QUANTUM TECHNOLOGIES

PATENTS, PUBLICATIONS & INVESTMENTS LANDSCAPE

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ANALYSIS OF THE PATENTS LANDSCAPE FOR QUANTUM TECHNOLOGIES

The first quantum revolution enabled inventions such as the laser and transistor, the basic building block of computers and smartphones. The nascent second quantum revolution, which is all about controlling individual quantum systems, such as atoms, ions, molecules, or even photons to a greater extent than before, allows the emergence of a new generation of optical and electronic apparels that use quantum effects to significantly enhance the performance over that of existing 'classical' technologies.

Quantum technologies create significant opportunities for new businesses but could also have significant implications for national security or information privacy. Significant investments have been made over the past 5-10 years, in both the public and private sectors, to explore, develop or even market the first practical products.

Several governments have launched large multi-year plans with funding in excess of US$1 billion - USA, Canada, Europe (EU), UK, China, Germany (see for instance [1], [2] or our next publication[1]). In the private sector, thirty-two venture capital financing operations for start-ups were carried out in 2018, for a total annual investment of $173m [3]. In 2019, the numbers were even greater and 2020, with $479m just for the first semester will be a record year despite the Covid-19 crisis[1].

In parallel, many large multinational companies already working in the telecommunications, computer or sensor markets are recognizing the potential of quantum technologies and are investing in their development and commercialization.

The analysis of the patent landscape is a proven way to assess the economic potential of new technologies and to measure the level of transposition of the results of what has so far been essentially a field of research, into new products, likely to stimulate economic growth and contribute to societal progress.

In June 2020, we carried out an extensive search and analysis of patents related to quantum technologies published since 2010 using the database proposed by Orbit[2].

We counted 9,905 patents over the period 2010-2020. As the publication delay for patents is generally 18 months, the information for the years 2019-2020 is not complete and some patents from 2018 are certainly missing. We see a strong increase in the number of patents filed since 2012, which has accelerated further since 2015, with an average annual growth rate of 27.15%.

The vast majority of innovation in quantum technologies comes from China and the USA, recently overtaken by the Chinese. Chinese patent production is more than twice that of the USA and alone accounts for 52% of patents in our fields of study. The USA and China account for more than 75% of the patents.

Among the 20 key players, representing 20.2% of the patents, 11 are Chinese, including the leader, Ruban Technology, which operates in the field of digital communications. IBM and Intel complete the podium. With 6 American multinationals in the TOP20, places for other nations are limited.

[1] "Global public and private investments landscape", Michel Kurek, Ecole Polytechnique, July 2020.

[2] Specialized analysis software from the publisher Questel, one of the leaders in the field of patents databases: https://www.questel.com

Chinese innovation focuses on technologies for securing communications by using the quantum properties of light (particularly photon entanglement) while the US retains a large advantage in quantum computing. We illustrate Chinese advances in the field of quantum communications with the example of SGCC, the world's largest electricity distributor.

The growth of patents in the specific field of quantum computing is even more staggering than that of other quantum technologies. Their number has increased 11-fold in six years. While China has made progress in recent years, it is still far behind the USA, which has filed 51.4% of patents in this field. The landscape of key players mixes American and Japanese multinationals, specialized startups, universities and civilian or military government agencies.

1. Objectives

A literature search prior to our study allowed us to identify some existing documents analyzing the patent landscape for quantum technologies [4]–[8]. Some are focusing on quantum computing, others are not recent or poorly framed by their search strategy. In the end, we wanted to get a personal, broad and objective view, by conducting our own patent search and analysis. The points we wanted to address are the following:

- Evolution over time of the number of patent applications filed
- Geographical Distribution of Applicants and Fields of Innovation Covered by Patents
- Identification of the 20 key players and their main areas of innovation
- Case study of a particular Chinese assignee, SGCC
- Analysis of the most patent-active areas of technology
- Distribution of Patent Citations among Applicants
- Focus on quantum computing and quantum computing with a narrower search key

2. Methodology

In June 2020, using both the Orbit (Questel[3]) and Patseer (Gridlogics[4]) patents databases, we searched and analyzed the patent families related to quantum technologies. We finally selected the former provider whose data seemed more complete. Through our research strategy, we favored a broad exploration extending to the key areas of what is often referred to as the second quantum revolution, namely:

- Quantum Computing
- Quantum communication (telecommunication, network, security, cryptography)
- Sensor, metrology, quantum imaging
- Quantum simulation

These areas can also be found in various official documents detailing the diverse government initiatives (e.g. for the EU "Quantum Technologies Flagship Report" [9]).

To build our search equation, we combined criteria related to the presence of keywords and classification according to the IPC (International Patent Classifications) or CPC (Cooperative Patent Classification) standards:

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(((TAC:(((quantum wd1 (comput* OR (data w proces*))) OR q?bit? OR (quantum memor*) OR (quantum AND (random access memory)) OR qram OR (quantum err* correct*)  OR (quantum inform*)) OR ((quantum* AND (entangl* OR superposit* OR *coherence? OR nonlocalit* OR teleport*)) OR (quantum metrolog*) OR (quantum sensor*) OR ( cold atom?) OR (atom* AND interferomet*) OR (ion? trap*)) OR (((simulat* OR model*) AND ((quantum OR photon* OR electron?) WD5 (entangl* OR superposit* OR spin?))) OR (quantum simulat*)) OR ((quantum w key?) OR qkd OR (quantum random number) OR qrng OR ((quantum OR entangl*) AND cryptol*) OR (quantum network?) OR (quantum repeat*) OR (quantum communica*))) AND SPRY:[2010 TO 2020])) OR AC:(H04L9/0852 OR H04L9/0855 OR  H04L9/0858 OR G06N10*))
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This query allows us to retrieve information on patents with a priority date[5] equal to or later than 2010, containing in their Title, Abstract, or Claims the generic keywords mentioned in the box above. For the query performed on the Patseer database we had explicitly added the IPC/CPC categories: H04L9/0852, H04L9/0855, H04L9/0858 and G06N10*. The first three classify patents in quantum cryptography, while the last, G06N10, was created in 2018, specifically for patents dealing with quantum computers.

[3] https://www.questel.com/
[4] https://patseer.com/
[5] The priority date is the filing date of the very first patent application for a given invention.

The IPC, CPC organizations review their classification at least once a year. It should be noted that previously, patents for these computer models were classified under G06N99/002 ("*Subject matter not provided for in other groups of this subclass*", i.e. what is not classified elsewhere). The creation of a specific code is a normal recognition given the strong evolution of the number of patents on the subject.

3. Analysis

3.1. Annual change in the number of patents filed

Before focusing on the period of our study 2010-2020, it is interesting to visualize the evolution of the number of patents in our research fields without any date limit.

With the full database, we have thus identified 15,245 patents, of which 13,208 are post-2000. The oldest patents date back to the 1950s, and it was not until 1992 that the 100 patents per year mark was passed.

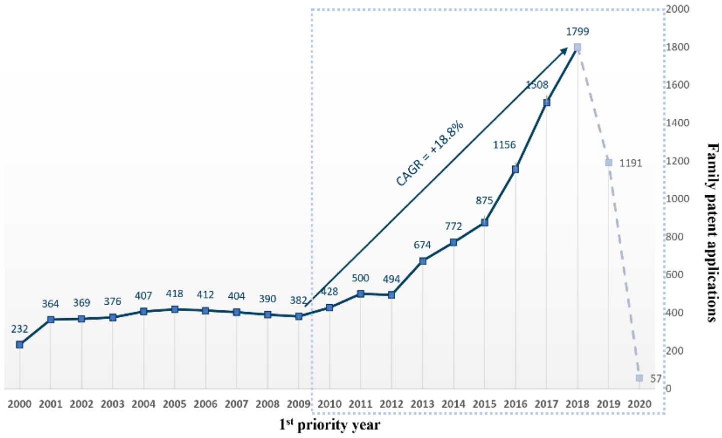

Figure 1: Evolution of the number of patent families since 2000

Figure 1 shows the annual change since 2000. After a period of stability between 2001 and 2009, the number of patents began to increase, particularly from 2012 onwards, from 382 (2009) to 1,799 (2018), i.e. +371%, which translates to a compound annual growth rate (CAGR) of 18.8%. Over the last three years recorded (2015-2018) the CAGR has even reached 27.15%.

Before beginning the analysis of the last ten years, it should be recalled that there is always a delay in the publicly available information on patents due to the 18-month delay between the filing of an application and its publication or to the secrecy requested by the applicant. This explains the behavior seen on the previous curve (Figure 1) since 2018. Over the last 10 years, we now have 9,905 patents.

Figure 2 presents the recent evolution of the number of patents by field of application (as defined by the IPC/CPC classification systems). It shows the increasing shares of those relating to computer technology

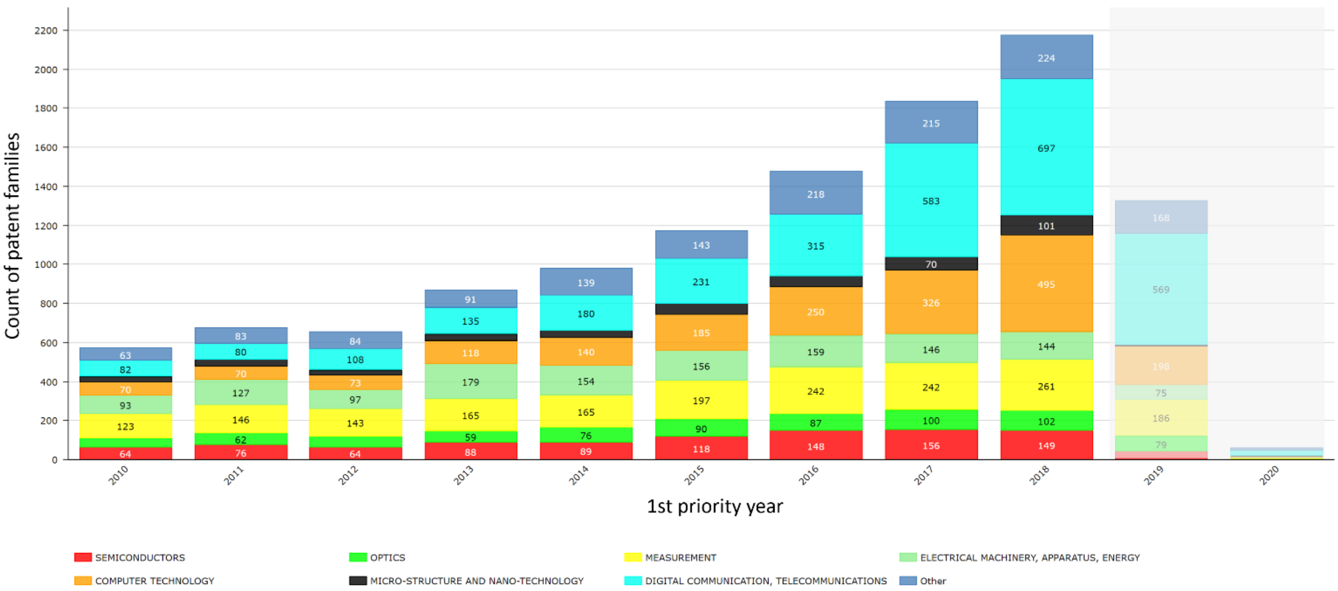

Figure 2: Evolution and distribution by field of the number of patents

(495 patents in 2018 - orange) and communications (697 - cyan). For the latter, many deal with cryptography, and in particular with quantum key distribution (QKD): 650 out of the 697. Patents can be associated with several fields, which explains why the cumulative total per year is higher than that shown in Figure 1.

3.2. Geographical distribution

As is the case in other sectors[10], whether one looks at the geographical distribution (Figure 3) from the perspective of the priority country[6] or the location of the inventor (R&D), China has become the world leader in terms of patents filed over the period (5,161 or more than half of the 52.1% of global patents), ahead of the USA (2,401, about 24%) and Japan (768, 7.8%). This is a remarkable fact since in 2013 China was still behind the UK[6].

South Korea is also in the TOP5. Canada's rank, and to a lesser extent Germany’s one and a few other countries such as France, depends on the metric used - country of priority vs. location of the inventor. Canada is known for its creativity and ecosystem in the field of quantum technologies. D-Wave is a well-known Canadian company in quantum computing with the majority of its numerous patents[11] registered as International Patent (WO) with the US as country of priority. When counted by location of the R&D center, Canada ranks 7th (235) ahead of France (126).

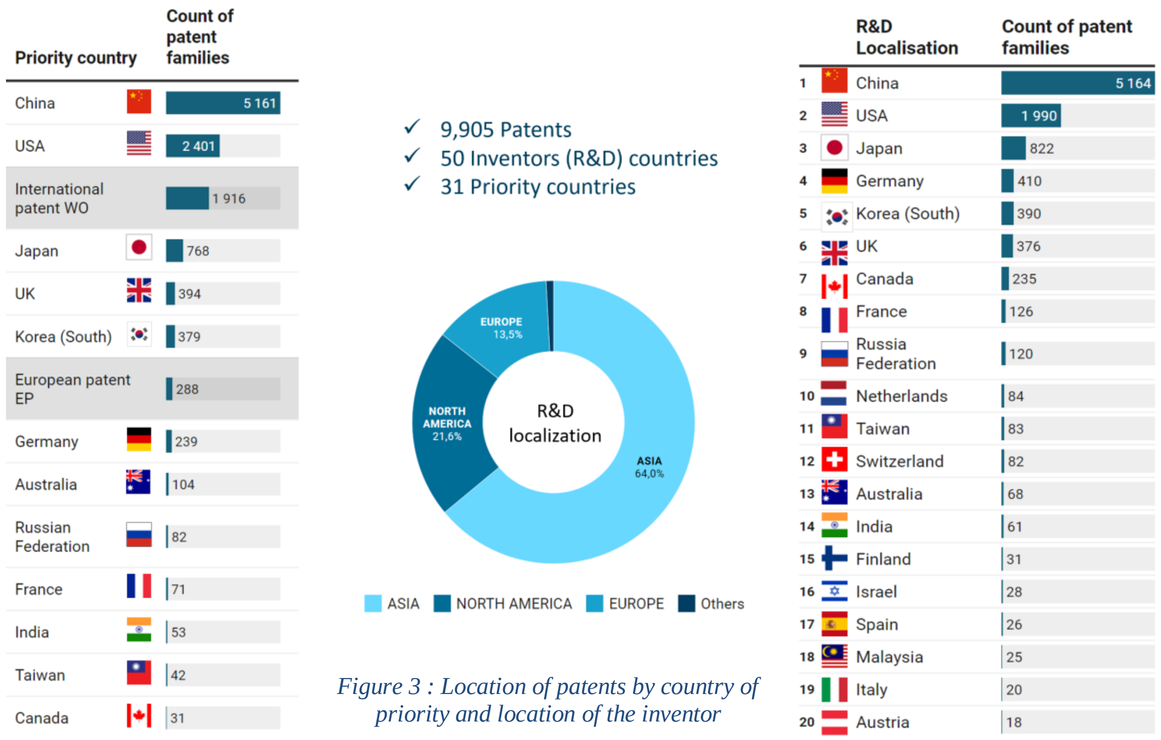

Figure 3 : Location of patents by country of priority and location of the inventor

Together with China, Japan, South Korea, Taiwan, India and Malaysia, Asia accounts for 64% of patents (6,597). USA and Canada 21.6% (2,230) and Europe at large (including the EU, UK, Switzerland and Russia) 13.5% (1,394). The contribution of other continents is minimal, although Australia stands out as a place of active innovation.

The relative evolution of China is confirmed in Figure 4 by the number of patents filed per year and per priority country. It is explained by China's massive investments and production in the fields of secure communications using the laws of quantum physics (*non-cloning theorem*) but also by other political elements explained in the following chapter.

[6] The priority country is the country in which the earliest filing of a patent application is claimed.

China has become the leader in the field of quantum communications (Figure 5). Since the launch of the Micius satellite, followed by the world-first successful test in June 2017 of the 1,200 km quantum link involving the satellite and a ground station[12], the country has continued to develop secure communication technologies and is currently putting in place the necessary building blocks for the construction of a quantum communication network (the record obtained this year for the transmission of quantum information via optical fiber over a distance of 50 km [13] is evidence of this).

	CN	US	JP	GB	KR	DE	RU	FR
2010	110	107	79	24	25	18	5	10
2011	128	145	87	33	26	26	6	6
2012	155	147	77	16	28	19	5	3
2013	231	185	93	46	26	20	10	4
2014	313	171	89	54	36	20	3	8
2015	385	214	82	31	38	36	7	9
2016	588	245	72	29	40	41	13	6
2017	885	280	67	29	82	19	8	10
2018	1 157	363	53	29	60	23	11	9

Figure 4: Number of patents per year per priority country

For its part, the USA remains the leader in technologies related to the construction of quantum computers (computer technology, electrical machinery, semiconductors, nanotechnology).

	CN	US	WO	JP	EP	KR	CA	GB	DE	AU	TW	IN	RU	BR	SG	IL	ES	FR
DIGITAL COMMUNICATION	2 010	400	332	216	170	192	39	55	17	38	41	45	19	19	14	14	15	5
MEASUREMENT	1 280	833	668	527	500	132	195	162	147	97	36	80	34	28	19	35	25	29
COMPUTER TECHNOLOGY	902	1 106	810	324	375	224	188	85	78	140	71	66	32	30	34	17	11	14
ELECTRICAL MACHINERY, APPARATUS...	775	853	656	418	455	136	166	231	161	35	67	61	22	19	26	8	10	10
SEMICONDUCTORS	482	616	509	357	226	202	88	54	60	71	142	32	16	7	32	3	3	14
OPTICS	421	353	268	259	147	98	36	41	43	21	65	23	18	10	9	6	7	10
TELECOMMUNICATIONS	354	226	173	100	88	60	42	39	28	21	18	23	11	13	13	6	6	2
MICRO/NANO STRUCTURE	169	361	310	136	169	106	73	33	35	66	30	27	12	5	16	4	3	8
ANALYSIS OF BIOLOGICAL MATERIALS	140	249	227	131	179	70	110	21	25	90	15	39	18	31	11	44	24	6
BASIC COMMUNICATION PROCESSES	136	254	179	118	96	51	53	25	30	48	14	14	10	10	13	5	7	2

Figure 5: Distribution of patents by country of priority and technology field

Generally speaking, for all nations, we must qualify the observation by noting that the fact of filing or not filing a patent is apprehended in a very different way depending on the country. To cite the example of France, only 15% of French startups hold at least one patent during their start-up phase, compared to 23% in Germany and 22% in the USA and China [14].

