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Patent analysis of selected quantum technologies

Martino Travagnin, MT

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Contact information
Name: Martino Travagnin
Email: Martino.Travagnin@ec.europa.eu

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Contents

Abstract

An analysis of patent applications filed in the European Patent Office Global Patent Index database is presented for quantum computing, quantum key distribution, quantum entanglement, and cold atom interferometry. We address methodological issues and show how patenting trends evolved in the last two decades, identifying main players and applications areas.

1 Introduction

In the last 5-10 years, various initiatives have been taken by several governments to take advantage of developments in Quantum Technologies. A common characteristic is the effort to translate results of what has until now been mostly a field of academic research into new products, with the potential to spur economic growth and contribute to societal progress. This purpose is evident in the EC "quantum flagship" programme, launched in Vienna in October 2018 ([1]), and in the USA National Quantum Initiative, approved by the congress in December 2018 ([2]).

Patent analysis is a well-established way to gauge economic potential of new technologies. Several studies have been done on patenting trends in quantum technologies, as summarized in Appendix 1. All these studies rely on search tools based on key words and International Patent Classification (IPC) or Cooperative Patent Classification (CPC) codes, and there is no indication that they have been made by people with a background in quantum physics. In these conditions, they carry the risk of attributing to the field being investigated a consistent number of patents belonging to other technological areas ("false positives"), therefore inducing the reader into the perception of a higher technology readiness level than the one actually reached, and of a larger interest by industrial players. This risk is compounded by the fact that the main aim of most of these reports is to raise the interest of potential customers and investors in the area. Such an aim is particularly evident in the market analyses which have been prepared and are sold by several tech consultancies, see Appendix 2. As a general rule, we have found that they tend to present a much rosier picture of the technological readiness and market potential of these technologies than it is reasonable to expect.

The aim of this note is to present an objective view of the patent landscape in some selected quantum technologies. We focus on areas which constitute the core of what is sometimes called the "second quantum revolution", which hold the promise of exploiting phenomena such as superposition and entanglement by controlling individual quantum objects ([3]). In this domain, quantum computing and quantum key distribution are by far the applications for which more patent applications have been filed to date. We also performed some searches to analyse patents exploiting effects such as entanglement and cold atom interferometry, which can be important in sensing applications.

We employed both Cooperative Patent Classification (CPC) codes and key words to perform queries in the Global Patent Index database of the European Patent Office. What sets our work apart from the studies already published is that, for each application retrieved in the database, we have (i) read title and abstract (and in case of doubts the entire text with its claims) to filter out false positives (ii) attributed to the applicant the nationality of the country in which it is headquartered.

According to our estimates, the fact of not actually reading the content of patent applications can result in a percentage of false positives as high as 20%. This percentage depends heavily on the keywords used: we present a case of a very reasonable text search which results in 80% of false positives: it is clear that in such conditions any analysis on the results of the query is devoid of sense.

We have also noted that the practice of inferring the nationality of the applicant from the one of the patent office where the application is filed, as is automatically done in all the published studies, results in non-negligible fraction of errors. Several players have established research laboratories outside the country where they are headquartered, and

([1]) https://qt.eu/

([2]) https://www.congress.gov/bill/115th-congress/house-bill/6227

([3]) The reader is referred to previous JRC reports for a background, see https://ec.europa.eu/jrc/en/research-topic/quantum-technologies patent applications are often filed in the country which hosts the laboratory. Other players file their applications in the national patent office of a country which is not the one where the research has been actually carried out.

We think this work can contribute to clarify the state of play in quantum technologies, by identifying players and countries, and possible application areas. This will help funding agencies and investors to optimize support mechanisms and target investments; in addition, it sets a sort of "initial condition", which in due course could be used to assess how successful technology push programs have been.

Continuous support and stimulating discussions with Adam M. Lewis are gladly acknowledged.

