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National Strategy on Quantum Technologies

SACLAY

January 21, 2021

Summary

Editorial

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President of the Republic
French

Quantum technologies project us into the France of 2030, the one we are building through France Relance and investments for the future: a world where computer performance will be dazzling and the sensitivity of sensors extreme, a world where we will be able to identify very quickly the remedy for a pathogenic agent, simulating molecules, deciphering messages that are currently indecipherable and communicating in a perfectly secure manner.

A new technological revolution is looming and France will play its full part in it. To aim high, we must look far. If, in the management of a health crisis, responsiveness counts, the deep forces of a country are built at least over years, if not decades. This long period of scientific work, this anticipation required by discovery and experimentation, is at the heart of our investment policy in research and technological development.

Today France has all the keys in hand to open the doors of quantum innovation. The excellence of our scientific tradition, of course. The quality of our training. Talented women and men. A booming scientific, entrepreneurial and industrial ecosystem. Actors who build bridges between their skills that make them stronger. In fact, in the race for these new technologies, we are in a very good position. And we are still going to force the pace.

France's quantum strategy will give a big boost to training, scientific research and technological experimentation, while strengthening industrial value chains. With this plan, we intend to permanently establish France in the first circle of countries that have mastered quantum technologies. It is about nothing less than conquering our sovereignty in this technological field which will shape the future.

This momentum is accompanied by a responsibility, which we bear in conscience, so that this quantum revolution benefits the common good, because it is full of promise for the future, for our health, our security, our communications. France, a pioneer in research in the field, is thus giving itself every chance of seizing the technological opportunity that is opening up to it.

This strategy, which represents an overall commitment of €1.8 billion, will require a cumulative effort from the State of nearly €1 billion by 2025, and includes European and industrial funding.

Beyond this powerful national dynamic, France will seek to lead other European countries, including Germany and the Netherlands, towards a common horizon, with the ambition of making Europe the global center of gravity. quantum technologies.

At the heart of this crisis, I deeply believe that we must act, think, search as explorers, inventors, pioneers, pursuing the great European epic of the scientific spirit.

We have every reason to believe it.

Editorial

In the context of global recovery, France can and must position itself at the forefront of the technologies that will make the world of tomorrow. Through the unprecedented forward shift they announce, quantum technologies constitute both a threat and an opportunity.

Although still demanding to implement, the first applications give us a glimpse of the immense capacities of computers, communication networks and quantum sensors, the mastery of which would confer a strategic advantage, often dreamed of in terms of 'supremacy', but nevertheless very real. for the States which would have it, and would constitute a source of asymmetry in all the multilateral fields.

This is the extraordinary scale of the sovereignty challenge that we are facing, and that France has chosen to take up with its quantum strategy. Based on the heritage of excellent research in the field, a favorable industrial ecosystem and an enthusiastic entrepreneurial spirit, this strategy provides means and a common sense over time to the many players in this community, to anchor and perpetuate France in the first circle of quantum powers.

It will be a captivating scientific and intellectual adventure, from which will emerge a new discipline at the crossroads of physical, computer and mathematical sciences, which will have to overcome many conceptual and technical obstacles at the frontiers of our mastery of matter. It will also be a structuring technological and industrial journey, at the heart of the actions that we will carry out over the next 5 years, with the permanent objective of creating economic value, sustainably backed by a complete industrial sector, the talents that we will train and the new jobs that will result.

We will carry this momentum with all our strength, so that it contributes to creating a fruitful European dynamic, and that quantum technologies join the list of founding achievements of our common history, when we are aligned to the best of ourselves.

Florence Parly
Minister of the Armed Forces

Bruno the Mayor
Minister of Economy, Finance and
RELAUNCH

Frederique Vidal
Minister of Education Superior, Research and Innovation

Cedric O
Secretary of State for Digital

Quantum: a technological “Big Bang”

The shortening of computing times by a factor of one billion, which quantum computers will provide in the next 5 to 10 years, constitutes a major technological breakthrough. Industry will benefit from new simulation and optimization tools with significant societal impacts, particularly in terms of health, environment or energy, thanks to the possibility of dynamically simulating molecules and their action, opening a new era of chemistry. , or to accurately predict epidemic spread or optimize traffic systemically in real time. In addition, atomic ultra-cooling techniques will make it possible to exceed the precision of our atomic clocks and quantum sensors will revolutionize our future battlefields, by bringing new navigation functionalities without satellite, or even new detection capabilities.

Quantum technologies represent significant issues of competitiveness and sovereignty and tomorrow we will be in difficulty if we do not eventually have our own technological capacities in the field or if we do not adapt our tools to these new realities. The power of quantum computers would allow, for example, whoever benefits from them first and intends to do so, to unilaterally break the encryption keys that are today inviolable, in particular those based on the RSA encryption protocol, used for example for our secure payments by credit card. This is why it is crucial to protect against this type of threat with appropriate cryptographic measures, and to test its robustness with our own means of quantum computing.

Quantum technologies and computers will, in the medium term, confer a certain strategic advantage on the economic actors who have seized upon them. With regard to the challenges of economic growth and sovereignty, and following the example of the main great world powers, the United States, China, the United Kingdom or Germany, we are today setting up an ambitious national program : France has the means to seize the opportunity of quantum technologies and become a world leader in this field.

Today, France has the main assets to establish itself as a major scientific and industrial competitor in quantum technologies, in particular thanks to the historical positioning of its research on various key technological bricks ranging from the component to the use, but also its industrial precursors and its dynamic ecosystem of start-ups.

Based on these strengths, the quantum strategy should allow France to enter the first circle of countries that master quantum technologies. Highly systemic, this strategy aims to enrich and affirm our capability on the scientific and technological level, but also in the industrial value chains, the development of human capital or even the anticipation of skills needs for these markets, by gradually doubling the pool of specialists by 2025, in order to guarantee and sustain our independence in this technological field which will shape the future.