Concerning China, the situation is interesting. Chinese patents are generally considered to be "of little value"[15] because in Chinese research centers, one of the key performance indicators (KPIs) is strictly linked to the number of patents filed, at the very level of state policy. As a result, they file a lot of patents in the country, but if they try to patent the same technology abroad, they are often denied due to lack of novelty.

That said, the explosion in the number of Chinese patents is not specific to our topic of interest. It is general since China has become in 2019 the main patent applicant according to the World Intellectual Property Organization [10].

3.3. Distribution by Assignee

A total of 2,802 applicants contributed to the 9,905 patents identified over our study period. It should be noted, however, that especially for patents, the names of the applicants often appear with spelling variations, which certainly inflate the count a little.

The list of the 20 organizations with the most patents filed is presented in Figure 6. These key players alone account for 20.2% of patents filed.

Unsurprisingly, we find 11 Chinese organizations, mostly specialized in communications (Figure 7). China is the only country for which we have universities in this TOP20, which can be explained by the incentive for patenting coming from local politics, already mentioned.

Alongside Chinese universities, a number of companies, such as Anhui Asky Quantum Technology (Qasky), QuantumCTek and even more recently Ruban Quantum Technology have started to apply very actively and are commercializing their products. In terms of number of patent filings, Ruban has become a leader in its field (quantum telecommunications) in just a couple of years (Figure 8).

	Assignees	Count of patent families
1	RUBAN QUANTUM TECHNOLOGY	167
2	IBM	163
3	INTEL	150
4	MICROMASS	137
5	THERMO FISHER SCIENTIFIC	125
6	QUANTUMCTEK	117
7	UNIVERSITY OF SCIENCE & TECHNOLOGY OF CHINA	116
8	TSINGHUA UNIVERSITY	112
9	ANHUI ASKY QUANTUM TECHNOLOGY	107
10	BEIJING UNIVERSITY OF POSTS & TELECOMMUNICATIONS	104
11	TOSHIBA	102
12	STATE GRID CORPORATION OF CHINA (SGCC)	98
13	SHIMADZU	83
14	GOOGLE	81
15	MICROSOFT TECHNOLOGY LICENSING	81
16	D WAVE SYSTEMS	79
17	ELECTRONIC SCIENCE RESEARCH INSTITUTE CHINA ELECTRONICS TECHNOLOGY	77
18	ZHEJIANG SHENZHOU LIANGZI NETWORK SCIENCE & TECHNOLOGY	71
19	SOUTH CHINA NORMAL UNIVERSITY	67
20	DALIAN INSTITUTE OF CHEMICAL PHYSICS	64

Figure 6: The TOP20 Assignees

In the ranking, five American multinationals are present, including four: IBM, Intel, Google and Microsoft that stand out for their production in the software and hardware areas of quantum computers. Superconductors and semiconductors are the physical platform solutions used to implement the quantum qubits chosen by IBM, Google and many other companies.

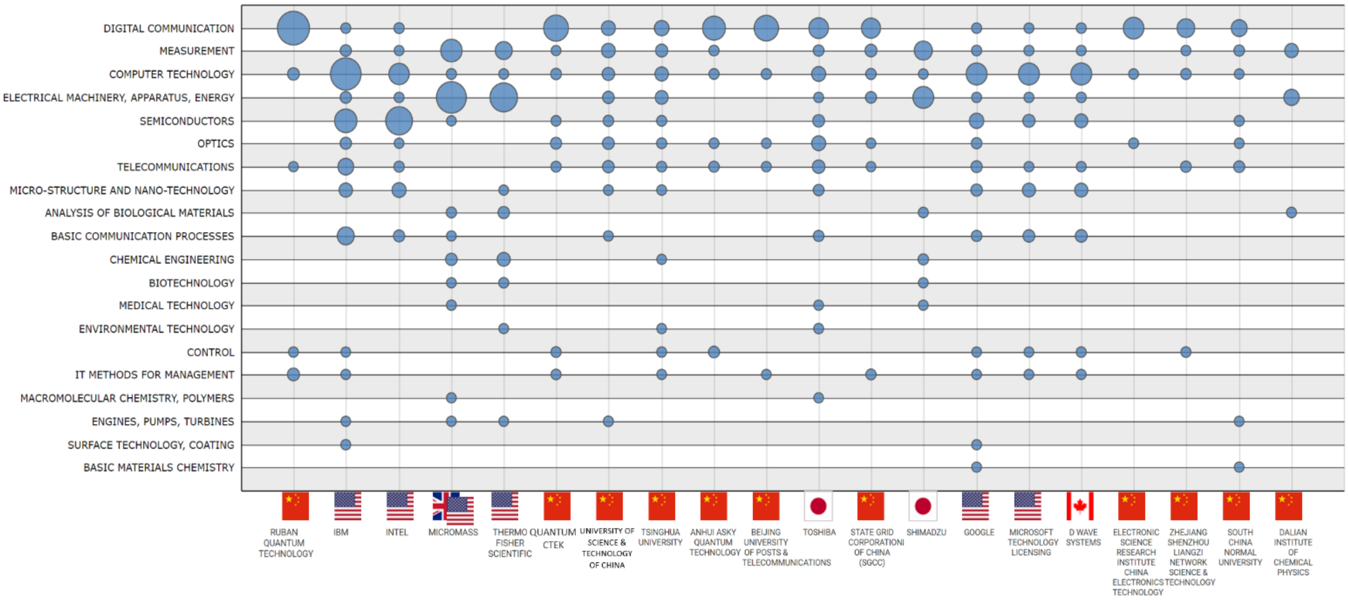

Figure 7: Key players and their patents by technology area

ThermoFischer Scientific produces scientific instruments, laboratory equipment for research or industry. Micromass, owned by Waters, an American multinational, but formerly British, is in a way the only representative of the Old Continent. Japan is here with 2 groups, Toshiba and Shimadzu, one of the leaders in analytical instrumentation. The Canadian D-Wave, which has already been marketing for several years annealing-based quantum computers, is positioned very close to Google and Microsoft in terms of number of patents and fields covered.

The analysis by applicant, proposed in Figure 8, highlights the patent strategy (increased investments/ patents from IBM) and identifies new entrants such as Quantum Ribbon and Electronic Science Research Institute or those who are no longer involved (Zhejiang Shenzou). This information also helps to explain the spike in telecom patent applications in recent years as several Chinese players have filed a large number of such applications over a short period of time.

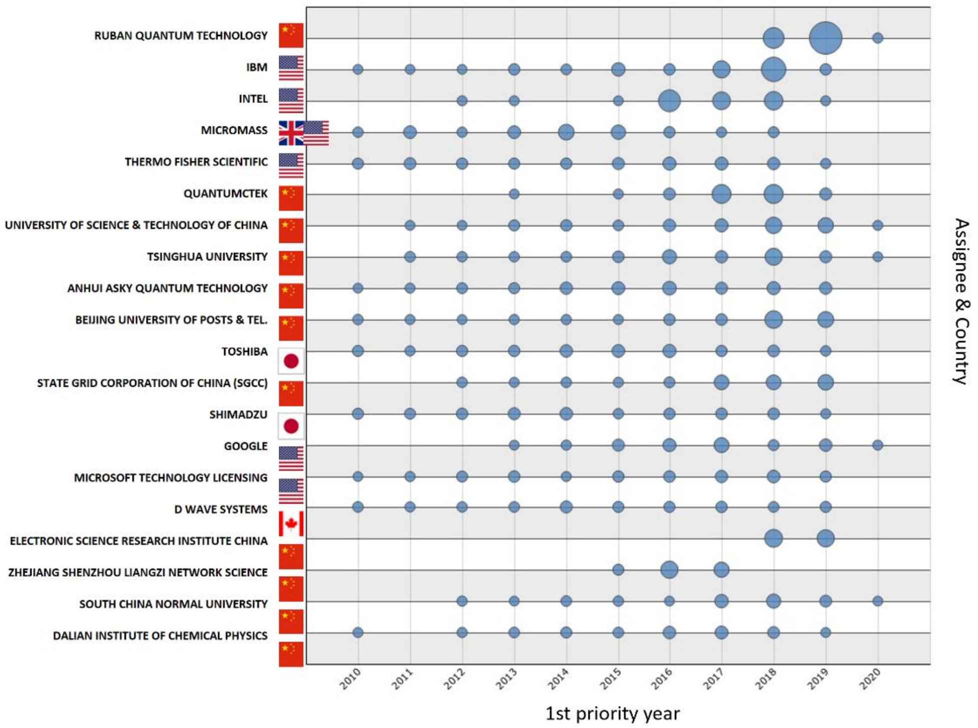

Figure 8: Annual change in the number of filings by the 20 key players

3.4. Case study: Grid & Quantum, the State Grid Corporation of China (SGCC) galaxy

In the electricity sector, the security of electricity and communications networks is crucial for energy network operators, and in particular the latter will have a direct impact on the normal operation of the electricity network.

The State Grid Corporation of China (SGCC or 国家电网公司) is the world's largest grid operator, carrier and distributor of electricity. It is in the world TOP5 in terms of revenue, employs 927k people and has a monopoly of 1.1 billion customers[7].

Since 2012, the company has been focusing on quantum technologies. It has organized a number of research projects dedicated to quantum technologies to study the feasibility of securing power grid communications, and the implementation of multi-user encryption key quantum distribution protocols.

As shown in figure 6 tofigure 8, SGCC has increased its patent filings from year to year and now claims 98 patents. Nearly two-thirds (64 patents or 65.3%) relate to telecommunications (protocol, quantum distribution of secret keys - QKD) and 16.3% to measurement systems (Figure 9**Error! Reference source not found.**). The same illustration also shows the close link with the University of Science and Technology of China (USTC) through the SGCC Electric Power Group's subsidiary specialized in electricity.

In 2013, in collaboration with SGCC, a team of USTC researchers successfully experimented with the use of quantum (secure) communication protocols and the transmission of quantum signals in the

[7] https://en.wikipedia.org/wiki/State_Grid_Corporation_of_China

overhead power cable environment of several SGCC power plants [16].

During the 2016 G20 Hangzhou summit, a subsidiary of SGCC deployed its quantum communication technology for secure voice/video/data communications.

In 2017, a demonstration of a quantum communication network was set up by SGCC between Beijing, Shandong, Anhui, Jiangsu, Zhejiang and other cities, which provided an opportunity to verify the operation of the system according to various vital parameters. Since then, developments have continued.

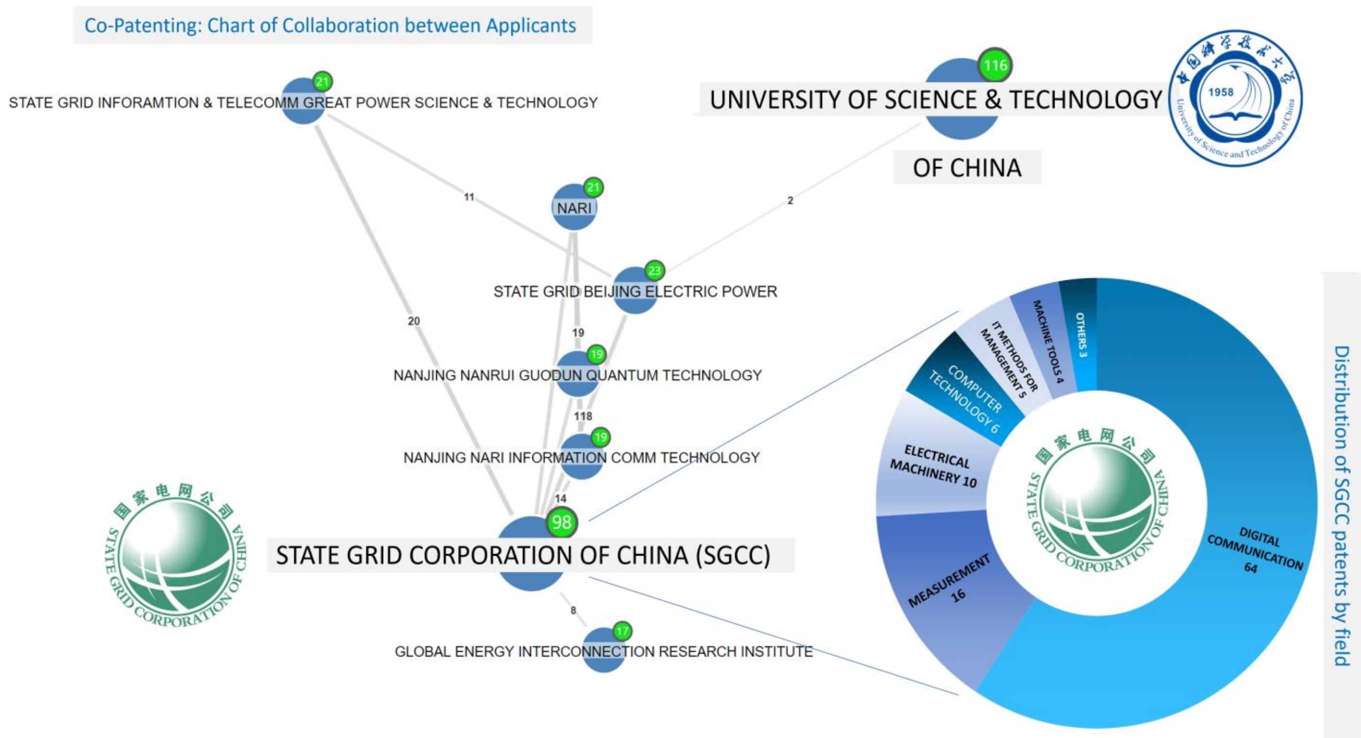

Figure 9: SGCC, world leader in GRID, at the heart of a quantum communications research network (Adapted graph and Orbit source)

While this brief description reflects the current effervescence in China around quantum communications, it also highlights the attractiveness of this region of the world for these technologies.

Thus, South Korea (5th applicant) innovates and invests a lot in the field. SK Telecom co., the South Korean wireless telecommunications operator, has just taken control of the Swiss start-up ID Quantique, a global specialist in quantum cryptography, and has thus taken over the Geneva-based company's portfolio of 18 patents[17].

Nevertheless, quantum communication technologies are not the only area of interest for researchers and companies in the rest of the world and we propose some additional elements of analysis in the following section.

3.5. Additional information on the fields of application of patents

In this section, we return to the fields of the patents collected in our study by presenting some graphs directly adapted from the Orbit database.

Figure 10 allows us to identify the diversity of patents using a categorization by technological field based on groupings of ICP codes (patents can appear in several categories). The color code nevertheless shows a concentration on the fields of electrical engineering (computer technology, digital communication), instrumentation (measurement) and chemistry (in the broad sense, materials, nanostructure).

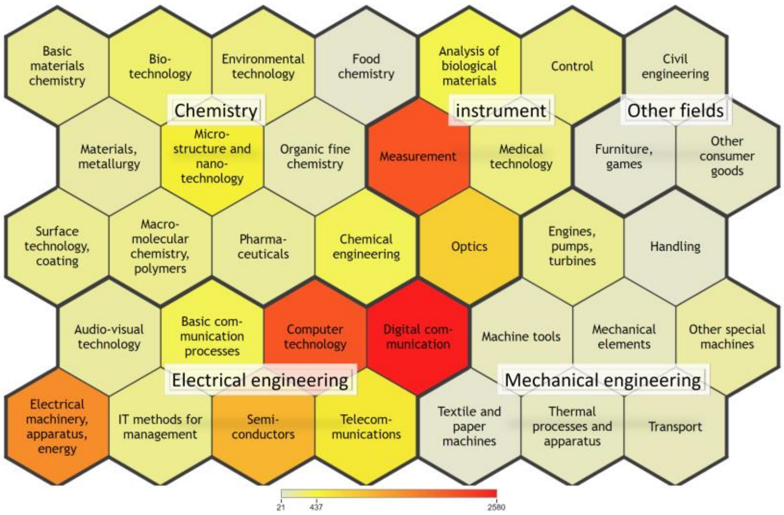

Figure 10: Overview of technological fields (source: calculated from Orbit on 9,905 patents)

Figure 11 is an illustration of the most commonly used technical concepts in the investigated industry crossed with our sample of patent filings[8]. This hierarchical view is interesting as it helps to distinguish the main topics tackled by the quantum technologies. We can note that several clusters that are clearly visible could have been grouped together, for example: *Qubit* and *Quantum Computer*.

A word about quantum simulation, the number of patents is very low while the academic literature is not particularly so. The explanation seems to be related to the fact that the patentability of simulation methods (such as modeling or AI) is complex and often rejected by patent authorities [18].

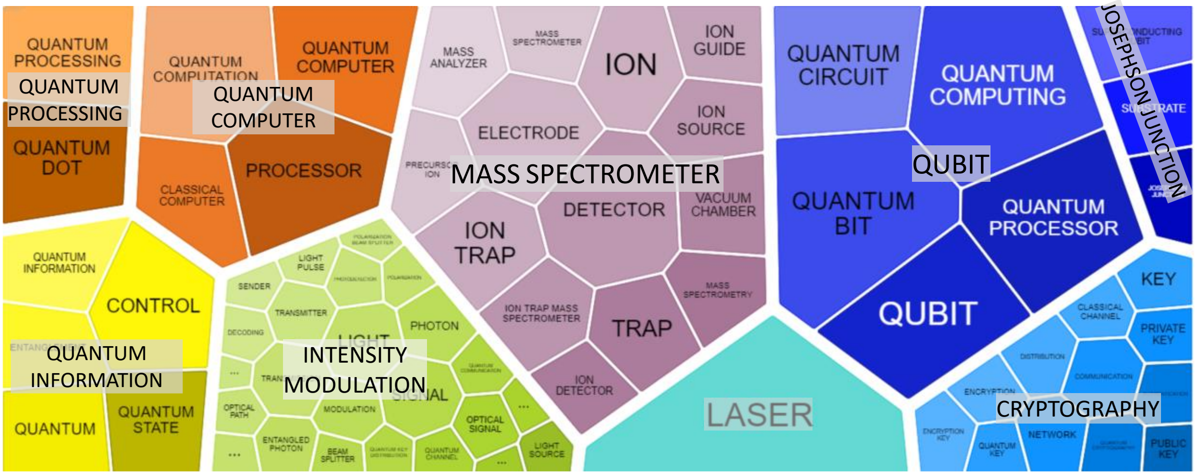

Figure 11: Concept clusters (source: calculated from Orbit on a sample of 9,905 patents)

Quantum technologies (computing, communication, sensors & metrology, simulation) benefit from a common theoretical and experimental base: the underlying fundamental science, Quantum Mechanics.

