknowledges the need for new cryptographic algorithms to protect against future quantum computer attacks. Both leaders recognized the potential for QIST to address pressing scientific questions for the benefit of humanity and deeply transform many sectors of the economy. They expressed their shared commitment to work together to reach common goals based on shared values, grounded in a belief that QIST can solve some of the most pressing scientific problems and offer new capabilities over traditional devices.

Dr. Charles Tahan and Dr. Neil Abroug highlighted the importance of international collaboration and discussed plans for a joint workshop to bring together quantum researchers from both countries. This joint statement will facilitate cooperation between the American and French ecosystems, with the goal of developing useful and robust quantum technologies to address the challenges facing both countries.

FRANCE ENFORCES THE PROTECTION OF **STRATEGIC QUANTUM ASSETS**

Quantum technologies raise significant security and defense issues. Although industrial or military applications are still in their infancy, their potential to change the strategic situation remains very high. In the short term, the focus is on quantum sensors, which are the most advanced technologies. In the longer term, quantum computing and post quantum cryptography are major game changers.

Aware of the associated security risks and convinced of the necessary protection against malicious entities, France relies on several protection measures to counter the threat of capture or misappropriation of knowledge, know-hows and technologies developed in the country. With the National Scientific and Technological Potential Protection, relevant laboratories and companies take part in raising awareness and can take appropriate measures to increase their protection. Moreover, entities that beneficiate from public investment are compelled to taking protection measures adapted to their characteristics. France also pays great attention to its companies in the sector, to warn them against economic coercion and threat. For example, under certain circumstances defined by law, an acquisition by a foreign investor of a French entity which carries out research and development in quantum technologies, should be authorized by the Minister of Economy.

As a key asset for our future economy, the French authorities monitor closely any foreign interest or takeover in quantum sector, without harming any potential international and European cooperation. In mirror with its substantial funding, the French Government helped in 2022 the business to mitigate the risk of such situations in almost 50 cases. It’s a raise of over 150% in comparison with the previous year.
A large majority of these risks can be originated outside of EU.

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