Socio-economic impacts

Take better care

At a time when supercomputers around the world are mobilized to search for a suitable remedy for the Coronavirus, quantum computers could become one of the most powerful tools ever designed to fight against health crises, making it possible to identify very quickly the remedy for a pathogen.

As of today, several quantum start-ups, including some in France, are developing hybrid software solutions between supercomputers and quantum computers to discover new therapies. With a quantum computer, we will be able to do advanced simulation and thus design drugs no longer empirically, but in a deterministic way. Quantum computers could also provide the analytical power needed to predict the spread of a pathogen before it turns into an epidemic.

Eat better

The "Haber-Bosch" process of nitrogen fixation for the manufacture of ammonia-based fertilizers, marketed in 1913 and still used today, has greatly contributed to the eradication of famine in developed countries. However, by involving extreme temperature and pressure conditions, this process remains very energy-intensive.

For decades, chemists have tried to improve the energy efficiency of this process. Thanks to their ability to efficiently simulate physical and chemical interactions at the atomic level, quantum computers could contribute to the identification of an efficient bio-inspired catalyst for the production of ammonia under normal conditions of temperature and pressure. Research work carried out on this subject has shown that it would take just one hour of calculation by a quantum computer of a few hundred qubits to solve this problem. This could be achieved in the next few years.

With 3% of global natural gas production used for the Haber-Bosch process, we spend €11 billion on natural gas every year, and emit 7.6 billion tonnes of CO_2 to create ammonia to produce fertilizer. By helping to reduce the energy footprint of fertilizer production, quantum computing could then offer substantial prospects for savings and a reduction in the ecological impact of the agri-food industry.

Better combat climate change and its effects

Along with health and food, the fight against climate change is the area for which quantum computing holds the most hope for the next two decades. CO_2 is naturally absorbed by the oceans and vegetation. Nevertheless, human production of CO_2 has exceeded the natural absorption rate for many decades. One way to reverse this trend is to capture CO_2 to transform it back into a more complex molecule.

We know of a set of catalysts capable of capturing CO_2, but most require rare metals or are difficult to produce and expensive to deploy. Observation of the biological processes of CO_2 assimilation, such as photosynthesis, nevertheless supports the idea that there may be catalysts that can easily capture CO_2 at a lower cost. However, finding such a catalyst is a daunting task without the ability to simulate the molecular properties of the different candidates.

With its capabilities to simulate molecular dynamics and search in huge combinatorial chemical spaces, quantum computers could identify an economically viable process for efficient recycling of CO_2 and production of by-products of interest . like hydrogen or carbon monoxide.

Better anticipate natural disasters

The anticipation of natural disasters is the field where quantum sensors embedded in satellites take on their full meaning, particularly in the context of climate change in which we live.

The development of cold atom accelerometers operating in satellites in low orbit will be able to measure the variations in the field of gravity caused in particular by the variation in the distribution of masses on the ground. This mass distribution can have different causes related to different types of natural disasters:

- The loading of groundwater, harbingers of flooding or drought;
- The development of biomass, with the seasonal cycle, the variability of which can signal structural changes in ecosystems;
- The movements of matter in the basement, which can create stresses that will be released during earthquakes.

The information collected by these sensors could be valuable for anticipating and better managing environmental crises. Beyond the sensors, the processing of information thus collected by sufficiently powerful future quantum computers will make it possible to characterize the harbingers of natural disasters.

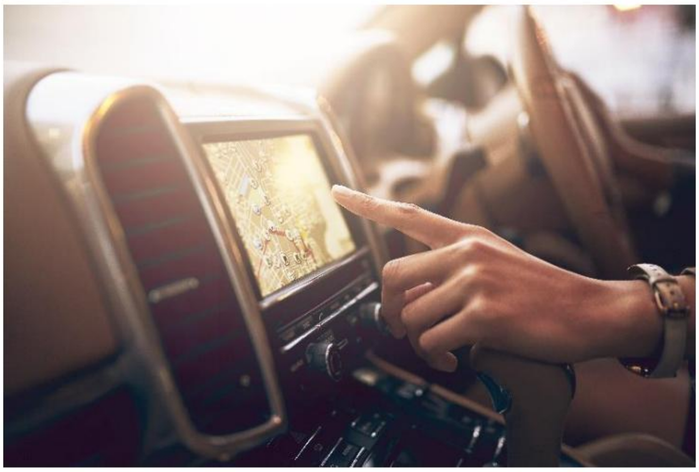
Move better

At peak times, many drivers simultaneously request the shortest possible routes, but current navigation services handle these requests individually.
They do not take into consideration the number of similar requests, including in areas where other drivers plan to share the same route segments. With similar departure times, an individual GPS app that gives everyone the same route to their destination will inevitably create congestion instead of smoothing it out.

What if we could develop a more holistic routing system – one that could take into account all the different route requests from drivers and optimize route suggestions so as to minimize the number of vehicles sharing the same roads?

It might save everyone some time. However, the number of factors involved – thousands of vehicles, millions of possible routes and destinations – mean that even supercomputers do not have sufficient computing power to find the optimal solution in good time and optimize traffic. in large scale.

By being able to efficiently solve what is akin to the classic "traveling salesman" problem, quantum computers could provide drivers with balanced routes, resulting in smoother traffic, more efficient journeys and even pollution reduction.



Better produce

Chemistry is still a largely empirical discipline. Although "theoretical chemistry" attempts to describe the mechanisms of self-assembly and other phenomena involved in interactions, chemists still favor heuristic rules to make predictions about the behavior of a molecule, a set of molecules, or a material.