A discovery made in a particular field of this science can be instrumental in helping several technologies and/or fields of application simultaneously. Ion trapping, cold atoms and superconducting Josephson junction are technologies used both in sensors and in quantum computing, where these three techniques are candidates for being the physical medium capable of encoding the quantum information unit, the qubit. Similarly, a breakthrough in the control of photons can be beneficial in many areas including quantum communications, measurement, and qubit manipulation.

[8] The concepts are defined by an algorithm proposed by Orbit

3.6. Quotes between assignees

The following analysis will illustrate the citations between patents of different owners. This information makes it possible to identify innovations that have strong interactions between them. At a higher level, an assignee whose patent portfolio is strongly cited by most other players is likely to be a pioneer portfolio.

For the sake of clarity of presentation, we have limited our analysis to the owners of more than 20 patents in the portfolio and for which there are more than 6 citations.

The relation graph (Figure 12) that emerges shows three distinct clusters whose two formation criteria seem to be the technology field and the world region.

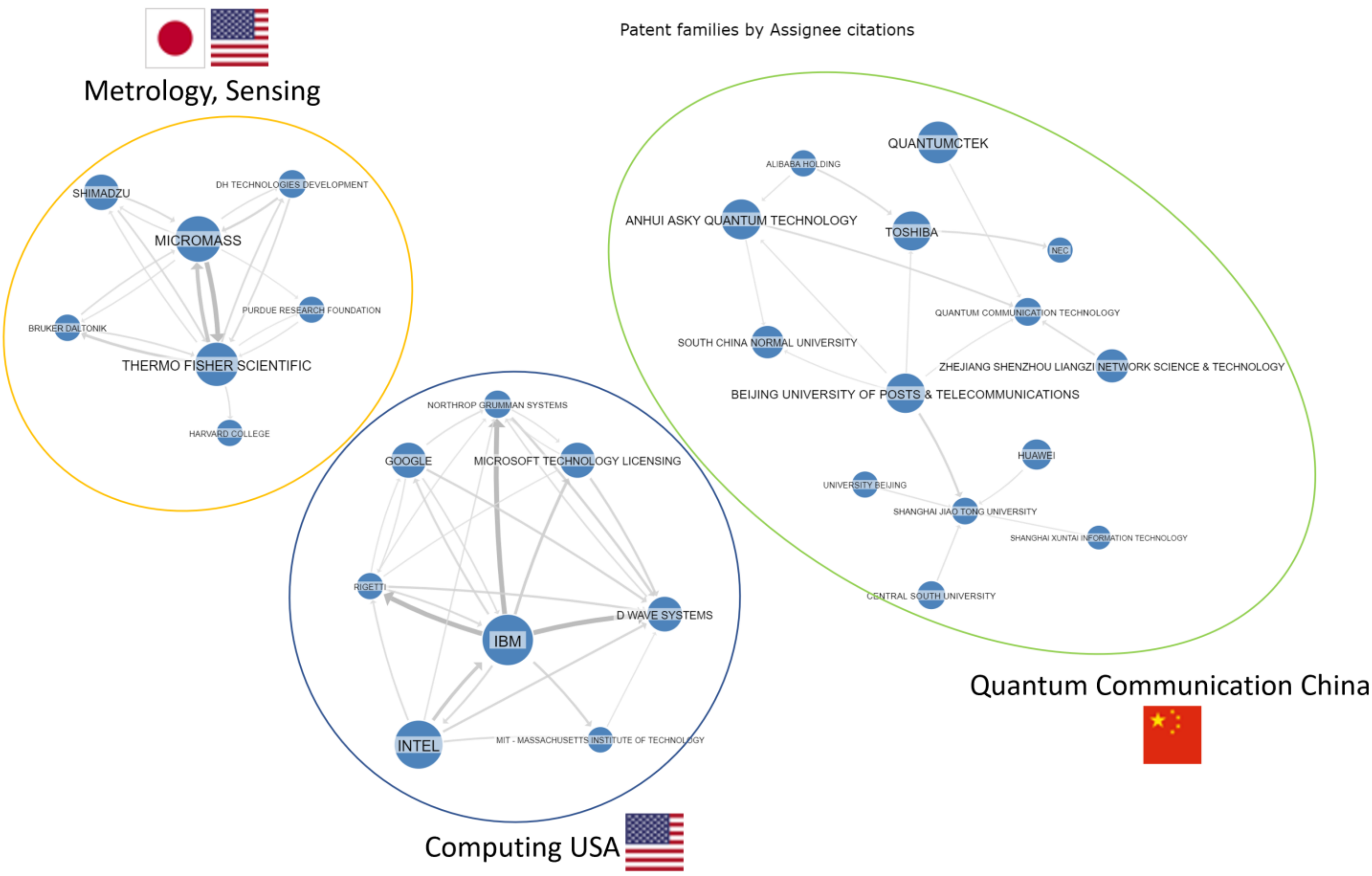

Figure 12: Relations between patent applicants by their mutual citations (Source: calculated from Orbit)

The cluster related to quantum communication technologies (green ellipse) is mainly made up of Chinese organizations (universities and companies), Toshiba and Nec being the exceptions.

The quantum computer is the heart of a North American cluster (blue ellipse) in which we find the American multinationals already mentioned (IBM, Intel, Google, Microsoft), the two specialized startups Rigetti and D-Wave (Canada) and Northrop Grumann, the American defense conglomerate.

The only university or research institute present here is MIT. It should also be noted, on the one hand, IBM's propensity to cite the patents of its colleagues and, on the other hand the fact that D-Wave can really be considered as a precursor insofar as their patents are often cited.

The third cluster is the one of metrology, and sensors with Micromass, Thermo Fisher, Shimadzu among others. Present in this cluster is Harvard College, a member of Harvard University.

A question now arises: how do we explain that the picture of patent citations crystallizes in this way? While we were talking about a common basic science, it seems that in practice patent applicants rather refer to patents covering the same field of technology.

Added to this is the fact that it seems that authors from one country are more likely to cite patents from the same country. Is it any wonder that technological spillovers and flows essentially materialize in close proximity? In the end we will not decide here, the subject is complex and is certainly not specific to the sectors of quantum technologies.

3.7. The patent landscape in the field of quantum computing

We propose in the last section of this patent analysis to zoom in on quantum computing. Our search equation is reduced to the use of the new IPC/CPC specific code G06N-10/00 identifying "*Quantum Computers, i.e. Computer Systems Based On Quantum-Mechanical Phenomena*"[9] as well as the old CPC code G06N-099/002.

((G06N-099/002)/CPC OR (G06N-010/00)/IPC/CPC) AND PRD >= 2010

Without the date constraint, we have 1,975 patents in the database, of which 1,550 have been filed since 2010.

Annual filings (Figure 13) were limited to a few dozen between 2000 and 2012, varying between 27 and 58 patents depending on the year[10].

Since 2012, their number has increased very sharply, multiplied by 11, from 39 to 429 in 2018, which represents a CAGR of 49.1%.

Thirty-two countries have filed at least one patent with a priority date after 2010. The twenty most active countries account for 98.5% of patents filed (TOP20 - Figure 14).

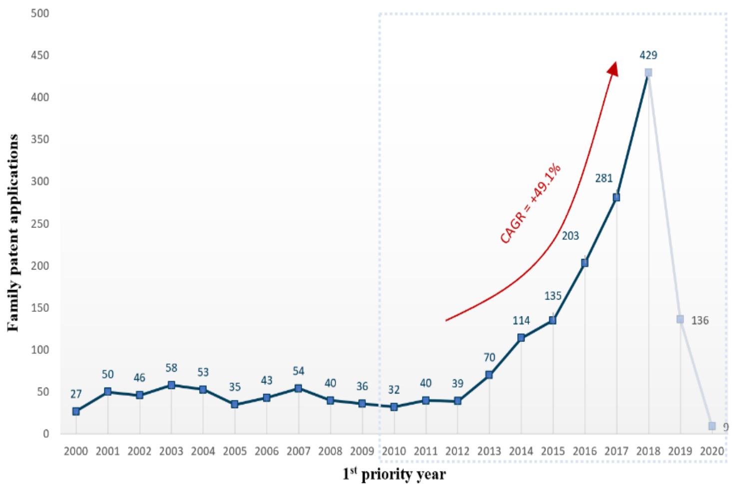

Figure 13: Evolution of the number of patents families in quantum computing

The TOP5 and TOP10 countries represent 81.5% and 93.7% of patent filings respectively.

The USA (874 or 51.4% of patents) is well ahead of China (185, 10.9%) and Canada (160, 9.4%). If all European patents are counted, Europe (in the broad sense: EU (143), UK (65), Switzerland (33), Russia (5)) would be in second place with 246 patents (14.5%) ahead of China.

[9] https://www.wipo.int/classifications/ipc/en/

[10] The annual figures in this analysis are slightly lower than those shown in Figure 2 because we did not add to our second search equation the keywords that would identify older patents not classified in the IPC/CPC categories.

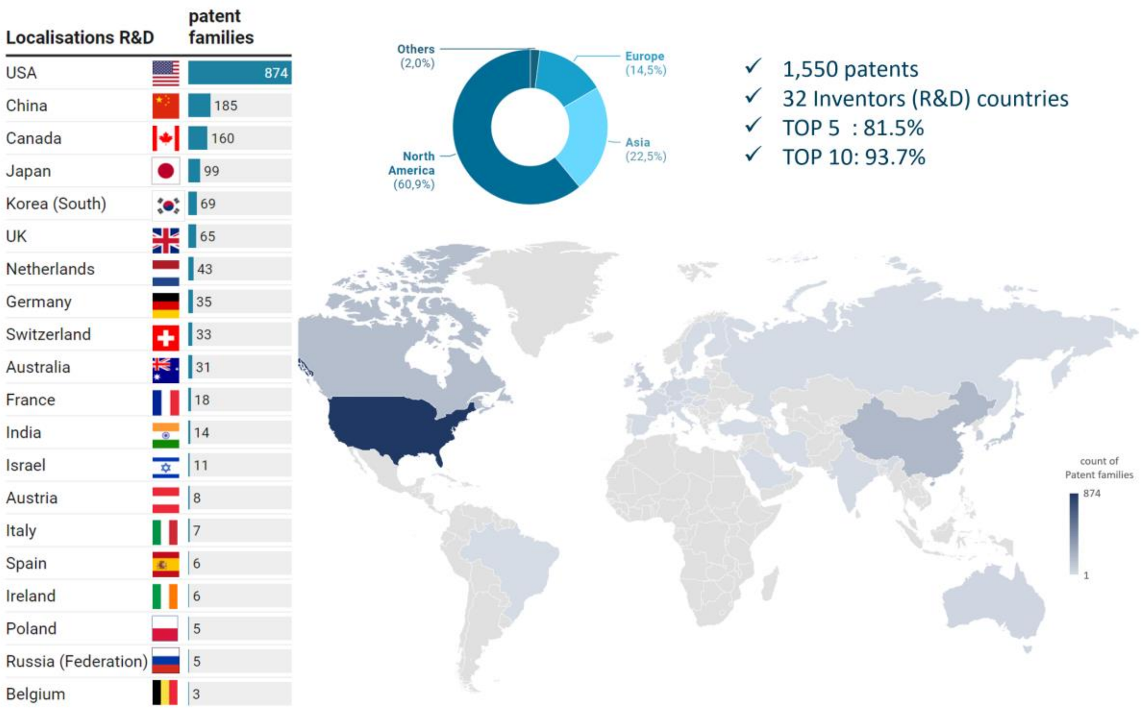

Figure 14: Geographical breakdown by location R&D

Figure 15 lists the 39 organizations that have filed more than 5 patents since 2010. 45% of the patents are held by TOP10 applicants, 33% by TOP5. Unsurprisingly IBM is the key player in the sector, but the typologies of players are quite diverse.

We have in this list different categories of players:

- US IT giants (IBM, Intel, Microsoft, Google),
- Asian conglomerates, rather Japanese historically positioned on telecoms and electronic equipment (illustrated by a mobile phone (▯) on the graph: Hitachi, Toshiba...),
- Startups specialized (🦄) in quantum computing that have built a quantum computer or have this hardware objective (D-Wave, Rigetti, Origin Quantum, IonQ, PsiQuantum). Others are more oriented towards software (1QBit, Zapata) or communication security (Quantum ID). Special mention should be made of Hefei Origin Quantum, a Chinese startup, a first for this country, which is positioned on a full-stack offer (vertical offer of hardware and software products),
- Defense and security sector organizations (Northrop Grumman on the corporate side, US Navy and US Army on the military side) are also present alongside some civilian agencies and government research establishments (Sandia).
- The academic sector (🎓) is well represented here with 12 institutions of different nationalities, half of which are American.

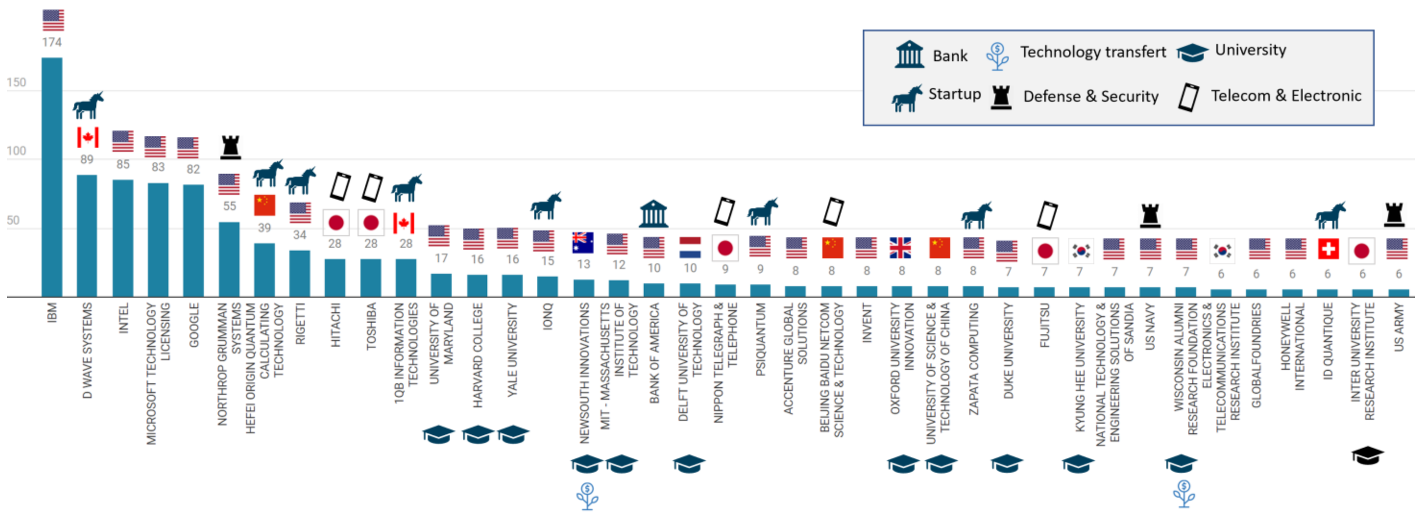

Figure 15: Organizations holding 6 or more patents since 2010

As can be seen in Figure 16, the technical problematics related to the development of a quantum computer are mostly addressed in the patents of our sample, whether the aspects directly related to the different possibilities of physical implementation of qubits (quantum dot, superconducting qubit, trapped ion...) or to those of their environment (qubit control, vacuum, microwave, laser).

While 1,438 patents refer to this type of subject, other topics are addressed (Figure 17) such as those related to communications security (QKD), quantum random number generation (QRNG) and as well some applications are detailed (IT methods for management, chemical engineering, or even transport).