On the other hand, a quantum computer would make it possible to calculate with precision the comprising of the largest molecules. Quantum computers may hold the key to the predictive power that “classic” methods of theoretical chemistry lack. In other words, quantum computers could transform chemistry from an art of rules of thumb to a science based on prediction through numerical simulation, thus opening a new era of this discipline.

Better protect against threats to communications security

Cryptography is used to ensure the confidentiality and integrity of communications in the face of threats ill-intentioned listening or modification traffic. The mechanisms asymmetric technologies used today, such as RSA, will be threatened by the possibility of a sufficiently powerful quantum computer.

Faced with this threat, it is necessary to implement new mo communication security dalities cations. This is the research field of post-quantum cryptography. Replacing current mechanisms with new quantum-computer-resistant mechanisms keeps the current communications infrastructure unchanged.

With regard to symmetric encryption mechanisms, used to secure very sensitive information, nothing allows us to say, at the present time, that they would be seriously threatened by quantum computers.

Better prepare for future conflicts

In a modern conflictuality where technological superiority remains a major if not decisive asset, the defense sector systematically exploits the opportunities offered by all innovations, which may come from the civilian world.

The implementation by foreign powers of equipment and weapon systems integrating quantum technologies will give them a strategic advantage. However, this reinforcement of power must lead to adapting our defense tool, under penalty of downgrading. Even if the implementation of quantum solutions in our defense system were not sought, the full investment of this sector by foreign States would require a response. Post-quantum cryptography shines this mechanism very well.

In addition, sensors, cryptography, calculation and communications must be subject to permanent monitoring in order to anticipate, detect and appropriate any development that could constitute a "game changer" for military operations.

Certain applications, particularly in the field of quantum sensors and computers, open up interesting prospects for defence:

- Quantum inertial navigation, in particular using cold atoms, makes it possible to position oneself in space without the services of “Geolocation and Navigation by a Satellite System” (GNSS). These technologies could reach operational maturity within 5 to 10 years;

- In the context of electronic warfare, better precision in the measurement of time/frequency gives a strategic advantage to the armed forces in terms of electromagnetic interception and robust communications. ;

France's assets in the race for the universal quantum computer

France has differentiating assets to become one of the first nations to achieve the feat of developing a universal quantum computer: the excellence of its basic research in physics and computer science (CNRS, INRIA, CEA, ONERA), as well as the strike force of its technological and industrial research (Atos, STMicro, AirLiquide, Orano, and the startup ecosystem), particularly in the fields of microelectronics, supercomputers and enabling technologies.

In this case, France is the cradle of several major breakthroughs at the origin of the current advance of the major global technological companies. Furthermore, microelectronics technologies are one of the rare options today identified as likely to enable the scale-up of the quantum computer. Although the scientific, conceptual and technological obstacles remain considerable, the industrial fabric and the French research teams are among the best placed in the world to overcome them.

The superconducting qubits used by Google and IBM and the cold atom qubits are derived works by Daniel Estève and Michel Devoret at the CEA de Sa clay, as well as Claude Cohen Tannoudji and Jean Dalibard at the ENS Paris / Collège de France.

France in international competition

France's ambition is to be among the first nations to develop a large-scale universal quantum computer, providing it with technological sovereignty and contributing to Europe's strategic autonomy. France is one of the few countries able to meet this challenge of scale. Nevertheless, it will probably not be the only one and will have to deal with countries that have large communities (eg China and the United States) or also have a strong national plan (Germany, Netherlands, United Kingdom).

With this strategy, France wishes to take the lead in the emergence of companies that can become world leaders in quantum technologies, while strengthening the champions involved in the field (Atos, Thales, Orange, STMicro, Air Liquide, Orano, …) to create a competitive industry in the key application areas of quantum technologies, with direct repercussions in health, energy, climate, agri-food, pharmaceuticals, deterrence and intelligence .

Quantum strategy: 5 years to establish France in the first world circle

The quantum strategy will benefit from the exceptional investments that the Government has decided to make in sectors and technologies of the future, during and after the recovery, in particular by mobilizing the 4th Investments for the Future Program (PIA4). Announced by the Government at the beginning of January, these first national strategies respond to priority innovation needs or market failures: the State is thus mobilizing 12.5 billion euros over 5 years through the PIA to finance these investments , part of which as part of the #FranceRelance plan. Digital will occupy a central place: quantum, cybersecurity, artificial intelligence, 5G...

To find out more about the Government's acceleration strategies : https://www.gouvernement.fr/strategies-d-acceleration-pour-l-innovation

The strategy must enable France to be among the first countries to master key quantum technologies: quantum accelerators and simulators, business software for quantum computing, quantum sensors, quantum communications, post-quantum cryptography, enabling technologies, etc. .
In the field of calculation, the central theme of the strategy, it will become the first State to have a complete prototype of a first-generation general-purpose quantum computer from 2023. It will also be able to assert itself as the first nation to have a complete chain producing industrial Si 28 for the needs of the production of qubits on silicon.

The maturation period of these technologies, the software layers to be developed, or the training of talents, require the federating of players and efforts towards this ambition of building a complete industrial sector: it is a question of asserting oneself as a sustainable leader. sector, with the objective of creating 16,000 direct jobs by 2030 and eventually representing between 1 and 2% of French exports.

Highly systemic, the quantum strategy aims to enrich and affirm our capability on the scientific and technological level, but also in the industrial value chains, the development of human capital or even the anticipation of skills needs for these markets, by doubling gradually building up the pool of specialists by 2025, in order to guarantee and sustain our sovereignty over these critical technologies.

It is based on the following seven pillars, including 6 technological pillars and a transverse pillar.

Key objectives

- Mastering quantum technologies offering a decisive strategic advantage, including quantum accelerators, simulators and computers, business software for quantum computing, sensors, communication systems.
- In the field of computing, the central theme of the strategy:
  - o become the first State to have a complete prototype of a first-generation general quantum computer from 2023;
  - o be a world leader in the race for the scale-up universal quantum computer, by anticipating today the inherent risks linked to the low level of maturity and the complexity of the technologies currently being explored.
- Master the critical industrial sectors in the field of quantum technologies, in including enabling technologies
- To assert itself as one of the world leaders in cryogenics or lasers for quantum technologies.
- To be the first nation to have a complete chain producing industrial Si 28, in particular ment for the purposes of qubit production.
- Developing skills and human capital, strengthening technological infrastructures, creating an environment conducive to the intensification of entrepreneurship, technology transfer, and promoting attractiveness vis-à-vis international players and the best talents global.

The key numbers

- Cumulative State funding of approximately €1 billion over four years, for **an overall public-private commitment of €1.8 billion.**
- Creation of 16,000 direct jobs by 2030, in favor of an activity which will represent term between 1 and 2% of French exports.
- Training of 5000 new talents in quantum technologies, technicians, engineers, doc tors.
- Training through research of nearly 1,700 young researchers, with a doubling of the number of thesis per year: 200 new theses and 200 post-docs per year by 2025.
- Support for entrepreneurship to the tune of €120 million, in the form of matching funds dedicated to start-ups, whether in series A, B or C.
- Support for research via a Priority Research Program and Equipment (PEPR) endowed with €150 million.
- Support for industrial deployment and innovation for a total amount of €350 million.

Summary of funding

Breakdown by technological axis

Technological axes of the national strategy						Total 2021 – 2025 [M€]
NISQ	LSQ	Quantum sensors	Quantum Communications	Post quantum cryptography	Enabling technologies	
352	432	258	325	156	292	1815

Breakdown by support modality

Total 2021 – 2025 [€m]	1815
Research (CNRS, CEA, INRIA, ONERA, CNES organizations; EU programs, infrastructures)	725
Education (PhD, engineers, masters, technicians)	61
Technological Maturity	171
Disruptive innovation (quantum computer)	114
Support for industrial deployment (pilot lines and cryogenics)	224
Public Purchasing Policy (calculation, defence)	72
Entrepreneurship (investment funds, incubators)	439
Economic Intelligence (standardization, PI)	9

Breakdown by source of funding

Total 2021 – 2025 [€M]	1815
AIP 4	594
Grant to research organizations	274
Other national contributions	164
European funding	238
Private sector	545

1. Develop and disseminate the use of NISQ simulators and accelerators [€352 M]

Challenges

In recent years, commercially exploitable "NISQ" (Noisy Intermediate Scale Quantum) simulators and computers have become a reality while waiting for the "LSQ" quantum computer.
(Large Scale Quantum) able to scale. These machines are, as of today, tools for learning quantum computing. Very highly integrated ecosystems are being formed today around machines which, although they do not confer any proven quantum advantage, make it possible to anticipate disruptions while uniting and retaining an ecosystem of developers around Hardware-dependent development tools.

Field of action

By relying on GENCI (Grand Equipement National de Calcul Intensif), in charge of equipping national centers for intensive computing, and the CEA, designer and operator of the TGCC (Very Large Center for Calculation), the main French public computing center , France will host the world's first infrastructure of hybrid quantum computers, integrating, from a software and hardware point of view, quantum accelerators into a system of conventional supercomputers. The implementation of this world-class infrastructure, integrating various emulators and quantum computers based on various technological principles, will represent a strong lever for action making it possible to:

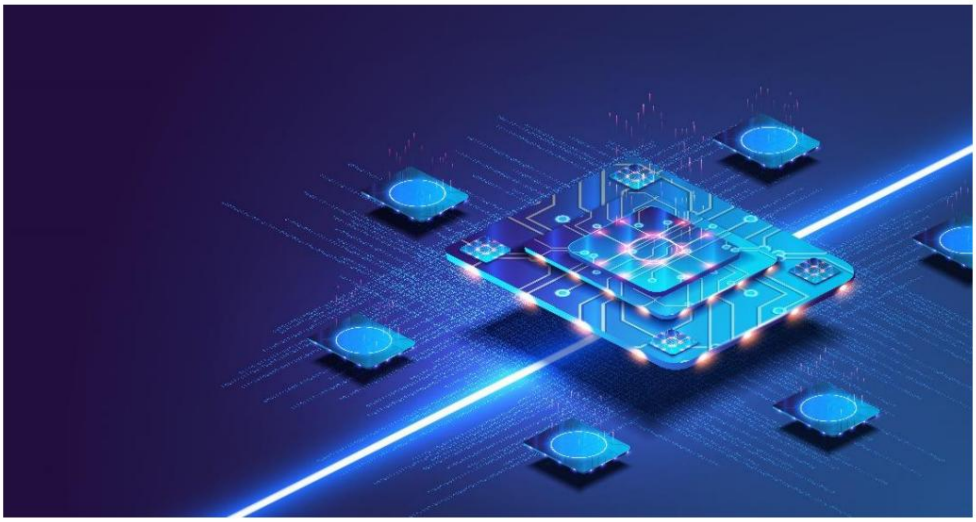
• Minimize the risk of dependence on a single technological option; •
Develop the software ecosystem, applications and uses; • Develop
the legitimacy and influence of France internationally.

When the time is right, the industrialization of quantum accelerators will be supported in particular by the deployment of pilot lines making it possible to refine industrial processes in an environment representative of production, while reducing the risks and the transfer cycle time to industry. .