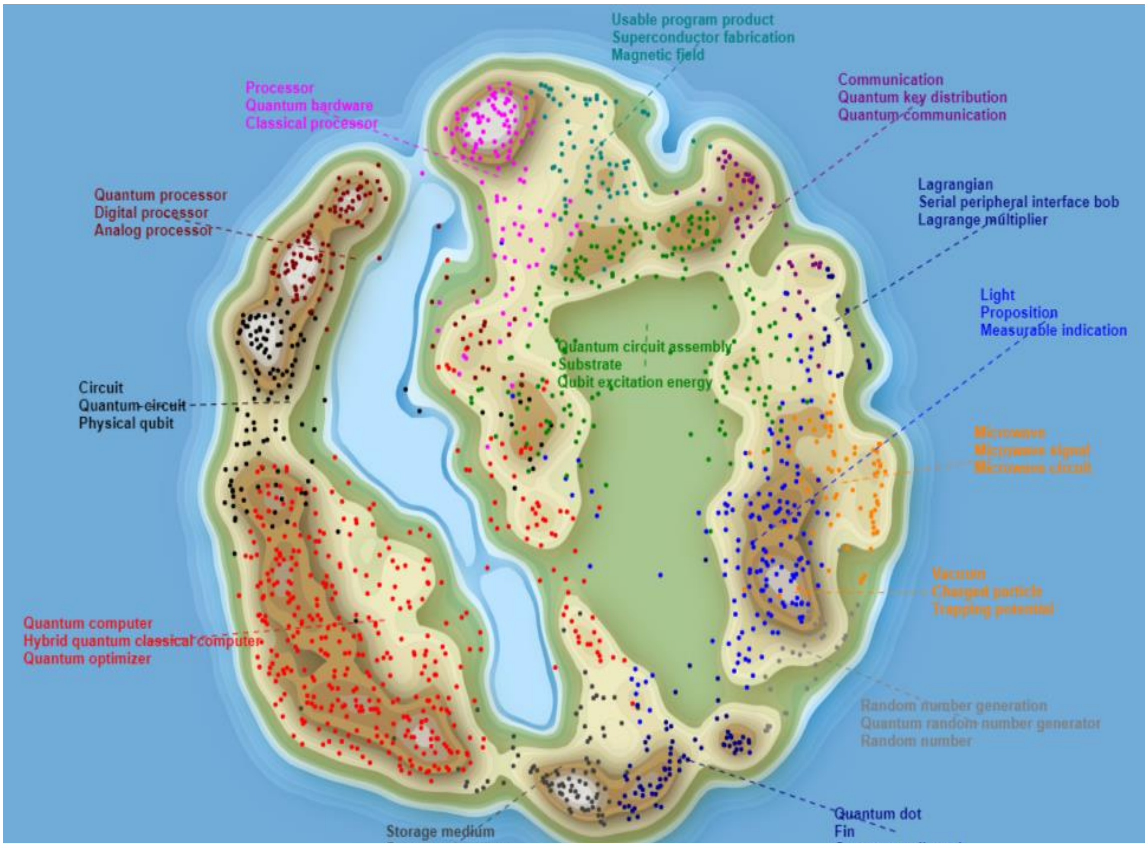

Figure 16: Map of technology clusters (Source: Orbit on sample of 1,550 patents)

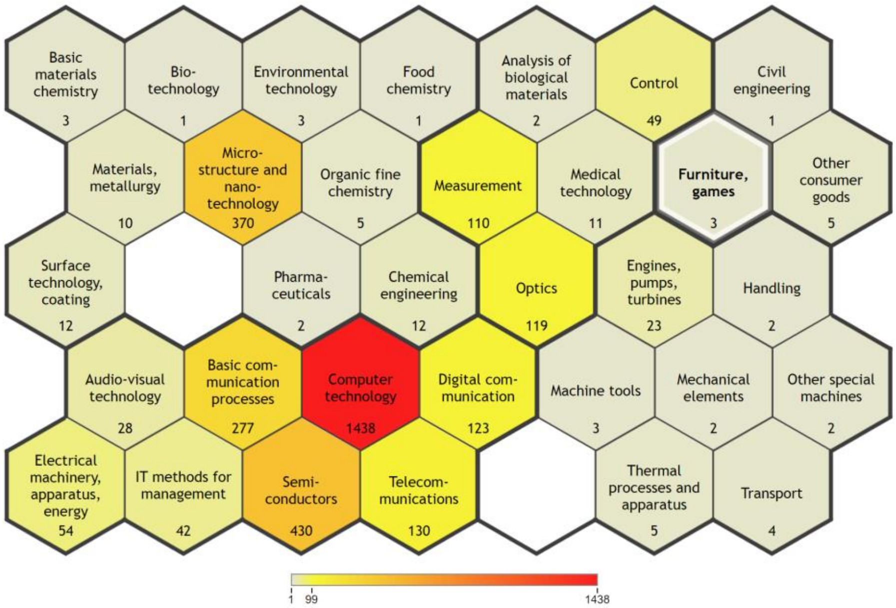

Figure 17: Technological fields (Source: Orbit on 1,550 patents)

4. Conclusion

The purpose of this study was to collect, analyze and aggregate patent information on quantum technologies with priority dates after 2009.

The analysis and collation of information confirmed the importance of China's role in the field of quantum telecommunications, which, together with the rest of their patent production, enables them to claim more than half of the patents filed.

The strong overall increase in the number of patents is multiplied in the specific field of quantum computing, which remains for the moment still under the domination of the USA, with more than half of the patented innovation in this field.

The diversity of players, ICT multinationals, startups, universities, technology transfer agencies, military and civilian government agencies is a reflection of the diversity of technologies explored and certainly a sign of the disruptive potential of these new technologies for many sectors of human activity: telecommunications, finance, transport, medicine, chemistry, new materials and molecules to name but a few.

SCIENTOMETRIC EVALUATION OF GLOBAL PUBLICATIONS RELATED TO RESEARCH IN QUANTUM COMPUTING FOR THE PERIOD 2010-2020

Based on the information indexed in the Scopus[11] database (www.scopus.com), we propose in this appendix a quantitative analysis of world scientific research in quantum computing from the perspective of publications on the subject. This scientometric study analyzes different indicators on publications (research papers, conferences, book chapters...) and cross-citations mentioning these publications. Few studies of this type exist on quantum computing, either the search parameters are too broad or too restrictive, or the studies are dated (for example [19] which analyses the period 2007-2016). We thus believe that our approach will bring some new elements of enlightenment.

The concept of quantum computing emerged in the 1980s with the work of Richard Feynman [20] and David Deutsch [21]. Today the proofs of principle are numerous and some products have even been marketed for several years (e.g. the Canadian D-Wave which sells quantum annealer[12] computers and recently offers a Cloud service [22], we can also quote IBM which also offers services in the Cloud, Google, Rigetti...). However, the technology is not mature and fundamental and applied research will take a long time [23].

In order to be in line with the research time scale and the study on patents that we presented in the previous appendix, we have chosen to carry out our analysis over a ten-year period (2010-2019) to which we have added the current production of 2020. The information was extracted and downloaded from Scopus on May 21, 2020. The year 2020 is therefore not complete. It is also particular due to the global SARS-CoV-2 health crisis.

In summary, we have identified a total of 15,602 publications for the decade 2010-2019. The average annual growth rate was 10.4% and, as of 21 May 2020, each publication was cited an average of 14.8 times.

For 2020, 677 references are currently counted, which, extrapolated over a full year, would mark a drop of about 20% in scientific production on the subject. The total sample includes a final total of 16,279 publications.

The top 10 countries, the most productive in terms of number of publications over the period, account for 98.9% of world publications. The USA accounts for the highest share (26.4%) ahead of China (22.8%).

Germany, Australia and the USA are the three countries whose publications were, in relative terms, the most cited. International collaboration was an important driving force for research in this field. For the top 10 countries, 8 out of 10 articles (83%) were from an international collaborative publication. Australia is the most collaborative country (130%) while India is currently more closed (33%).

Physics and computer science are the two most popular areas of research related to our topic. Our study identifies the 20 most productive organizations and authors, the 20 most used journals, as well as the 336 highly cited articles, with more than 100 citations per article.

[11] https://en.wikipedia.org/wiki/Scopus

[12] Quantum annealing is the principle used for these specialized processors for very specific optimization problems.

1. Objectives

By processing the information collected from the Scopus database, we seek in this study to qualify the interest of the scientific community on the theme of quantum computing through the analysis of different metrics related to its publications on the subject. We will develop here the following points:

- Evolution over time of the number of publications
- Impact of publications by the number of citations counted
- Geographical distribution, production of the 10 most prolific countries
- Distribution of research by scientific sub-domain
- Profile of the 20 most productive organizations and authors
- Preferred means of communication (articles, conferences, books...)
- Bibliometric profile of the 336 most cited articles

2. Methodology

On May 21, 2020 we queried Scopus from the search equation:

TITLE-ABS-KEY ("quantum comput*") AND PUBYEAR > 2009

This query allows us to retrieve information on documents published since 2010 containing in their title, abstract, or keywords combinations such as *quantum computer*, or *quantum computation*.

3. Analysis

3.1. Annual trends in global quantum computing research

Over the period 2010-2020 the number of publications is 16,279, rising from 895 in 2010 to 2,181 in 2019, representing a compound annual growth rate (CAGR) of 10.4%. As shown in Figure 1, the sharp increase in the years 2010-2012 was followed by an almost constant output between 2012 and 2015. Since 2015, interest in our subject has increased with an average growth of 9.6%/year[13].

The year 2020 will be a very special year. Due to the generalized containment we experienced following the SARS-CoV-2 pandemic, access to most laboratories has been blocked, research work has been slowed down and conferences have been cancelled. Extrapolating from the 677 publications published in 2020 at the time of writing, a decrease in full-year production is to be expected unless the period has been used for article writing.

Year	Total publications (TP)	Total citations (TC)	Citations par publication (CPP)
2010	895	41,136	46.0
2011	1,047	25,387	24.2
2012	1,459	32,953	22.6
2013	1,468	32,549	22.2
2014	1,492	27,628	18.5
2015	1,511	23,615	15.6
2016	1,711	22,529	13.2
2017	1,759	16,990	9.7
2018	2,079	13,755	6.6
2019	2,181	4,787	2.2
2020	677	207	0.3
2010-2020	**16,279**	**241,536**	**14.8**

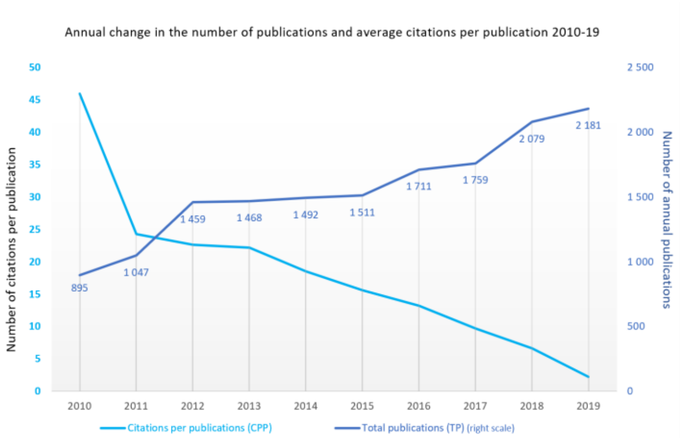

Figure 1 : Evolution of the number of publications and global citations in quantum computing research 2010-2020

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13 As a comparison, we have counted on Scopus the number of publications mentioning "Artificial Intelligence" over the period 2015-2019. We go from 21,703 publications in 2015 to 27,657 in 2019, i.e. a CAGR of 6.25%.

The total number of publications citing the 16,279 documents is currently 241,536. The average citation rate over the period 2010-2020 is 14.8 citations per publication.

The type of publications is shown in Figure 2. More than two thirds (67.7%) are scientific articles, almost 25% are conference or congress proceedings.

Article reviews represent 2.7% and book chapters 2.2%. Conference journals and complete books account for less than 1% each.

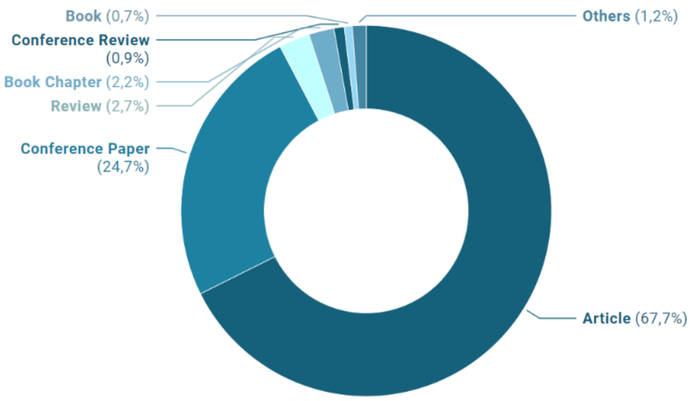

Figure 2: Publications types

3.2. Geographical distribution of world research in quantum computing

The "affiliation tag" and "country tag" metadata available in Scopus are used to define the country(ies) of origin of the institutions to which the author(s) of a document are affiliated at the time of publication.

	Pays	TP	%TP	TC	%TC	CPP	RCI	%ICPEI
1	USA	4,295	26.4%	108,128	44.8%	25.2	1.7	70%
2	China	3,706	22.8%	38,611	16.0%	10.4	0.7	44%
3	UK	1,428	8.8%	32,435	13.4%	22.7	1.5	120%
4	Germany	1,400	8.6%	38,339	15.9%	27.4	1.9	123%
5	Japan	1,106	6.8%	20,996	8.7%	19.0	1.3	99%
6	Canada	1,056	6.5%	23,104	9.6%	21.9	1.5	124%
7	India	991	6.1%	5,847	2.4%	5.9	0.4	33%
8	Australia	777	4.8%	20,777	8.6%	26.7	1.8	130%
9	France	699	4.3%	14,016	5.8%	20.1	1.4	117%
10	Italy	635	3.9%	10,522	4.4%	16.6	1.1	116%
	Total 10 countries	16,093	98.9%	312,775	129,5%	19.4	1.3	83.1%
	Total world	16,279		241,536		14.8		

*TP= Total Publication ; TC = Total Citation ; CPP = Citation par Publication = TC/TP ;
RCI = Relative Citation Index ; ICPEI = International Collaboration Publication Extended Index

Figure 3: Distribution of publications, citations and collaboration index for the 10 most productive countries in quantum computing research over the period 2010-2020

The table above (Figure 3) summarizes the seven metrics we calculated and analyzed. We will find them in other sections of this study but can define them here:

- TP: Total Publications,
- %TP: Total Publications as a percentage of the world total,
- TC: Total Citations in number and percentage (%TC),
- CPP: Citation Rate per Publication (CPP = TC/TP),
- It should be noted that overlaps are possible in quantity counts such as the number of publications (TP) or citations (TC). Thus, a publication co-signed by several authors whose affiliations are of different nationalities is counted for each of the countries involved.

- RCI: "Relative Citation Index" [24] compares the citation rate with the world average (the overall average citation rate in our study 14.8). It is calculated by dividing the average number of citations per publication in a given subfield by the global average citation rate for all publications. A RCI greater than 1 indicates a higher score against the global norm, a RCI less than 1 indicates a relatively lower performance.
- Finally, the International Collaborative Publications Extended Index (%ICPEI) will be discussed in the next section of this paper.

Over the period 2010-2020, the subject of quantum computing has been widely discussed since the panel of countries represented is very large, with 111 countries.

However, the concentration is very high. The TOP 10 most productive countries (Figure 3) account for 98.9% of publications. The USA and China stand out from the ranking. The USA dominates with 26.4% followed by China with 22.8% (Figure 4). The UK is third with 8.8%. France is in 9th position with 4.3% of publications.

As can be seen from Figure 4 to Figure 6, the UK and Germany, which are very close to each other, alternate in 3rd position both in terms of annual output and citations.

India in 7th position for the number of publications is only 10th for citations (Figure 4 & Figure 5). Its RCI index of 0.4 is almost 5 times lower than Germany and Australia's one which are the countries with the most cited articles (RCI = 1.9 and 1.8 respectively).

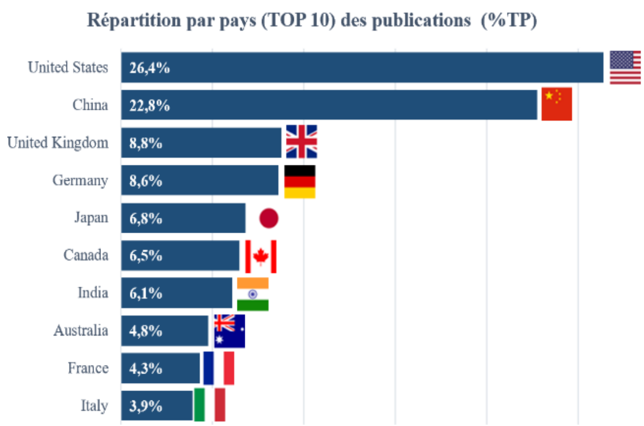

Figure 4: TOP 10 number of publications

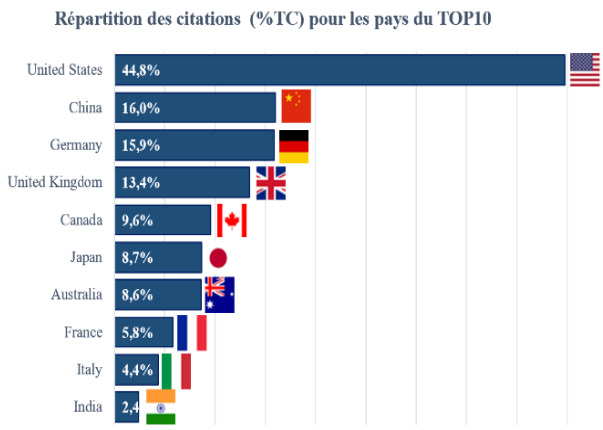

Figure 5:TOP 10 number of citations

In addition to the elements already mentioned, Figure 6 shows the recent dynamism in India and Canada, with China showing a slight decline in 2019.

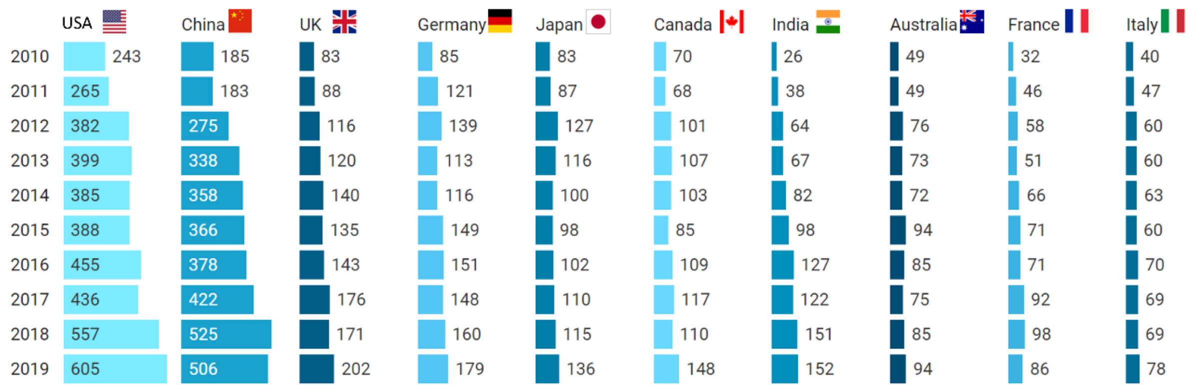

Figure 6: Annual change in the number of publications for the 10 most productive countries (2010-2019)

3.3. International Collaboration

The International Collaboration Publication Extended Index (%ICPEI) found in the table in Figure 3 is designed to measure collaboration on a particular research area by a country, an affiliated organization (university, company, etc.), or a particular author.

To our knowledge, this is the first time this index has been proposed in the literature in this form. It is an extension of the ICP (International Collaborative Papers) index which measures the ratio between the number of publications resulting from international collaboration and the total number of publications. The ICP credits a publication with the same value regardless of the number of nationalities of the co-signatories (or their affiliation organizations).

In this study, we propose and define an index that allows us to be more precise in measuring the international collaboration of a co-publication. Unlike the ICP index, a paper co-signed by 3 different countries, for example, will have a higher ICPEI metric than a paper co-signed by 2 countries.

Our index is defined as, for a reference country (or author or reference organization), the ratio between the number of international links for multinational publications and the number of publications. The nationality is defined by the country of the authors' affiliation organization at the date of publication of the papers.

$$\%ICPEI = \frac{\sum_{k=1}^{N} \begin{matrix} Number\ of\ countries\ involved\ in\ the\ writing\ of\ publication \\ number\ k\ other\ than\ the\ reference\ country \end{matrix}}{N},$$

$$with\ N = publication\ number\ of\ the\ reference\ country$$

Unlike the ICP, for a given publication with multiple authors, we count the total number of countries involved. The ICPEI of a publication with a single author is 0. The index of a publication with several authors affiliated with the same or different organizations but of the same nationality is also zero. A publication resulting from the collaboration of three universities belonging to three different countries (university_1 = university of country A of reference, university_2 = country B, university_3 = country C) has an index of 200%.

As can be seen in Figure 3, between 2010 and 2020, the international collaboration of the 10 most productive countries in quantum computing research varies from 33% to 130% with an average rate of 83.1%. The most collaborative countries are Australia, Canada and Germany (130%, 124% and 120%). The USA (70%), China (44%) and India (33%) are the countries that have collaborated the least.

3.4. Research distribution by subdomain

Using the classification of the Scopus database, we present in Figure 7 the ten main areas of publication work related to quantum computing.

The most represented categories are physics (32.6%), followed by computer science (17.5%) and engineering (14.8%). Mathematics and materials science subjects are roughly equal (11.7% and 11.4% respectively).

These figures have been normalized to account for the fact that some publications address several topics at the same time. Other statistics are presented in Figure 8. Multidisciplinary and chemical-related publications have the highest citation rate (CPP).

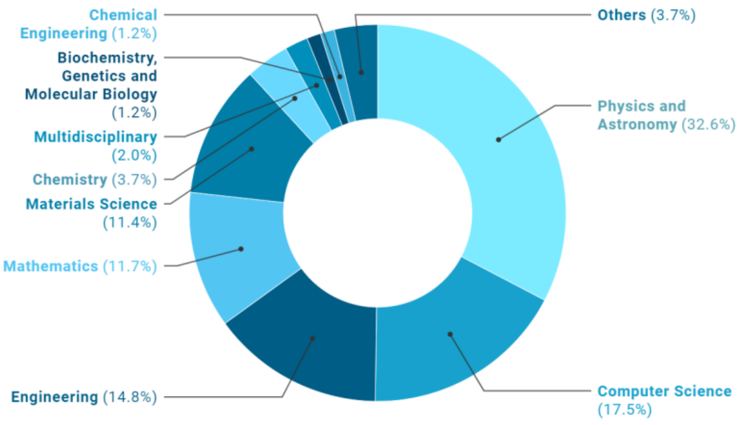

Figure 7: Breakdown by scientific sub-domain

Domain	TP	%TP	TC	CPP
Physics and Astronomy	10,004	32.6%	169,012	16.9
Computer Science	5,388	17.5%	33,011	6.1
Engineering	4,558	14.8%	32,803	7.2
Mathematics	3,583	11.7%	24,315	6.8
Materials Science	3,511	11.4%	40,940	11.7
Chemistry	1,140	3.7%	25,277	22.2
Multidisciplinary	627	2.0%	36,606	58.4
Biochemistry, Genetics and Molecular Biology	383	1.2%	10,125	26.4
Chemical Engineering	354	1.2%	9,177	25.9
Social Sciences	291	0.9%	2,024	7.0

Figure 8: Statistics on publications sub-domains 2010-2020

3.5. Distribution of the most cited keywords

The word cloud in Figure 9 highlights the most commonly used keywords in the various publications that emerged for our research.

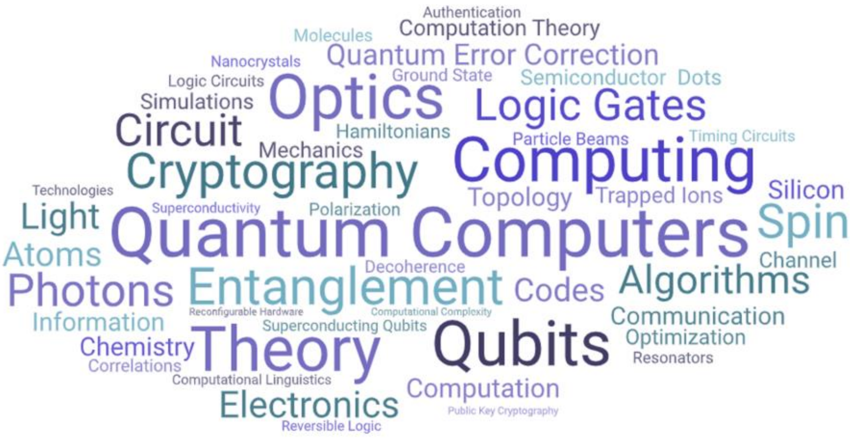

Figure 9: Cloud of the 50 most used keywords

The five most common keywords are "Quantum Computers" used 11,900 times, followed by "Quantum Optics" (4,558), "Quantum Theory" (4,068), "Quantum Computing" (3,325), "Quantum Entanglement" (2,962). Not surprisingly, it also includes the various technologies explored or used today to build quantum computers: photon, trapped ions, atom, superconducting silicon, nanocrystals, topological properties of matter [25].

Apart from elements related to hardware, application fields such as communication (cryptography), simulation (chemistry) and optimization are mentioned. Finally, algorithmic aspects have a good place with of course Qubits (quantum bits), error-correcting code, circuit and quantum logic gate [26].

3.6. TOP 20 Most Productive Organizations in the World

Between 2010 and 2020, 2,506 organizations (universities, companies, etc.) published on the subject of quantum computing, but the distribution is very uneven. Only 154 institutions have distributed more than 50 publications: 102 have published between 50 and 99 times, 29 have made between 100 and 149 publications, 17 between 150 and 299, and only 6 institutions have published more than 300 times.

Over the period 2010-2020, the number of publications from the 20 most prolific institutions (Figure 10) varies between 160 and 524. Together, the TOP 20 account for 31.2% (5,078) of global publications on the subject and 54.4% of citations (Figure 11).

Figure 10: TOP 20 Most Productive Organizations (Affiliations) in Quantum Computing 2010-2020

	Institution	TP	TC	CPP	RCI	%ICPEI	HI
1	Chinese Academy of Sciences, China	524	7 262	13,9	0,93	75%	38
2	University of Science and Technology of China	362	7 093	19,6	1,32	56%	40
3	University of Waterloo, Canada	354	9 234	26,1	1,76	121%	39
4	National University of Singapore	340	5 887	17,3	1,17	143%	38
5	CNRS Centre National de la Recherche Scientifique, France	316	7 073	22,4	1,51	116%	39
6	Centre for Quantum Technologies Singapore	306	5 401	17,7	1,19	152%	35
7	University of Oxford, UK	298	8 676	29,1	1,96	115%	45
8	Massachusetts Institute of Technology, USA	271	8 334	30,8	2,07	85%	39
9	Tsinghua University, China	268	5 272	19,7	1,33	80%	32
10	University of Maryland, USA	243	9 625	39,6	2,67	47%	42
11	National Institute of Standards and Technology, USA	208	8 431	40,5	2,73	70%	38
12	University of Tokyo, Japan	202	4 342	21,5	1,45	78%	31
13	Delft University of Technology, Netherlands	185	5 827	31,5	2,12	149%	39
14	University of New South Wales UNSW Australia	184	5 439	29,6	1,99	108%	30
15	Ministry of Education China	183	2 089	11,4	0,77	19%	21
16	ETH Zürich, Switzerland	178	5 086	28,6	1,93	149%	39
17	Harvard University, USA	170	8 864	52,1	3,51	113%	47
18	University College London, UK	164	3 206	19,5	1,32	132%	28
19	University of California Santa Barbara, USA	162	9 701	59,9	4,04	68%	42
20	Perimeter Institute for Theoretical Physics, Canada	160	4 673	29,2	1,97	116%	29
	Total TOP 20 institutions	5 078	131 515	25,9	1,75	99%	37
	Total world	16 279	241 536				
	Share TOP20 vs world	31,2%	54,4%				

Figure 11: Statistics on the TOP 20 Most Productive Organizations in Quantum Computing between 2010-2020

We observe after a more detailed analysis of this table:

- Nine institutions in the TOP 20 have published more than the group average (254): CAS and USTC in China, the University of Waterloo in Canada, the National University and its Quantum Technologies Centre in Singapore, the CNRS in France, Oxford University in the UK, MIT in the USA, and Tsinghua University in China.
- Eleven institutions have a citation impact above the group average (CPP=25.9): UCSB USA (59.9), Harvard USA (52.1), NIST USA (40.5), UMD USA (39. 6), Delft University Netherlands (31.5), MIT USA (30.8), UNSW Australia (29.6), Canadian Perimeter Institute (29.2), Oxford UK (29.1), ETH Zurich Switzerland (28.6), University of Waterloo Canada (26.1).
- Eleven institutions had international collaboration above the group average (99%): the top five are the Quantum Technology Centre Singapore (152%), ETH Zurich Switzerland (149%), University of Delft Netherlands (149%), NUS Singapore (143%), UCL UK (132%).
- Publications with co-authors are counted for each author and affiliation. Restated for these duplicates, we arrive at a total of 3,823 papers produced by the TOP 20, which in fact represents 23.5% of the world production (and not 31.2%). With the same logic, the number of citations for these documents is 94,986, which represents 39.3% of the world total (vs. 54.4%). This type of correction is not systematically carried out in scientometric studies (e.g. [19]) but it seemed interesting to us to clarify the numbers.
- The table shows the Hirsch index[14] ("h-index" noted here as HI) as calculated by Scopus on all the selected publications attached to each of the institutions concerned. According to this criterion, two institutions are above 45: Harvard USA (47) and Oxford UK (45).

3.7. TOP 20 most prolific authors

Several thousand researchers are contributing to research in quantum computing, but as most of the government roadmaps published so far around the world attest, their numbers are too small for future needs. Education and training in the field of quantum technologies are major objectives (see, for example, the strategic roadmap of the European Flagship published in February 2020 [28]).

In the course of our study we identified 22,755 authors. The overwhelming majority published only one to five articles over the last ten years. Only 88 authors have published more than 25 times: 54 authors from 25 to 34 times, 24 authors from 35 to 44 times, and 10 authors have 45 to 84 publications.

The number of publications of the 20 most prolific authors varies between 39 and 84 (Figure 12). Together, the TOP 20 account for 5.8% (945) of the world's publications on the subject and 15% of the citations (36,303).

We observe after a more detailed analysis of the table:

- Publications with co-authors on the list are counted for each of the authors. Restated for these duplicates, we count a total of 816 documents for the TOP 20, which in fact represents 5% of world production (and not 5.8%). For the same reason, the number of citations for these 816 documents is 28,872, which represents 12% of the world total (as opposed to 15%).
- Six authors have published more than 47.25 times, which is the average of the TOP 20 group: Wille (84), Nori (64), Munro (57), Drechsler (54), Guo (48), Morimae (48).

[14] Proposed by J. Hirsch in 2005 [27], the calculation of this index starts from the statistical distribution of citations to the work of a researcher, a department, a university or even a country. According to Hirsch: "A scientist has an index h if h of [his] N_p papers each have at least h citations, and the other (N_p - h) papers have at most h citations each". This index is now quite controversial: https://en.wikipedia.org/wiki/H-index.

	Author	Affiliation	TP	TC	CPP	RCI	%ICPEI	HI docs	HI auteur
1	Wille, R.	Johannes Kepler University Linz, Linz, Austria	84	887	10,6	0,7	160%	17	30
2	Nori, F.	University of Michigan, United States	61	2 520	41,3	2,8	261%	20	96
3	Munro, W.J.	Nippon Telegraph and Telephone Corporation, Tokyo, Japan	57	1 116	19,6	1,3	209%	16	50
4	Drechsler, R.	University of Bremen, Bremen, Germany	54	688	12,7	0,9	73%	15	36
5	Guo, G.C.	Chinese Academy of Sciences, Beijing, China	48	1 108	23,1	1,6	50%	17	17
6	Morimae, T.	Yukawa Institute for Theoretical Physics, Kyoto, Japan	48	677	14,1	1,0	86%	16	69
7	Pan, J.W.	University of Science and Technology of China, Hefei, China	46	3 214	69,9	4,7	102%	23	51
8	Gambetta, J.M.	IBM Thomas J. Watson Research Center, Yorktown Heights, United States	46	2 622	57,0	3,8	17%	26	77
9	Martinis, J.M.	Google LLC, Mountain View, United States	45	4 352	96,7	6,5	64%	27	48
10	Simmons, M.Y.	University of New South Wales (UNSW) Australia, Sydney, Australia	45	1 710	38,0	2,6	100%	17	86
11	Nemoto, K.	Research Organization of Information and Systems National Institute of Informatics, Tokyo, Japan	44	929	21,1	1,4	89%	13	37
12	Zhang, S.	Yanbian University, Yanji, China	43	520	12,1	0,8	33%	12	28
13	Schoelkopf, R.J.	Yale University, New Haven, United States	42	3 488	83,1	5,6	71%	26	69
14	Aspuru-Guzik, A.	Harvard University, Cambridge, United States	41	2 609	63,6	4,3	105%	22	15
15	Hollenberg, L.C.L.	University of Melbourne, Parkville, Australia	41	2 253	55,0	3,7	100%	17	51
16	Kwek, L.C.	National University of Singapore, Singapore	41	660	16,1	1,1	146%	13	59
17	Bhattacharyya, S.	RCC Institute of Information Technology, Kolkata, India	41	295	7,2	0,5	32%	10	38
18	Fowler, A.G.	Google LLC, Mountain View, United States	40	3 301	82,5	5,6	189%	23	33
19	Dzurak, A.S.	University of New South Wales (UNSW) Australia, Sydney, Australia	39	3 165	81,2	5,5	149%	19	36
20	Haghparast, M.	Islamic Azad University, Tehran, Iran	39	189	4,9	0,3	23%	8	12
		Total TOP20 authors	945	36 303	38,4	2,6	109%	18	47
		Total World	16 279	241 536					
		Share TOP20 vs World	5,8%	15,0%					

Figure 12: Statistics of the 20 most productive authors in terms of publications related to quantum computing between 2010-2020

- Nine authors have a citation rate above the average of the TOP 20 (CPP= 38.4): Martinis (96.7), Schoelkopf (83.1), Fowler (82.5), Dzurak (81.2), Pan (69.9), Aspuru-Guzik (63.6), Gambetta (57.0), Hollenberg (55.0), Nori (41.3).
- Six authors had an above-average rate of international collaboration (%ICPEI=109%): Nori (261), Munro (209), Fowler (189), Wille (160), Dzurak (149), Kwek (146).
- We have reported on the table the Hirsch index (HI) of the publications selected for each of the authors (i.e. dealing with quantum computing: HI docs) as well as the global "score" of each of them (i.e. for all their publications: HI author).

3.8. TOP 20 communication sources

Scientific journals (Figure 13) are the most used media for publications (11,670 or 71.7%). Conference proceedings represent 20.4%, book format 7.5% and commercial journals marginally 0.4%.

The number of publications of the 20 most represented journals ranges from 85 to 1,916. These 20 titles total 6,028 articles, i.e. 51.7% of the production of articles published in scientific journals that may deal with topics related to research in quantum computing over the period 2010-2020.

Physics journals are widely represented (Figure 14), for example the monthly Physical Review A, one of the titles of the American Physical Society (APS).

Fundamental and experimental research to determine the best physical support for quantum information is still very active [25] and is one of the challenges in the race for the universal quantum computer (hardware) and the candidate devices are multiple (photons, ions, atoms).

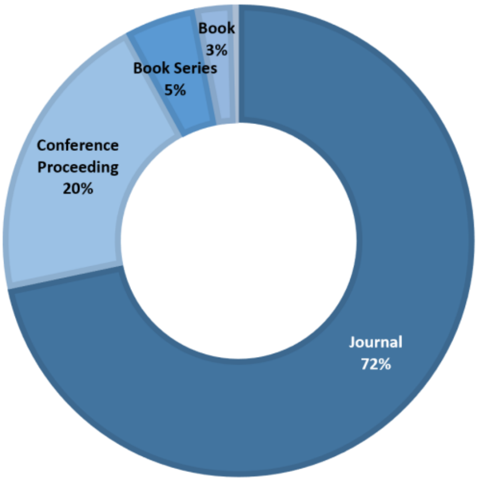

Figure 13: Source types

	JOURNAL TITLE	TP			
1	Physical Review A	1,916	11	Applied Physics Letters	133
2	Quantum Information Processing	738	12	Quantum Information And Computation	129
3	Physical Review Letters	730	13	Physical Review X	119
4	New Journal Of Physics	426	14	Wuli Xuebao Acta Physica Sinica	106
5	Physical Review B	331	15	Nature Physics	100
6	Scientific Reports	202	16	Optics Express	92
7	Chinese Physics B	174	17	IEEE Transactions On Information Theory	91
8	International Journal Of Theoretical Physics	167	18	Nano Letters	89
9	Nature	159	19	IEEE Access	86
10	Nature Communications	155	20	International Journal Of Quantum Information	85

Total TOP 20 Journal	6,028
Total World Journal	11,670
Share TOP20 vs World	51,7%

TOP 20 – EDITORS 2010-2020

Figure 14: TOP20 most publishing journals between 2010-2020 and their editors

To conclude this section, we present in Figure 15 the evolution of the number of papers related to quantum computing published by the TOP 20 of scientific journals between 2010 and 2019.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Physical Review A	87	99	216	218	166	237	253	236	236	131
Physical Review Letters	38	37	93	102	74	68	74	73	88	61
Quantum Information Processing	8	20	39	85	67	75	114	94	118	73
New Journal of Physics	20	27	40	43	49	46	59	41	60	36
Physical Review B	22	21	19	35	24	32	36	31	31	54
Scientific Reports		1	8	9	20	32	45	32	20	26
Chinese Physics B	5	12	22	19	24	23	10	19	28	11
International Journal of Theoretical Physics	7	6	3	10	21	12	20	21	25	29
Nature	16	17	12	10	8	7	14	17	22	26
Nature Communications	3	6	10	18	19	19	15	16	18	25
Applied Physics Letters	4	7	9	14	21	19	15	17	14	11
Quantum Information and Computation	17	11	8	9	19	16	12	8	12	12
Physical Review X		2	7	3	21	11	21	10	28	12
Wuli Xuebao/Acta Physica Sinica	3	2	6	7	5	17	13	9	26	17
Optics Express	1	3	3	8	10	16	10	10	15	13
Nature Physics	12	9	5	8	6	9	5	9	9	15
International Journal of Quantum Information	17	11	8	7	12	5	9	1	9	6
IEEE Transactions on Information Theory	5	6	6	9	16	9	3	9	9	12
Nano Letters	3	1	4	8	5	4	12	9	18	19
IEEE Access				1	3	3	4	12	11	32
TOTAL	268	298	518	623	590	660	744	674	797	621

Figure 15: Evolution of the number of papers published in the TOP20 journals related to quantum computing over 2010-2019

3.9. Most cited publications

Among the 16,279 publications identified in our sample, only 11,183 have at least one citation to date. The most referenced publication is a scientific article with a total of 9,739 citations. The average is 14.8 citations per publication.