2. Develop the Passing Quantum Computer at the LSQ scale [€432m]

Challenges

The development of quantum computers capable of scaling or "LSQ" (Large Scale Quantum) aims to make possible calculations and modeling of a complexity greater by several orders of magnitude than what can be treated with traditional supercomputers. , even accelerated with NISQ qubits. From a few hundred/thousands of fault-tolerant qubits (logical qubits), the use of these machines will considerably accelerate innovation and the marketing of products from industrial sectors that rely on long phases of validation.
France is considered to be one of the rare countries capable of taking up this challenge, thanks to the excellence of its history in upstream and technological research, and to its micro-electronics industry; it is also the challenge that involves the most uncertainties on the schedule and risks given the low level of maturity and the complexity of the technologies currently being explored.



Field of action

With regard to technological components, the actions will aim to explore, derisk and hybridize different solutions for the design and manufacture of robust qubits and high-performance logic gates compatible with the microelectronics industry, then select the most promising candidates for a scaling up, among spin qubits on Silicon, transmons on Silicon, Silicon/Germanium, cat-qubits, topological qubits, photonic qubits, flying qubits, etc.

The development of these different ways of hardware architectures will have to be held in the spirit of a continuum between the NISQ and the LSQ while emphasizing the hybridization of technological platforms compatible with industrialization, in terms of transition scale and build quality. These paths will be pursued simultaneously while enriching each other, all within a global multidisciplinary approach.

In terms of system architecture, an Innovation support action will aim to develop a computing micro-architecture and piloting electronics, which can control and correct the errors of various scalable qubit technologies.

On the algorithmic level, the action will aim to develop algorithms robust to noise and able to take full advantage of a quantum computer scaling up to address the most complex problems: protein folding, CO_2 sequestration , production bio-inspired catalysts etc.

3. Develop Quantum Sensor technologies and applications [€258 M]

Challenges

Quantum sensors are among the quantum technologies historically supported by the State through its support for upstream research, the most mature of which open up to various promising applications: navigation, geological prospecting, earth observation, interception, detection, seismography, magnetometry , materials science, etc. Nevertheless, the complexity of their implementation and the extreme environment often necessary for their operation currently limit outlets to very specific markets, which compromises long-term industrial viability. It is necessary to support the increase in maturity of these technologies towards applications and markets, while promoting their integration into the systems that could benefit from them, in order to develop a civilian market, a source of economic viability.

Field of action

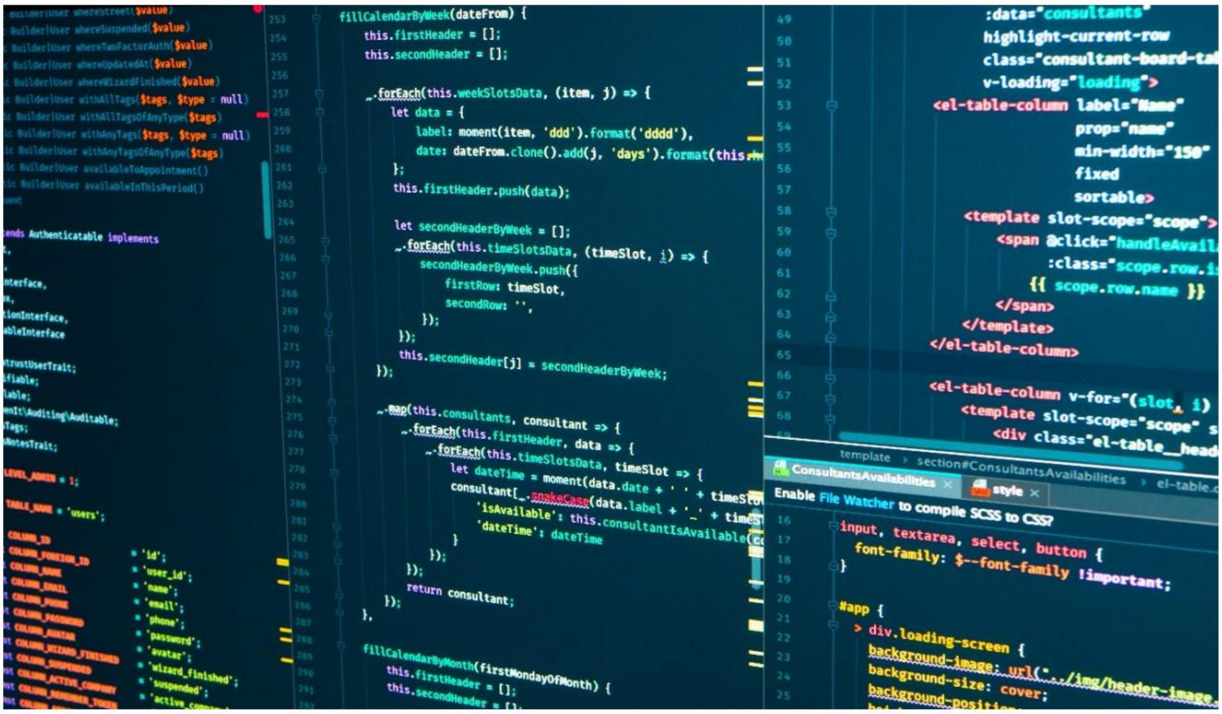
In terms of cold atom sensors, actions will be aimed at consolidating France's position in these technologies and developing the next generation of inertial sensors, magnetic sensors and atomic clocks. For the most mature technologies (Rydberg atoms, superconductors, diamond impurities, etc.), the action will aim to support the integration of elementary bricks into their system environment, in particular by improving their characteristics in the face of embarkability constraints, while meeting the objectives of sovereignty and reappropriation of value chains in terms of sensors.