For the rest of this section, we will limit ourselves to paper (or article)-type publications, which number 11,014 (i.e. nearly 68% of our database). The articles cumulate 206,308 citations, i.e. 85.4% of the total number of citations 241,536.

The distribution of the number of citations is very spread out, as can be seen in Figure 16 representing the number of citations per paper in descending order and on a logarithmic scale.

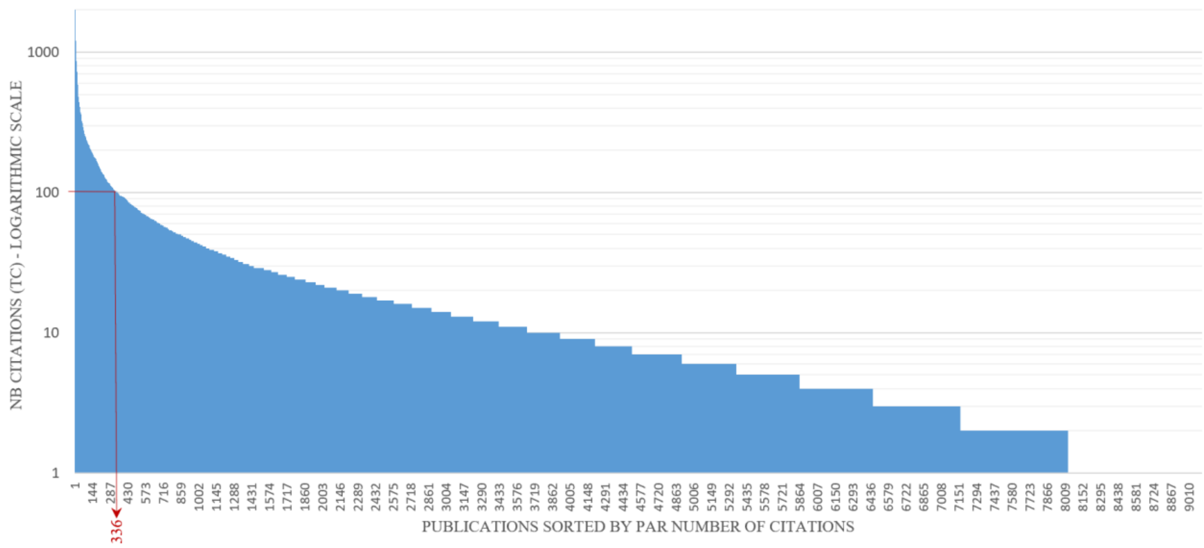

Figure 16: Distribution of number of citations per article (logarithmic scale)

We now focus on articles that received more than 100 citations during the reporting period. This excludes articles from 2020, which are too recent to have reached this threshold. This should in no way prejudge their qualities.

To date and over the research period under consideration, 336 articles meet this criterion, representing 2.06% of the world's publication output and 3.05% of the articles. As can be seen from the histogram of the distribution of the number of citations per paper (Figure 17), the distribution of the number of citations is very skewed.

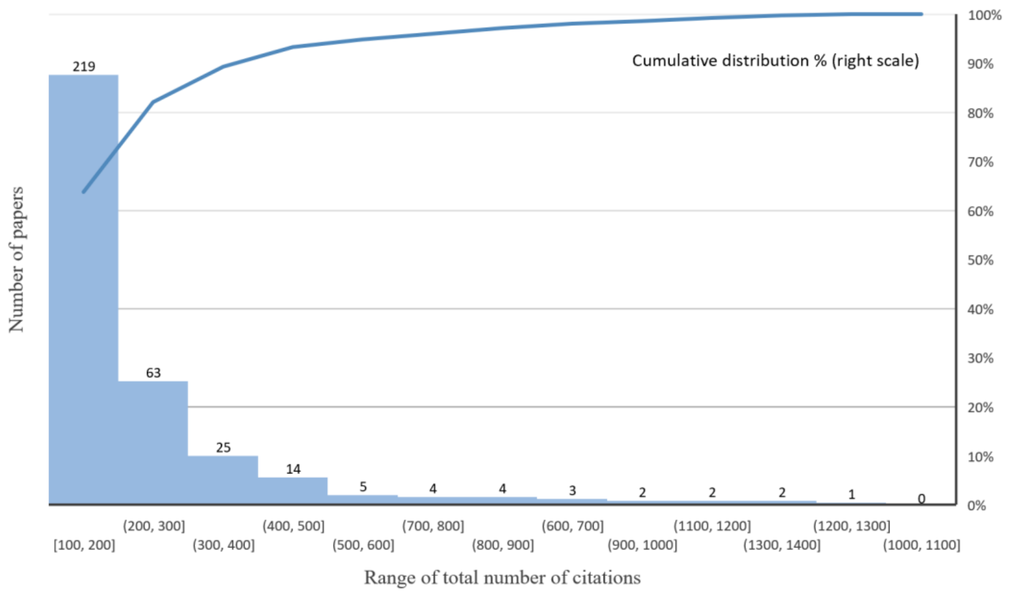

Figure 17: Cumulative histogram of the number of citations per article (%) – 1 article with 9,739 citations excluded

Other observations are interesting:

- Among the 336 most cited articles, 219 have between 100 and 200 citations, 63 have between 201 and 300 citations, 25 have between 301 and 400 citations, 14 have between 401 and 500 citations per paper. At the end of the distribution an article not represented on the histogram has 9,739 citations[15] alone.
- The 336 papers accumulate 88,262 citations (from 51,990 documents), i.e. an average of 262.7 citations per paper.
- Some 40 countries contributed to these publications. The USA largely dominates with 168 publications (50%), ahead of Germany (67) and China (53). France is in 10th position with 20 articles.

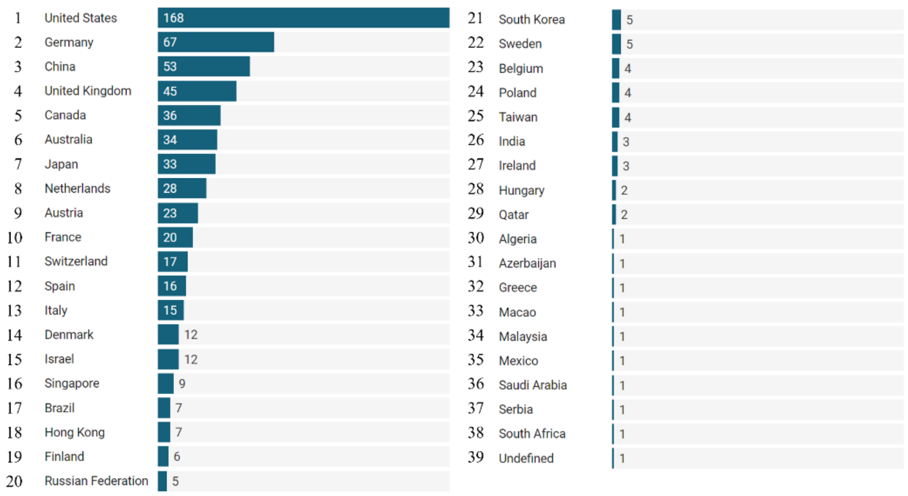

Figure 18: Origin of the institutions that published the 336 most cited articles (> 100 citations)

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[15] This paper in condensed matter physics written by Kane and Hazan [29] deals with topological insulators and superconductors, which are one of the possible technologies for the construction of a universal quantum computer.

- The most present keywords are represented in the word cloud in Figure 19 :

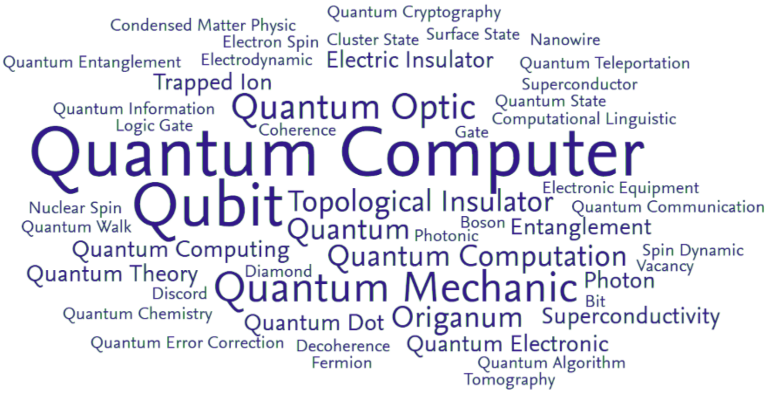

Figure 19: Words cloud for the most cited 336 articles

- The 336 articles were written by 1,747 authors from 369 institutions. The ten most active authors and institutions are shown in Figure 20, and it can be seen that 6 of the top 10 institutions are American.

	Author	Articles	TC	CPP	HI
1	Martinis, John M.	12	3,345	278.8	73
2	Pan, Jianwei	12	2,570	214.2	77
3	Sank, Daniel Thomas	10	2,605	260.5	41
4	Wenner, James	10	2,605	260.5	41
5	Cleland, Agnetta N.	9	2,846	316.2	55
6	Roushan, Pedram	9	2,404	267.1	31
7	Chen, Yu	9	2,354	261.6	32
8	Frunzio, Luigi	9	2,342	260.2	52
9	Schoelkopf, Robert J.	9	2,319	257.7	69
10	Lu, Chaoyang	9	2,167	240.8	40

	Institution	Authors	Articles	TC	CPP
1	University of California at Santa Barbara	62	25	7,271	290.8
2	Harvard University	46	24	5,330	222.1
3	Austrian Academy of Sciences	29	18	5,136	285.3
4	University of Science and Technology of China	85	17	3,457	203.4
5	Delft University of Technology	59	17	2,891	170.1
6	Massachusetts Institute of Technology	27	17	4,309	253.5
7	National Institute of Standards and Technology	58	17	4,015	236.2
8	University of Waterloo	24	15	3,021	201.4
9	University of Maryland, College Park	31	14	4,541	324.4
10	Yale University	46	14	3,743	267.4

Figure 20: TOP 10 authors and institutions by number of articles for the most cited articles

- According to our findings presented in Figure 21, 195 of the 336 papers (58%) are the result of collaboration between at least two institutions of different nationalities. 63 (19%) were written within the same institution by at least two authors. 67 papers (20%) were the result of collaborations between several authors in the same country and finally 11 papers (3%) were published by a single author.

Types of collaboration	(%)	Articles	TC	CPP
International collaboration	58.0%	195	45,689	234.3
Only national collaboration	20.0%	67	26,170	396.5
Only institutional collaboration	19.0%	63	12,771	202.7
Single authorship (no collaboration)	3.0%	11	3,354	304.9

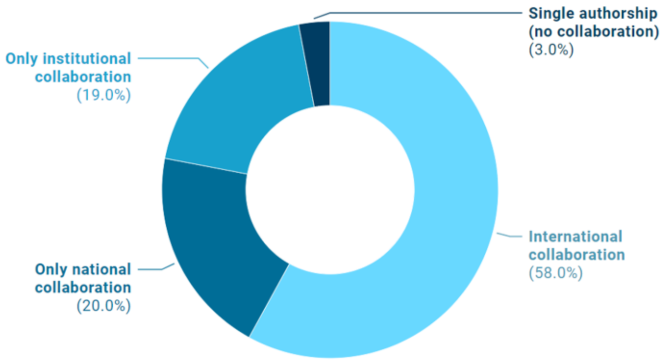

Figure 21: Types of collaboration for the 336 most cited articles

4. Conclusion

Our study provides a quantitative and qualitative description of research in quantum computing around the world during the period 2010-2020. It is based on the information referenced in the Scopus transdisciplinary database of the publisher Elsevier.

At the time of writing, 16,279 publications closely related to the subject of quantum computing research have been disseminated worldwide with an average annual increase of about 10% per year over the last 10 years. However, it is highly likely that research and publications will be impacted in 2020 by the SARS-CoV-2 health crisis.

The top ten countries dominating the world of quantum computing research are: USA, China, UK, Germany, Japan, Canada, India, Australia, France and Italy, with a share of 98.9% of global publications. The publications have a high impact of 14.8 citations per article on average over a 10-year citation window.

Six of the ten most productive countries had a relative citation index (RCI) above the group average of 1.32. The two scientific fields that publish the most on topics related to quantum computing are physics (32.6%) and computer science (17%). For physics, we can mention theoretical and experimental work on the different possible approaches to store and manipulate quantum information at the particle level (leading to the future hardware of the quantum computer). As for computer science, it deals with the subject of software, quantum programming, error correction algorithms, communication protocols, cryptography, etc.

The twenty most productive institutions are located exclusively in developed countries, such as the USA (5), China (4), United Kingdom (2), Singapore (2), Canada (2), Australia (1), Japan (1), Switzerland (1), the Netherlands (1) and France (1). Institutions in countries such as Australia and Canada stand out for their propensity to collaborate, while China and India are more isolated.

More than two-thirds of the world's publications on the subject have appeared in specialist journals. The top 20 journals account for more than 50% of total article production. Among the institutions that published the most cited articles, 6 out of 10 are American. Research in quantum computing is global but is currently highly concentrated.

GLOBAL PUBLIC AND PRIVATE INVESTMENT LANDSCAPE

Quantum mechanics is the fundamental theory of the atomic and subatomic particles constituting the objects of the universe and the forces animating these objects. According to physicists, it is the best theory we have in physics but for which a certain number of uncertainties remain [30].

Quantum technologies based on this fundamental science are for the most part nascent. In recent years, various initiatives have been put in place by several nations around the world to foster the development of these potentially disruptive technologies. Mastering them is seen by many states as a major challenge to their sovereignty and economy.

The issue of sovereignty relates to two main related topics: quantum computers and secure quantum communications systems. There is a risk of facing, in the near future, quantum machines capable of breaking the encryption mechanisms widely used nowadays in civilian or military life.

But these rapidly advancing technologies are also an opportunity for societal development. They have the potential to create fundamentally new ways of obtaining and processing information and to provide hitherto unattainable solutions to problems related, for example, to energy and health. Like AI, quantum technologies represent an asset for the responsible development of our societies, but they also raise important ethical issues.

Threats and opportunities, a twofold analysis that justifies significant public and private investments, the content and evolution of which we propose to analyze over the last ten years.

This study is in two parts. In the first section, we summarize government strategies and investments in quantum technologies in the main countries and regions of the world. In the second part, we take stock of the private funding - especially venture capital - available to support startups in these fields.

1. Public development plans and investments

In this first section we wish to provide an overview of global governmental strategies and subsequent financial support for quantum technologies. Figure 1 illustrates all the States or unions of States having devoted or budgeted the equivalent of approximately 1 B€, which is the case of the European Union for example. Within the EU, countries such as Germany also have their own budget.

The French plan is not yet confirmed but we have chosen to represent it with a conservative figure of 1B€ - the Forteza report (see table below) advocating 1.4B€. Meanwhile, most budgets have recently been increased (Germany, USA, UK, India, Israel). The Chinese budget reflects the considerable efforts made by this nation to develop its know-how in the fields of quantum applications (communications, computers, metrology and sensors) and to support national defense efforts, as well as civilian innovators. The table in Figure 2 details the elements known to date at the global level.

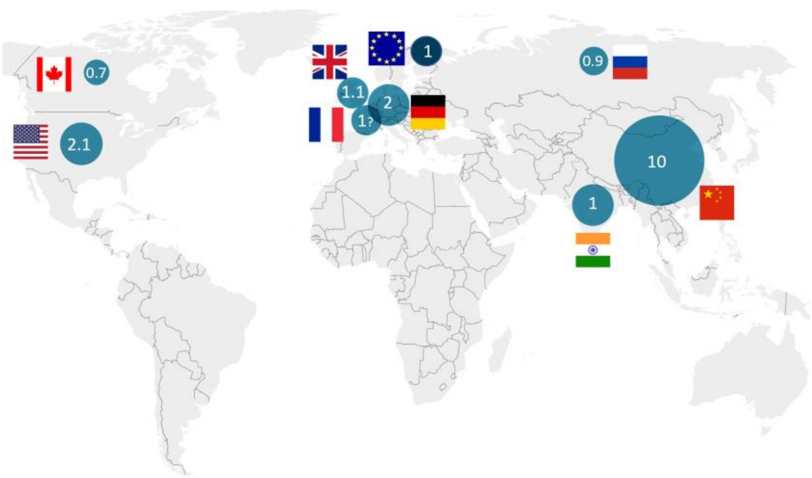

Figure 1: Significant government investments (~€1 billion or more)

COUNTRY	STRATEGY	GOVERNMENT INVESTMENTS
USA[1,2,3]	In 2018, signing of the National Quantum Initiative (NQI) Act. The NQI mandates the federal government agencies (NIST, NSF and DOE) to catalyze the growth of the quantum technology sector through collaboration with universities and private industry.	The NQI has committed $1.2 billion in funding over five years. In February 2020, the American presidency added $860m to the budget (including $492m in 2021).
Canada[4,5]	In 2017, various public institutes (National Research Council of Canada, Natural Sciences and Engineering Research Council of Canada, Canadian Institute for Advanced Research) have published a symposium report calling for action on: 1. Maintain and Develop Canadian Excellence in Quantum Science 2. Stimulate innovation to seize the opportunities of quantum.	Canada has invested more than one billion Canadian dollars (€660m) in quantum research over the past decade.
UK[6,7]	As early as 2013, the United Kingdom (UK) was one of the first European countries to define an action plan and invest in quantum technologies. In 2015, the progress report clarified the national strategy by identifying five priority areas for action: 1. Enabling the establishment of a strong base of capability in these technologies in the UK 2. Stimulating applications and market opportunities in the UK 3. Developing a local skilled workforce 4. Creating the right social and regulatory environment 5. Maximizing benefits for the UK through international engagement.	The UK National Quantum Technologies Programme has invested over £1 billion since its inception in 2014 (public + private) in two main waves: £270m in 2014 and £350m in 2019.
EU[8,9]	Initiated in 2016, and actually started at the end of October 2018, the European Commission has launched a dedicated program (Quantum Flagship Program) whose objectives are to: 1. Consolidate and develop European scientific leadership and excellence in quantum research, including the training of relevant competencies 2. Boosting a competitive European industry in the field of quantum technologies to position Europe as a leader in the future global industrial landscape. 3. Make Europe attractive and dynamic for innovative research, business and investment in quantum technologies, thus accelerating their development and market uptake.	The Quantum Flagship has received funding of 1B€ over 10 years.
Germany[10,11,12]	In 2018, the German Federal Government has presented a framework programme as part of its High-Techs strategy to bring quantum technologies to the market. The country's ambitions were confirmed in the Post-Covid plan published by the Chancellery in June 2020.	To the €650m that the government wanted to invest in the development of quantum computers (in particular with IBM), the German Chancellery has just added €1.35G (June 2020), which thus represents an envelope of 2B€.
Switzerland[13]	Local players in the quantum technology sector have published the document *Quantum at the Crossroads*, which describes the Swiss quantum landscape and calls for increased investment to help Switzerland build on its quantum strengths.	The National Centre of Competence in Research (NCCR "QSIT - Quantum Science and Technology"), science technology has received funding of CHF 38m between 2010 and 2017.

France[14]	At the end of 2019, the report of the parliamentary mission (Forteza Report) was delivered. It contains 6 recommendations: 1. Deploy on French soil a state-of-the-art quantum computing infrastructure for research and industry. 2. Launching an ambitious technological development program 3. Set up a program to support the development of uses 4. Creating an effective innovation environment 5. Deploy an appropriate economic security strategy 6. Establishing effective governance This report should serve as a basis for the preparation by the government of a French quantum plan.	The Forteza report recommends an investment of 1.4 B€. The French plan, currently being drawn up, is expected in the coming months and should amount to 1B€.
Netherlands[15,16]	In 2015, the cooperation between Delft University of Technology and TNO (The Netherland Organization for Applied Scientific Research) was formalized by a strong 10-year financial commitment, strongly supported by various Dutch In 2019, the Netherlands published a National Quantum Technology Program identifying 4 areas of action to strengthen its role in quantum technologies: 1. Breakthroughs in research and innovation (with 6 topics: computer, simulation, sensor, communication, algorithm, post quantum cryptology) 2. Ecosystem development, market creation and infrastructure 3. Human capital: education, knowledge and skills 4. Societal dialogue on quantum technologies.	135m from six entities will be invested in QuTech, the Institute for Quantum Technology at the University of Delft and TNO (The Netherland Organization for Applied Scientific Research) over 10 years.
Russia[17]	In 2012, the Russian Quantum Center was created, a research center dedicated to the three main fields of quantum technologies (Computers, Communications, Sensors and Metrology). At the end of 2019, Russia announced its five-year plan on quantum technologies by proposing to inject nearly $1B. This envelope is part of a 258 billion rubles (3.7 B$) program for research and development in digital technologies, which the Kremlin has deemed vital for the modernization and diversification of the Russian economy. At the present stage, 3 companies are responsible for developing the plan in each of the areas.	Russia wants to invest $1B over the next 5 years in basic and applied research on quanta conducted in major Russian laboratories, said the country's Deputy Prime Minister. Half of the funding would be public, the rest private.
Israel[18,19]	In 2018 the Israeli state decided to create a fund to support Israeli university research in the fields of quantum technologies. At the end of 2019, the government launched a much more ambitious quantum plan. The committee in charge of the plan further recommends expanding systems development and research in the field of quantum communications, quantum sensors in industry and defense, materials, and cloud computing; supporting the construction of a quantum component infrastructure; building a physical infrastructure in academic institutions to be shared by different disciplines and research groups; and investing in the consolidation of international cooperation efforts. TELEM (National Centre for Research and Development) and MAFAT (Ministry of Defense) are the main agencies involved.	After creating a fund with limited capital in 2018 ($27m), the new 2019/2020 quantum plan would represent an investment of $362m over five years.
India[20,21,22]	For a long time the potential of quantum technologies was not widely recognized in India. India is a fairly new player in the sector, which started by investing in 2018 in a $27.9m 5-year plan. In 2020, the government has just decided to invest a lot in computers, communication and quantum cryptography.	The investments increase the five-year plan from $27.9m to $1.12B.

Japan[23,24]	In 2018, the Japanese government launched the Q-LEAP initiative, which invests in R&D projects in quantum technologies in the following areas: - quantum simulation and quantum computing (goal to build a 100 qubits computer at 10 years) - sensors and quantum metrology.	Japan is planning more than 30 billion yen ($280m) for quantum applications as part of a 10-year plan. The Q-LEAP program includes a budget of $200m over 10 years. The total investment made by these funding agencies in the field of quantum information science and technology over the last 15 years amounts to $250 million.
China[25,26,27]	In 2016, China announced a focus on quantum communications and computing as part of its 13th Five-Year Plan (2016-2020). By 2030, China intends to expand its quantum communication infrastructure, develop a universal quantum computer and build an efficient quantum simulator. A dedicated National Laboratory for Quantum Information Sciences (Hefei) is being established and has received $1B to get started while additional funding is available through other national or regional initiatives.	The government plan that includes the establishment of the Hefei centre is estimated at $10B.
Australia[28]	In June 2020, the National agency CSIRO (Commonwealth Scientific and Industrial Research Organization) published its roadmap on quantum technologies recommending: 1. Developing a National Quantum Technology Strategy 2. Attract, develop and retain the best talent in the field 3. Exploring effective funding mechanisms 4. Assessing industry capacity and infrastructure.	125mAUD$ (76m€) of investments between 2017 and 2019.
Singapore[29]	Since 2007 quantum research is centralized in the Center for Quantum Technologies (CQT) of the National University of Singapore (NUS) with funding of about $15m annually. The centre works on quantum computers and quantum cryptography.	
South Korea	In February 2019, the Korean government announced a 5-year investment plan to develop key technologies for quantum computing. The goal is to complete the demonstration of a 5 qubits usable quantum computing system with over 90% reliability by 2023.	44.5 Billion Won (about 33m€/40m$)
Taiwan[30]	The Taiwanese programs has two interesting aspects: - The Ministry will provide grants of $1.9m to each research program approved by the referring academic and industrial sectors for the development of components, algorithms, computers or quantum communications. The Ministry has already approved three five-year projects proposed by research teams from local universities. In addition, the semiconductor manufacturer TSMC has been identified as the first industrial participant in the - the department has signed an agreement to work with IBM's cloud-based quantum computing platform.	The Taiwanese government will fund multiple quantum research efforts with an annual amount of 60 million Taiwanese dollars (approximately US$1.9 million) per project.

Figure 2: Government plans for quantum technologies (strategies and amounts)

Reference lists: government plans and amounts invested

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2. From public to private investment

Considering the potentially disruptive nature of the products that would emerge from current research, we saw in the previous section that governments have decided to invest massively in these areas, most of them with a triple challenge:

- The sovereignty issue, with, for example, the ability to properly protect sensitive information that is currently encrypted but potentially decipherable over time by a sufficiently powerful and reliable quantum computer.
- The technological challenge, with the desire to be at the forefront of these new fields either by capitalizing on a tradition of scientific excellence (USA, UK, Germany, France) or by developing one (China).
- The economic issues, with the stimulation of national or regional industrial frameworks on these subjects.

For the time being, research is mainly carried out by the public sector in the major countries that are investing in it, but given the expected benefits[16], some very large private digital players (Google, Intel, Microsoft, IBM, Honeywell, Amazon, Alibaba, Baidu, etc.) have embarked on R&D programmes, particularly in the field of quantum computing.

The amounts of investments are generally difficult to assess except when they are made public by the companies' communication departments. This was the case, for example, in 2014 when IBM announced that it was investing more than $3 billion over five years in two major R&D programs aimed at pushing back the limits of silicon chip technology [32] by possibly exploring new parallel paths. This included, among others, the development of a quantum processor. At the end of June 2020, six years later, IBM has a fleet of 18 quantum computers. Access to this fleet is available on the Cloud, with some machines freely available (IBM Q Experience[17]) and others reserved for IBM and members of the IBM Network Q[18].

Alongside these big names, the private enterprise landscape is beginning to thicken with a few hundred startups at various stages of maturity.

Data on investments made in start-ups by private investors (individuals, investment funds, third party companies) or public funds are sometimes present in databases such as Pitchbook[19] or Crunchbase[20] when they are not confidential. We have been able to extract and cross-check such information for about a hundred startups. Over the 2010-2020 period, we have identified nearly 300 investment transactions of various types (seed scaling, expansion, etc.).

As shown[21] in Figure 3, it was from 2012 onwards that investors began to take an interest in start-ups in the sector. The year 2017 was particularly active, with more than $300m invested, almost triple the previous year's figure, and it was mainly in *quantum computing (hardware)*.

With an average of $200m per year, investment then stabilized for two years, and recently increased very sharply in the first half of 2020. During this six-month period, nearly $480m was used to finance the development of quantum startups, i.e. 58% more than in the record year 2017. As in 2017, it is once

[16] For example, in 2019, the BCG consulting firm estimated cost savings and increased opportunities for users of quantum computing that could exceed $450 billion a year within 20 years and $850 billion after that [31].

[17] IBM Q Experience is an online platform that allows users to access a set of IBM quantum processors in the Cloud, https://www.ibm.com/quantum-computing/technology/experience

[18] IBM Q Experience is an online platform that allows users to access a set of IBM quantum processors in the Cloud, https://www.ibm.com/quantum-computing/technology/experience

[19] https://pitchbook.com/

[20] https://www.crunchbase.com

[21] We have adopted here a classification identical to that of the Nature [4] article "the quantum gold rush", oct 2019: *quantum computing, quantum software, quantum communication...*

again quantum computing which concentrates the majority (80%) of financing agreements in the first half of the year.

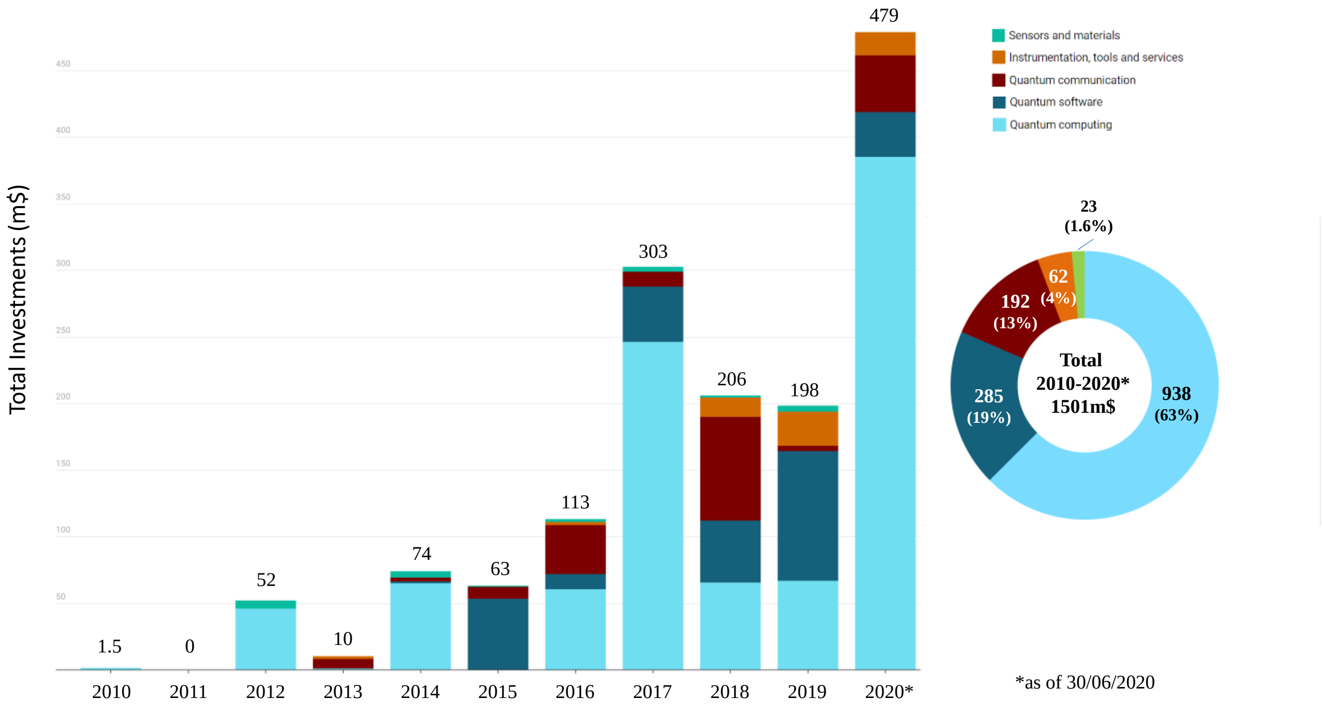


Figure 3: Disclosed investments in Quantum Technology Startups 2010-2020

In total, since 2012, $1.5 billion has been invested in quantum technology startups (80 listed in the database). Nearly two-thirds of the declared investments (62.5%) were devoted to 15 companies working on the construction of quantum processors (hardware). The software part, represented by 37 firms, raised 285m$. The 12 firms working on communications $192m. Finally, 9 startups working on measurement or detection techniques based on quantum physics and 8 building basic components used by the other companies received $23m and $62m respectively.

Figure 4 complements this analysis of the amounts invested by the number of deals per year and sector. Their number has increased since 2015 with a strong acceleration in 2018 when many "small" investments were made. With 24 deals in the first half of 2020, it seems that the momentum of the past years has not been slowed down by the Covid-19 crisis. It is currently the software companies that benefits the most from investments while sensors and metrology are the poor relations of the sector.

Of course, this list of startups, whose financing is known, is not exhaustive. Many are working in stealth mode or in an embryonic state. A more complete inventory of startups is available from the author upon request.

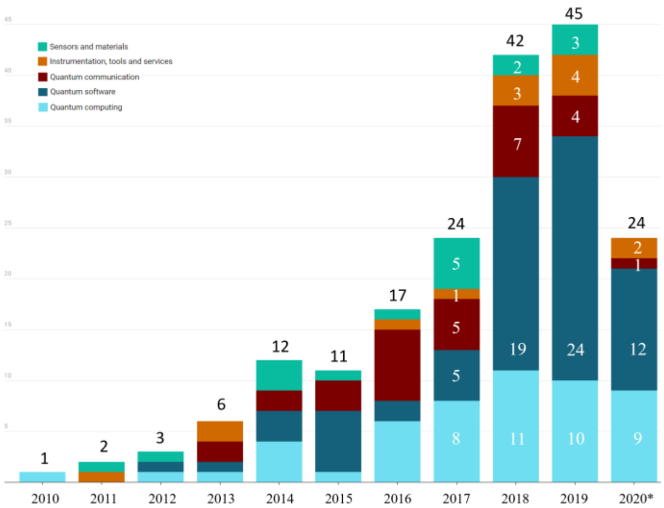
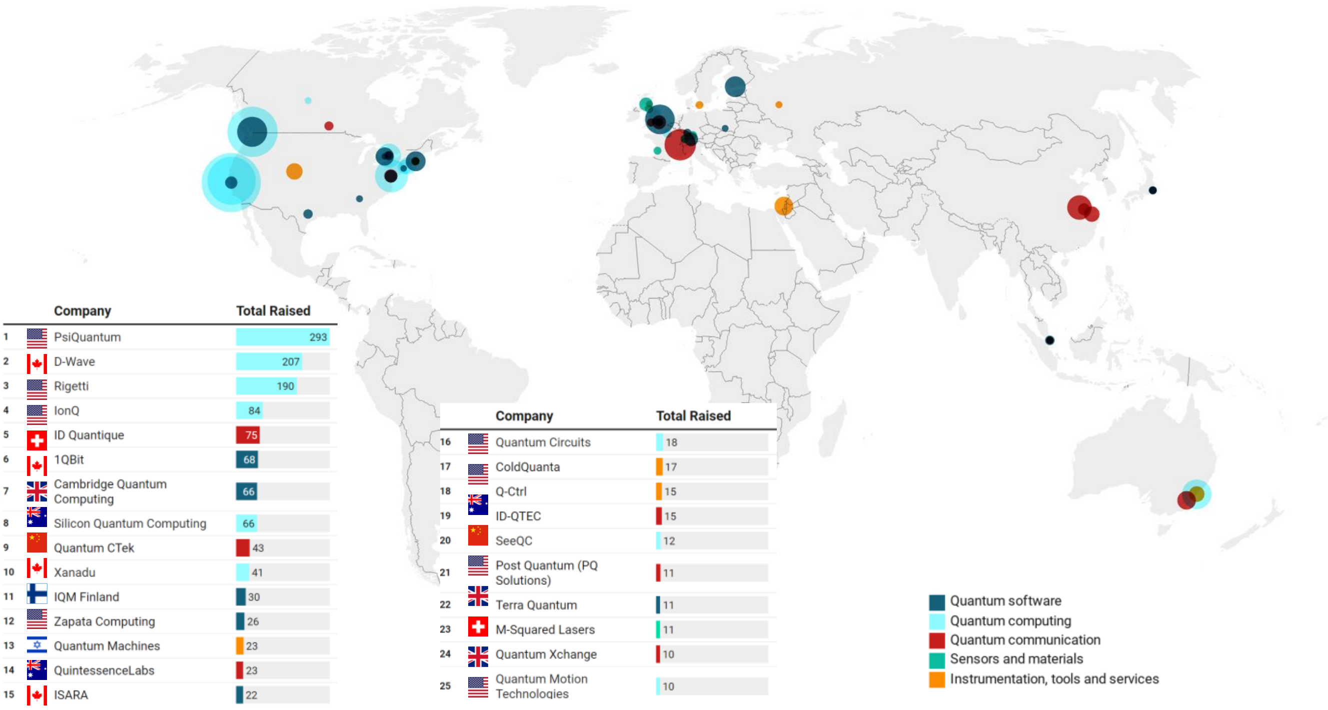


Figure 4: Evolution of the number of financing deals since 2010

We now illustrate in Figure 5, the location as well as the list of the startups having received an investment of more than 1m$ and the 25 most important among them. The largest are essentially in North America (PsiQuantum, D-Wave, IonQ, Rigetti).