In order to maximize the "market surface" and strengthen the economic viability of these technologies in the longer term, a wave of "Challenges" will aim, in 2022, to allow the identification of new civilian markets to take over from the defence: nano-MRI, industrial control in hostile environments, field analysis, molecular analysis for chemistry and biology, study of materials under high pressure for energy storage, etc.

4. Develop the Post-Quantum Cryptography offer [€156m]

Challenges

In the "era of the quantum computer" capable of decrypting, possibly retroactively, data protected by current public key algorithms, security agencies recommend guaranteeing the confidentiality and integrity of information systems and state communications today. If the need to develop and use post-quantum algorithms, that is to say resistant to quantum cryptanalysis, is now a consensus, it remains to define these algorithms. There are several families of post-quantum cryptography algorithms and various mathematical problems and variants are used to build the security of these schemes. However, for most of them, there is not yet an international consensus on the level of confidence that can be had in their safety.



Field of action

In order to organize the progressive migration towards post-quantum cryptography and to master the hardware implementations guaranteeing performance and security, the quantum strategy will carry out work in the fields of algorithmic development, hardware implementation and experimental validation.

The transition to post-quantum algorithms will not be abrupt. A transitory period will be necessary, where the post-quantum algorithms will cohabit with the current mechanisms in order to be reassured that the post-quantum algorithms do not introduce regressions compared to the existing one. Since candidate algorithms for standardization consume more resources than their classic analogues, an action will aim to explore the possibilities of implementing these new algorithms in specialized hardware devices with limited resources. Finally, certain quantum sensors will be explored in the light of this field of application, as they could offer, in the relatively short term, new capacities for cryptanalysis and characterization of physical attacks on cybersecurity equipment.

5. Develop quantum communication systems [€325m]

Challenges

By allowing the distribution of entangled states, quantum communications can have several promising applications inaccessible with current technologies: long-range interferometry, time reference for the synchronization of atomic clocks, networking of quantum computers, quantum distribution keys, etc. Networking of quantum sensors for very long-range interferometry and ultra-precise time distribution will be of interest, for example, to scientists, financiers, energy suppliers, etc. Remote access to quantum computers and the sharing of calculation between several quantum computers makes it possible to associate several processors in order to increase their capacities exponentially, as well as to make it possible to locate these machines in computing centers distant from users.

Europe and France in particular have been pioneers in these technologies. By supporting research and innovation in this field, France will maintain its scientific leadership, in particular to increase its autonomy vis-à-vis quantum devices not mastered in Europe.

Field of action

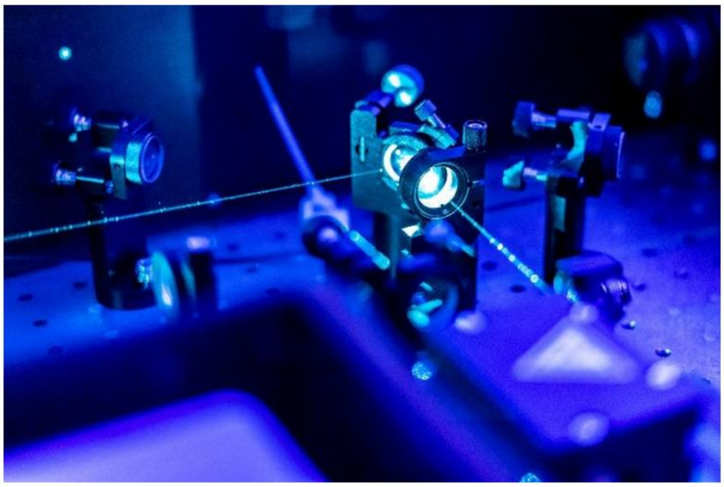
The practical use of quantum communications will be based on the ability to develop quantum photonic components that can be integrated into existing communications infrastructures without requiring specific deployments, which will constitute a major focus for guiding activities in this field. In addition, they will lead to the experimentation and evaluation of the deployment of quantum photonic components in prototypes of existing fiber communication networks, emphasizing the aspects relating to the triptych throughput, distance of the links established, and security criteria. Based on two experimental fiber communication networks, one in the Nice region, the other in Ile de France, the new communication components and protocols will be tested and optimized in real conditions. In addition, France will continue to be part of the European work carried out in EuroQCI.

On the algorithmic level, the action will aim to develop new communication protocols for distributed quantum computing, blind quantum computing or “Blind Quantum Computing”, long distance interferometry protocols for earth observation and space, the distribution of atomic clocks, as well as to imagine future applications of quantum communications.

On the other hand, due to their relative youth, quantum communications have not been intensively evaluated in terms of cybersecurity, unlike classical communications. On this level, if theoretically quantum communications are invulnerable to attacks based on the laws of physics, practical realizations introduce vulnerabilities potentially exploitable by an attacker. In order to strengthen the resilience of quantum communications devices to physical attacks, action will be dedicated to identifying and correcting vulnerabilities in quantum communications systems.

6. Develop a competitive enabling technology offer [€292m]

Challenges



Cryogenics, lasers and low-noise electronics are strategic enabling technologies for quantum technologies as well as for other fields (nuclear fusion, astronomy, etc.), which requires supporting and developing our autonomy over the short term, by bringing out a competitive French offer securing supplies Promoting mastery by French industrial players of these technologies in the nationals. very short term opens interesting export outlets, in addition to quantum technologies, in large instruments science, medical devices, and space electronics, in an international context marked by polarization around a limited number of players. In the long term, mastering these technologies could enable French industrial players to become leading suppliers in several sectors.

Field of action

The need to gradually increase the number of qubits per quantum processor exacerbates the constraint of operating in an extreme cryogenic environment, which lies not in reaching sub-Kelvin temperatures but in the power required to cool large volumes including the qubits, the wiring and the electronics placed in the intermediate stages. Actions will focus on finding an optimal balance point between the temperature tolerance of qubits and the performance of industrial cryogenic technologies, which is a prerequisite for envisaging the passage of quantum computers to scale.

In addition, the development of new lasers for cooling and manipulating atoms will benefit from support aimed at improving the reliability, yields, power, spectral agility and stability of existing lasers, as well as developing new lasers capable of to manipulate a new class of atoms with promising quantum properties for computing and sensors.

Finally, to promote the embarkability and environmental resistance of the components at the system level, the actions will make it possible to apprehend the problems of interest such as miniaturization, hardening, in order to make the devices compatible with the conditions of use. . In addition, work will also be expected on the specific maintenance processes in operational condition that these specific technologies may require.

7. Structure the ecosystem transversally

Challenges

To support and convert scientific and technical work into a lasting competitive advantage, it is essential to develop skills and human capital through initial and continuous training, the strengthening of technological infrastructures, to create an environment favorable to the intensification of entrepreneurship, technology transfer, promoting attractiveness vis-à-vis international players and the best global talent.

Action areas

Develop skills and human capital

The strategy should make it possible to create 16,000 direct and indirect jobs by 2030. This ramp-up should be based on different levels of training, combining initial training and continuing training, technical training, engineering and training through research. Industrial development teams in quantum hardware and software will be able to rely on experts whose initial training will be centered on quantum technologies. These experts will be able to supervise employees trained through an ambitious continuing education program. Initial quantum training will be reinforced in engineering schools and in masters through interdisciplinary programs combining quantum physics, quantum algorithms and engineering. Finally, training modules in quantum technologies will be introduced at DUT level, in order to train a sufficient number of technicians capable of participating in the industrial development of quantum technologies and their enabling technologies.

Strengthen technological infrastructures

Manufacturing platforms: the quality of the means of developing materials is essential to obtain performance at the highest level. Without it, the strategic sectors would be dependent on the provision of services by foreign infrastructures. The actions will therefore aim to provide the means to reach the highest international level, in particular for the development of functional nanomaterials.

Quantum metrology platform: metrology plays an essential role in the industrialization of emerging technologies, through the reliable measurement of performance. It allows the validation of technologies whose performance is superior to existing technologies, and thus their adoption by industry and the market. To preserve its competitiveness in the field, ensure its ability to support the emergence of its own quantum industrial sectors, and provide its industry with traceability vis-à-vis the International System of Units, France will equip itself with a quantum metrology platform which will bring together the skills and measurement facilities of the National Metrology Network.

Strengthen entrepreneurship and technology transfer

On the entrepreneurial level, quantum technologies face, like other “risky” areas, the difficulty of accessing quality risk capital from generalist funds. As part of the strategy, two funds involving management companies with strong quantum skills could complement the action of the first fund dedicated to the field in France (Quantonation) and could be supported by the State in funds of funds. Finally, the French Tech Souveraineté fund will complete the system to provide the necessary support to protect the capital of strategic companies.

In terms of technology transfer, the strategy will support “hub” type initiatives which will aim to increase the density of relations between industrial players, start-ups and academics, to support entrepreneurial projects and establish international links.

International cooperation opportunities

Through a leverage effect, State action will make it possible to mobilize more than €200 million from Europe, part of which via joint co-financing from the Commission, topped up in return for national financing. A consortium is already on track, co-funded by the EuroHPC joint venture, bringing together France, Germany, Italy, Spain, Ireland and Austria, to develop the first hybrid computer prototype integrating a quantum accelerator of at least 100 qubits by 2023, on the site of the Very Large Computing Center in Bruyères-Le-Chatel. This hardware and software platform will be the first step towards a 'European quantum hub', which will support the work of communities of scientific and industrial users, with a view to developing use cases that fully exploit these new computing capacities.

This momentum will be relayed by a Grand Défi NISQ, a public-private program which could give rise to a broadening of the collaborative dynamic with Germany. The purpose of this Grand Challenge is to create the conditions to use this hybrid platform as a common 'sandbox' infrastructure for quantum technologies, both hardware and software, in particular to conduct a performance benchmark depending on the nature of the integrated quantum accelerator (cold atoms, superconducting junctions, etc.), with the aim of exploring the extent of the capabilities offered by hybrid machines in terms of applications. Ultimately, it will aim to:

- make the most of existing quantum accelerators by integrating them into the more global context of high performance computing and by developing hybrid quantum-classical algorithmic solutions;

- Disseminate the use of quantum computing in priority sectors by developing software solutions and hardware-agnostic development environments based on programming languages and libraries dedicated to different application sectors.

It should also be noted that the theme of quantum computing is being intensified within the framework of the efforts that the European Commission is making in the field of supercomputing, in particular via the EuroHPC Joint Undertaking. The theme of quantum communications will be brought to the European level by the EuroQCI group, which is currently being set up under the aegis of the Commission.

In addition, France will be a source of proposals to intensify the historical joint dynamics in terms of research with the major nations of quantum technologies in Europe (the Netherlands, England, etc.), by exploring all the opportunities for collaboration with the ambition of reposition the global center of gravity of quantum technologies towards Europe.

Implementation

Execution will require cumulative State funding of approximately €1 billion over four years. This action by the State will be supplemented by European funding, and by the co-funding of manufacturers, whose involvement will be decisive for the success of this strategy, in order to strengthen their R&D activity, conquer new markets or relocate activities in France.

In support of entrepreneurship, institutional investors and trust funds will mobilize to support the emerging innovation ecosystem in the field and to bring out new national industrial champions.

All of this leads to an overall public-private commitment of €1.8 billion.

This commitment is up to the challenges and the ambition to assert itself as a long-term leader in the field, with the objective of creating 16,000 direct jobs by 2030, in favor of an activity which will represent term between 1 and 2% of French exports.