The case of the Swiss firm ID Quantique (IDQ), the only European firm in the TOP5, is interesting. Founded in 2001 as a startup specializing in securing communications using quantum cryptography devices, it has been marketing its services and products since 2004 to companies in various sectors such as finance and government. In 2018, it came under the control of the Korean mobile phone operator SK Telecom[17].

In May 2020, Samsung, SK and IDQ announced the launch of the first 5G mobile equipped with a Quantum Random Number Generator (QRNG) chipset [33], allowing users to securely use selected services by generating real random numbers that cannot be predicted (unlike pseudo random numbers generated using conventional algorithms).



	Company	Total Raised
1	PsiQuantum	293
2	D-Wave	207
3	Rigetti	190
4	IonQ	84
5	ID Quantique	75
6	1QBit	68
7	Cambridge Quantum Computing	66
8	Silicon Quantum Computing	66
9	Quantum CTek	43
10	Xanadu	41
11	IQM Finland	30
12	Zapata Computing	26
13	Quantum Machines	23
14	QuintessenceLabs	23
15	ISARA	22

	Company	Total Raised
16	Quantum Circuits	18
17	ColdQuanta	17
18	Q-Ctrl	15
19	ID-QTEC	15
20	SeeQC	12
21	Post Quantum (PQ Solutions)	11
22	Terra Quantum	11
23	M-Squared Lasers	11
24	Quantum Xchange	10
25	Quantum Motion Technologies	10

Figure 5: Location of startups having received investments superior to $1m between 2010-2020 and TOP25 lists (all numbers in m$)

It is now instructive to detail the distribution of investments made in quantum computing (hardware) by type of technology used by the different startups for the construction of qubits, the information support of quantum computers (Figure 6).

California startup PsiQuantum, founded in 2016, plans to develop a photonic quantum processor. It alone received $293m. This explains the large share of funding for photonic architecture (36%).

Photonic (or linear optical) quantum computers encode information in photons, not ions, atoms or electrons. Xanadu and ORCA Computing are developing a similar project.

The use of superconductivity for the construction of qubits mobilizes a larger number of players. Beyond the $225m invested in startups using these technologies, it is on this type of architecture that major players such as IBM, Google, Rigetti, Alibaba or even D-Wave are investing.

The purpose of this section is not to list the advantages and disadvantages of each of these technologies, but it is important to remember that not all qubits are equivalent. The family of superconducting qubits is itself particularly heterogeneous.

For instance, the superconducting qubits used by D-Wave have certain particularities that confine them to solving specific mathematical optimization problems. They are not used within quantum logic gate circuits as can be the case for IBM, Google or Rigetti startup computers.

The D-Wave computers, marketed since 2011, fall into the category of annealing computers. The company has received $207m, or 22% of the funds allocated since 2010.

Start-ups deploying physical platforms based on trapped ions raised $88m (9%), most of which was allocated to the leader IonQ. The Austrian firm Alpine Quantum Technology (AQT), a spin-off of the University of Innsbruck, recognized for its work on these same methods, is using grants and non-dilutive financing (the last one being $11.2m in 2019). The study of trapped ions as a medium for quantum information is also widely pursued in university laboratories and the recent arrival on this niche of the giant Honeywell [34] reflects the interest of all these different categories of players in this type of physical platform.

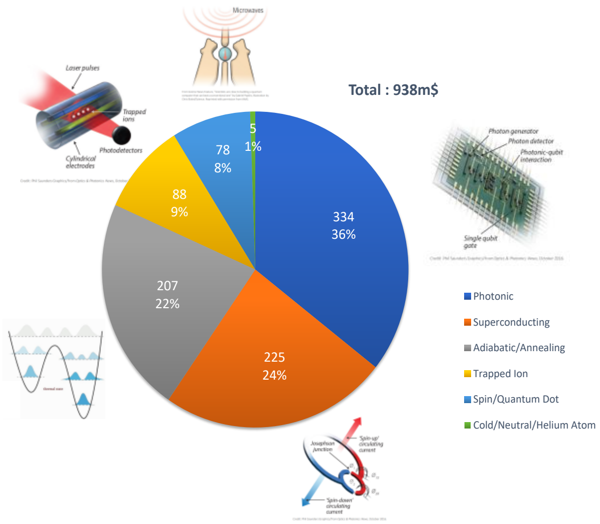


Figure 6: Breakdown of investments by technology of qubit for startups working on hardware

Australian startup Silicon Quantum Circuit (SQC), a spin-off from UNSW University, was established in 2017. It is working on the development of semiconductor-based qubits and has received $66m of investment since its creation. These promising technologies have received 8% of the investments. They are also being explored by other major players in the private sector such as Intel, as well as several research organizations such as the French CEA-Leti laboratory, which is at the forefront of European applied research.

Quite similar in principle to trapped ion technology, the use of neutral atoms is a more recent approach studied by various startups such as the French Pasqal, or the Californian Atom Computing. The ColdQuanta startup, which is collaborating with IonQ, is working on this technology in a broader framework than the development of quantum computers because it is also used in the development of ultra-sensitive measuring instruments and sensors.

Finally, it should be noted that topological qubits, on which Microsoft is working, and diamond-based qubits (NV Center) do not appear in our list of quantum computing startup funding.

It is interesting to compare the results of the 2019 survey conducted by renowned professor and entrepreneur Michele Mosca among 22 professionals in the quantum technology sector[35].

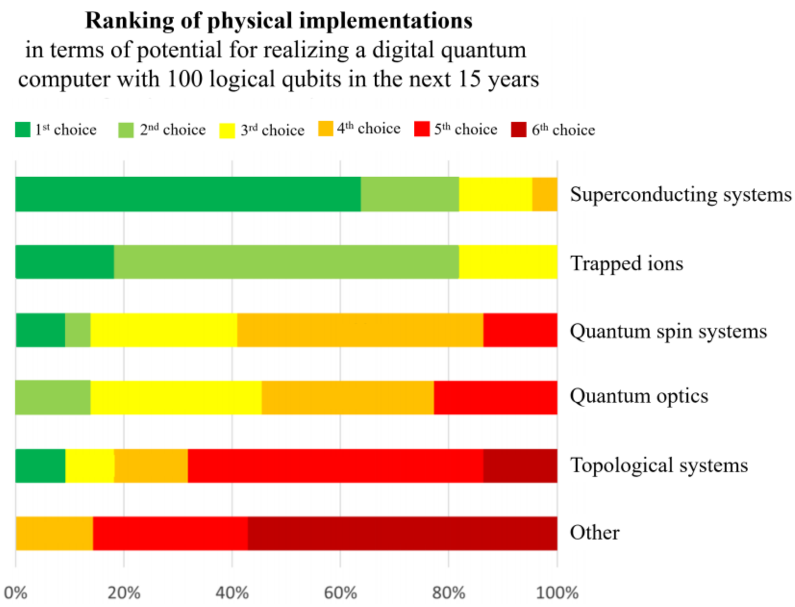


Figure 7: Ranking of opinions on the potential physical platforms for the specific purpose of realizing a quantum computer (Source: Global Risk Institute and evolutionQ Inc.)

The question was to rank physical implementations with the specific goal of achieving a digital quantum computer with 100 logical qubits (i.e. programmable with little or no physical errors) within the next 15 years.

The responses indicate a fairly general consensus (Figure 7) that the preferred platforms are superconducting systems and trapped ions. These results are in line with the investments made with the striking exception of linear-optical quantum computers. This suggests that while the technological potential is high, the investments seem very speculative for these types of qubits.

To conclude our overview of VC investments, we illustrate, in Figure 8, the capital links between venture capital firms and startups. We highlight the cases of Quantonation, a French investment fund created in 2018 specializing in Deep Physics startups - particularly in the field of quantum technologies - and D-Wave, founded in 1999, which claimed to be the world's leading quantum computing company.

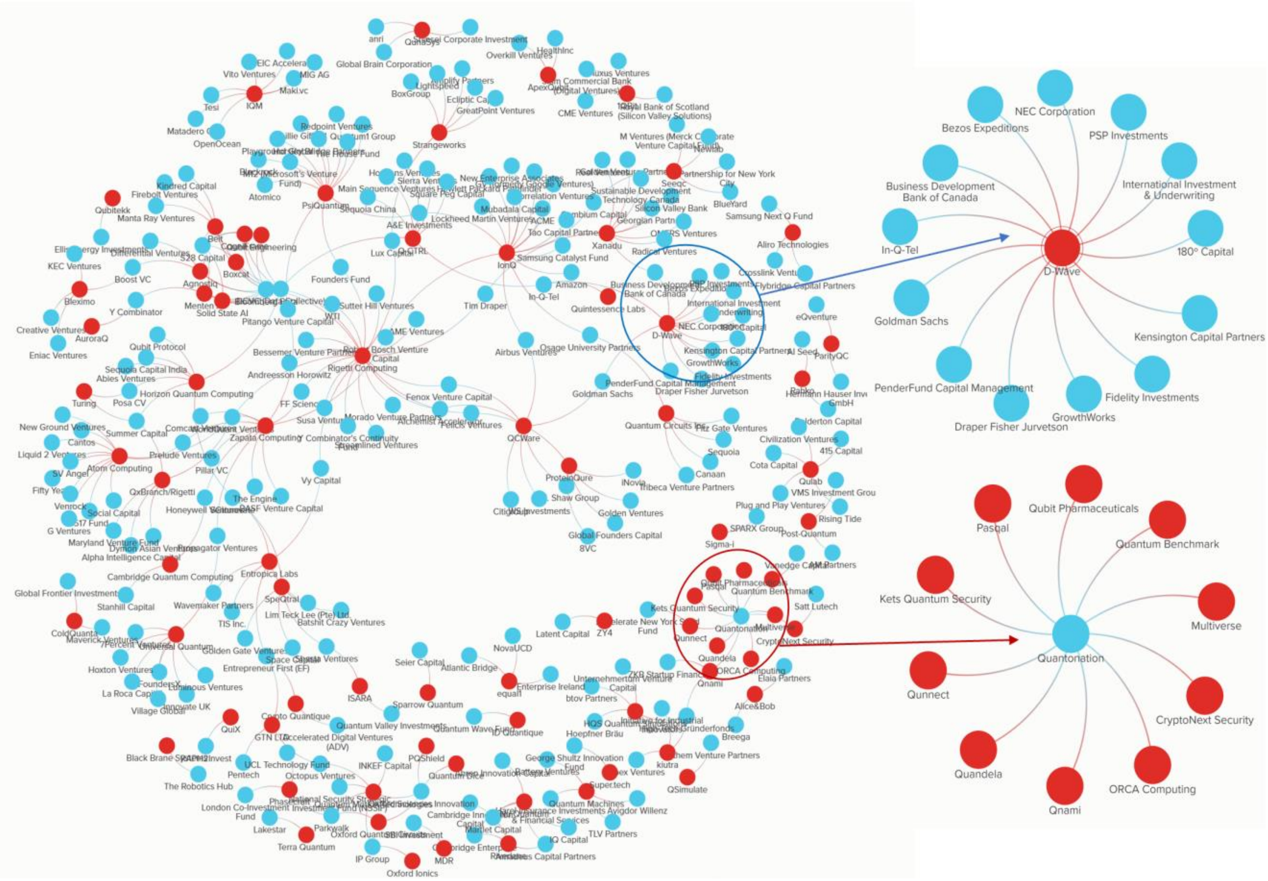


Figure 8: Mapping of Venture Capital (VC) investments into Quantum Startups (graph made from data from www.quantumcomputingreporting.com)

3. Conclusion

Quantum technologies are expected to have a major impact on society and the economy. The unique power of future quantum computers and the quantum internet[22] could provide solutions to major societal challenges such as energy, health and security. We are not just in the future or the conditional. Already today, measuring instruments using these same technologies offer accuracies unmatched by conventional instruments (see for example the gravimeters or clocks sold by the French startup Muquans).

A quantum race has begun all over the world. Western and Asian governments are rolling out strategic plans with substantial funding envelopes. Research institutions generally benefit first from these investments, as do start-ups, which can also count on increasing financial support from private investors (see geographical distribution and broad list in Figure 9).

As such, 2020 is expected to be a record year for private investment. The global health crisis does not seem to have slowed the pace of private or public investment as the German decision to triple its budget as part of its post-COVID plan has done.

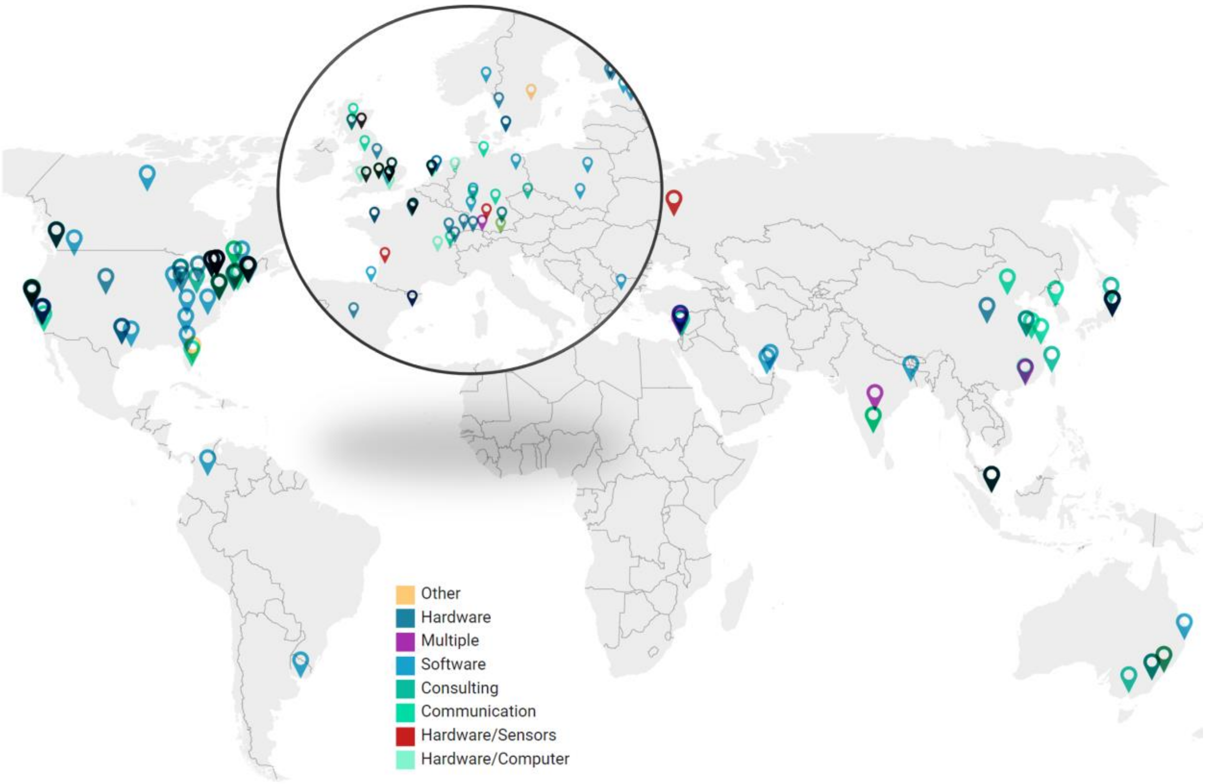


Figure 9: Geographical breakdown 222 startups
(Source: Pitchbook, Crunchbase, Quantum Computing Report, company websites)

Some major ICT players then complete the investment landscape with development strategies that mix R&D and marketing, such as IBM or Google. At the same time, these players are collaborating with public laboratories, sometimes in different regions. Microsoft is close to the University of Delft in the Netherlands with which it is working on topological qubits. IBM's "quantum" teams are geographically and probably financially close to the Swiss Federal Institute of Technology in Zurich (ETH). In China, Alibaba works hand in hand with the Chinese Academy of Sciences (CAS) and has other research laboratories elsewhere.

[22] Ultimate goal of the quantum communications sector in the (very) long term.

Ecosystems are being built. They are increasingly dynamic. The public/private, research/commercial divisions are becoming blurred or even superposed... Many startups have emerged from physics laboratory spin-offs and this is even the case in China (Quantum CTek, Origin Quantum Computing).

This disappearance of traditional cleavages is a striking feature of the global quantum ecosystem. This could have a very positive impact on the speed of quantum research and industrialization. But it could also exacerbate the risk of the disappearance (not to say teleportation) of individual nuggets (researchers) or entrepreneurial nuggets (startups) by the call of money. Faced with North America and China, the industrialization of research stemming from the scientific excellence of Europe (Germany, the United Kingdom, France, Austria, the Netherlands, etc.), or even local research itself, could suffer from the complexity and slowness of the public/private technology transfer process and the lack of appetite for long-term risks on the part of some local private financiers.

We have identified another empirical feature that could be a fundamental trend over the next 5 to 10 years. In recent months, platforms/networks have been developing that centralize the diversified supply of existing quantum computers: IBM Q Network, Microsoft Azur Quantum, Amazon AWS Braket.

So even if IBM offers access to its quantum computers developed on superconducting qubit technology, a user/customer of the Q Network can now also run his quantum software on the trapped ions of the AQT partner using the same programming language (IBM Qiskit). Similarly, Pasqal, a French startup developing a cold atom-based quantum processor, is collaborating with Google to provide access to its technology through Cirq, Google's open-source framework used for the Mountain View company's quantum computers (superconducting qubits).

The big players are therefore aware that it is necessary to diversify the offer while waiting for a leading physical qubit technology to emerge, which could indeed take several more years.

In the case of Amazon, whose ambition is not to create a quantum computer, we could even talk about the uberization of a market that is barely emerging. Small players make their hardware available at AWS in the same way that a “vehicule for hire” driver makes his vehicle available on a platform. Will small players be able to benefit from this modus vivendi in the medium/long term?

It is highly likely that, beyond the technological advances to come, the quantum landscape will continue to evolve in the near future, but that it will strongly depend on the actions undertaken today by the various private and public players.

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