Skills development involves initial and continuing training, i.e. nearly 5,000 new talents trained in quantum technologies by 2025, researchers, engineers, technicians, with new university courses open from the start of the next academic year.

The creation of an environment conducive to the intensification of entrepreneurship and the transfer of technology will help to develop our intellectual and industrial heritage, while cultivating our influence vis-à-vis international players in the field, in order to attract investment as well as the world's best talents. In particular, support for the emergence and growth of start-ups will be provided in particular through the mobilization of equity, with the ambition of reaching a total public-private amount of €310 million.

A major effort will be devoted to research, in particular via a Priority Research Program and Equipment (PEPR) endowed with a total amount of €150 million, around four structuring themes: robust “solid state” qubits, cold atoms, algorithms quantum, frontiers of computability and security.

Maturation, innovation and technology transfer will be the subject of unprecedented support in a variety of ways, such as the Great Innovation Challenges, programs for technological maturation or support for industrial deployment, including the total reached €350 million, with a multiplier effect expected from industrial investment.

Finally, the execution of the strategy will be carried out by an interministerial coordinator, who will steer its implementation under the responsibility of the Interministerial Council for Innovation, with the constant concern to maximize the industrial impact, employment and the creation of lasting economic v

Highlights in the national quantum ecosystem over the past 6 months

- June 2020: "Qubit Pharmaceuticals", a French research spin-off start-up (CNAM, CNRS, Sorbonne, University of Texas at Austin, Washington University), has just closed a pre-seed round thanks to the Quantonation help. This start-up is revolutionizing the field of advanced simulation software for drug development, thanks to the consideration of quantum effects in molecular dynamics. Today operated and fine-tuned on supercomputers, software solutions will be ready to generate radical breakthroughs as soon as they run on the first quantum computers.

- July 2020: The start-up Quandela, which develops single-photon sources with highly anticipated properties for optical quantum computers and communication networks, closed its seed fundraising at €1.5 million, led by Quantonation and followed by French Tech Seed from Bpifrance.

- Summer 2020: Atos has upgraded its commercial quantum simulator QLM with a new hardware architecture, which becomes QLM E(nhanced), the world's most powerful quantum simulator offering up to 12 times more computing power than its predecessor.
Atos QLM E offers new simulation opportunities for future NISQ quantum computers, which are expected to be commercialized in the coming years.

- September 2020: the startup Quandela launches Prometheus, its new generation of indistinguishable photon generator usable in quantum computing and cryptography.

- September 2020: Air Liquide acquired the French SME Cryoconcept, specialized in dilution refrigeration, a technology allowing very low temperatures to be reached. This movement marks Air Liquide's commitment to the field of extreme cryogenics, close to absolute zero, which is a crucial enabling technology for quantum technologies.

- October 2020: Thales develops atomic chip sensors, with the ultimate goal of achieving a complete inertial unit (combining accelerometers, a clock and a tri-axis gyrometer) based on miniature cold atoms and substantially more efficient than current technologies. One of the key functionalities has been demonstrated, allowing the manipulation of atomic clouds on chip, using radiofrequency currents.

- November 2020: Atos announces a partnership with Pasqal to develop a quantum accelerator based on neutral atom technology, intended to equip high performance computing systems. This technology would make it possible to strengthen the computing capacities of current computers and thus develop hybrid quantum-HPC systems that can be exploited in the short term.

- December 2020: the European HPCQS consortium, built around the Franco-German axis GENCI/ Jülich Research Center, has been selected by EuroHPC to produce in 2023 the first European computer integrating a quantum accelerator of at least 100 qubits. This consortium brings together the major French research organizations (CNRS, CEA, INRIA), as well as Atos and the start-up Pasqal, which will respectively deliver the supercomputer and the quantum accelerator which will be integrated into it. Work will start in the first half of 2021.

- December 2020: Thales develops a superconducting quantum antenna based on the use of networks of SQUIDs (Superconductor Quantum Interference Devices) capable of detecting a wide spectrum of frequencies. The detection of radiofrequency signals has been demonstrated up to 100 MHz with a 1cm quantum antenna, whereas the size of a conventional antenna is 1.5m.
- December 2020, Atos unveiled the “Q Score”, the first universal metric that makes possible the objectification of quantum computer performance and 'quantum supremacy'.
- December 2020: CEA Leti samples its qubits with electron spins which improves control qubits.
- December 2020: Pasqal and the team of Antoine Browaeys from IOGS publish several papers with a quantum simulation record with 196 qubits based on cold atoms.

Next calls for projects / 1 semester 2021

- **Priority Research Program and Equipment (PEPR), to support the research effort of the scientific community, endowed with €150 million around four themes:** robust "solid state" qubits, cold atoms, quantum algorithms, frontiers of computability and security (first quarter 2021);

- **Grand Challenge on the development of first-generation quantum accelerators (NISQ),** or 'imperfect' quantum computer, to prepare in 2022, an innovation action on the development of the scalable quantum computer (LSQ), or 'perfect' quantum computer (at the latest end of the first half of 2021);
- **Industrial Development Program relating to capacitating technologies,** such as Si28, cryogenics and lasers; this program supports collaborative public-private research and development activities at intermediate technological maturity (TRL3-6), close to the market but with a technological risk that cannot be borne by private players alone (from the first quarter of 2021);
- **Technology Maturation Program,** to encourage public-private collaborative research and development activities at intermediate maturity with medium-term market prospects, concerning sensor integration, error protocols and corrections, as well as post-quantum algorithmic (by the end of the first half of 2021 at the latest).

ÿ To find out more and follow the publication of calls for projects and programmes:

https://www.entreprises.gouv.fr/fr/numerique/politique-numerique/strategie-nationale-pour-technologies-quantiques

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