2 Quantum Computing

Cooperative Patent Classification code G06N99/002 is available to describe applications pertaining to ”Quantum computers, i.e. information processing by using quantum superposition, coherence, decoherence, entanglement, nonlocality, teleportation”. We have performed several queries on the European Patent Office Global Patent Index (EPO-GPI) database ([4]), using this specific code and several other key words linked to quantum computing. We retrieved the following numbers of patent families:

CPC = G06N99/002 : 993

WORD = ("qbit") or ("qbits") or ("qubit") or ("qubits") : 489

WORD = ("quantum computer") or ("quantum computers") : 276

WORD = ("quantum computation") or ("quantum computations") : 108

WORD = ("quantum memory") or ("quantum memories") : 61

WORD = ("quantum error correction") : 27

WORD = ("quantum simulation") or ("quantum simulations”) : 13

The union of the results of all the above searches (done with an inclusive OR) gives 1373 families: by reading titles and abstracts (and occasionally the text of the patent and its claims) we have deemed that among them 1149 are pertinent and 224 are false positives. A significant fraction of false positives concern inventions of encryption methods which are safe against attacks from quantum computers, based either on algorithms or on physical effects: some of them fall therefore under the investigation done on Quantum Key Distribution, described in the next Section.

For each application deemed to be pertinent to the quantum computing field, we have attributed to the applicant the nationality in which it is headquartered. The graph shown in Fig. 1 the number of applications filed by players headquartered in different countries as a function of the claimed priority year. It can be seen that:

1) After several years (1990-2000) of slow growth, the number of applications remained steady (approx. 50 per year) in the decade 2001-2012.
2) Since 2013, the number of applications has been growing again, reaching ~150 in 2016, the last year for which all applications have been disclosed. There is an optional confidentiality period of 18 months between the filing of an application and its disclosure.
3) The country where the largest number of applicants is headquartered is the US, followed by Japan, Canada, and Europe. Players from China seem to have stepped up their patenting efforts in the last 5 years, but numbers remain limited.

This last point is made apparent in Fig. 2, which additionally shows that other two important countries are Australia and South Korea; players from the rest of the world do not contribute significantly to patenting activity in quantum computing.

([4]) Queries done in July/August 2018

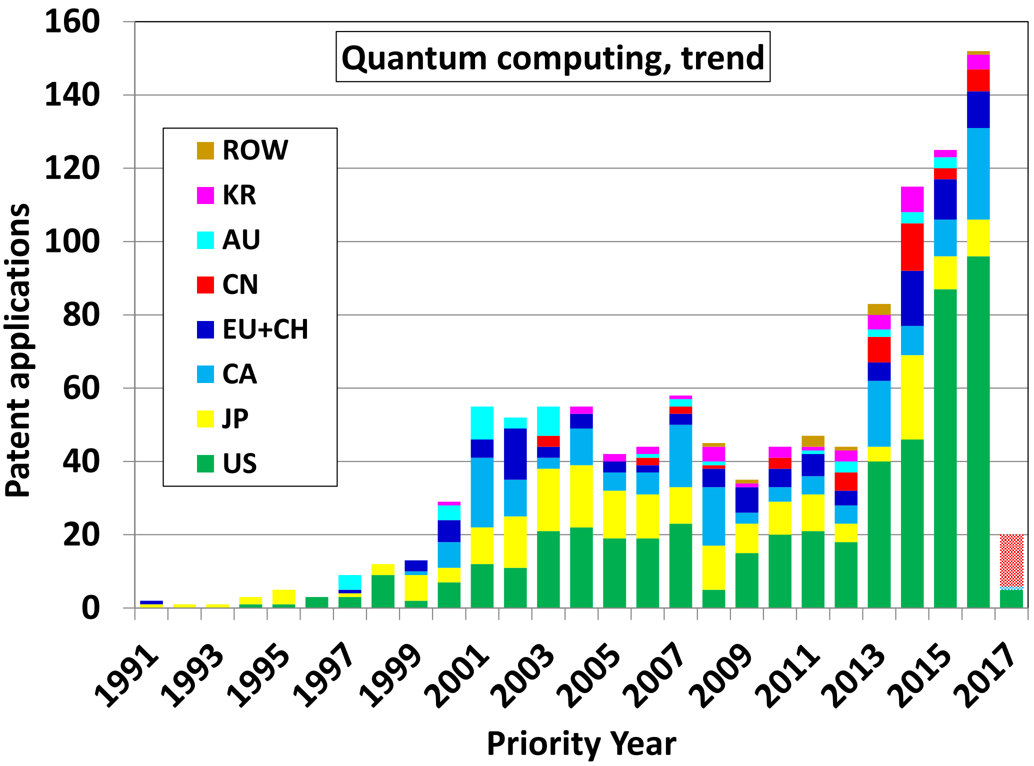

Figure 1: number of patent applications on quantum computing per year, according to the country where the applicant is headquartered. The bar for year 2017 is shaded, to highlight that results are provisional because of the optional 18-month confidentiality period between filing and disclosure.

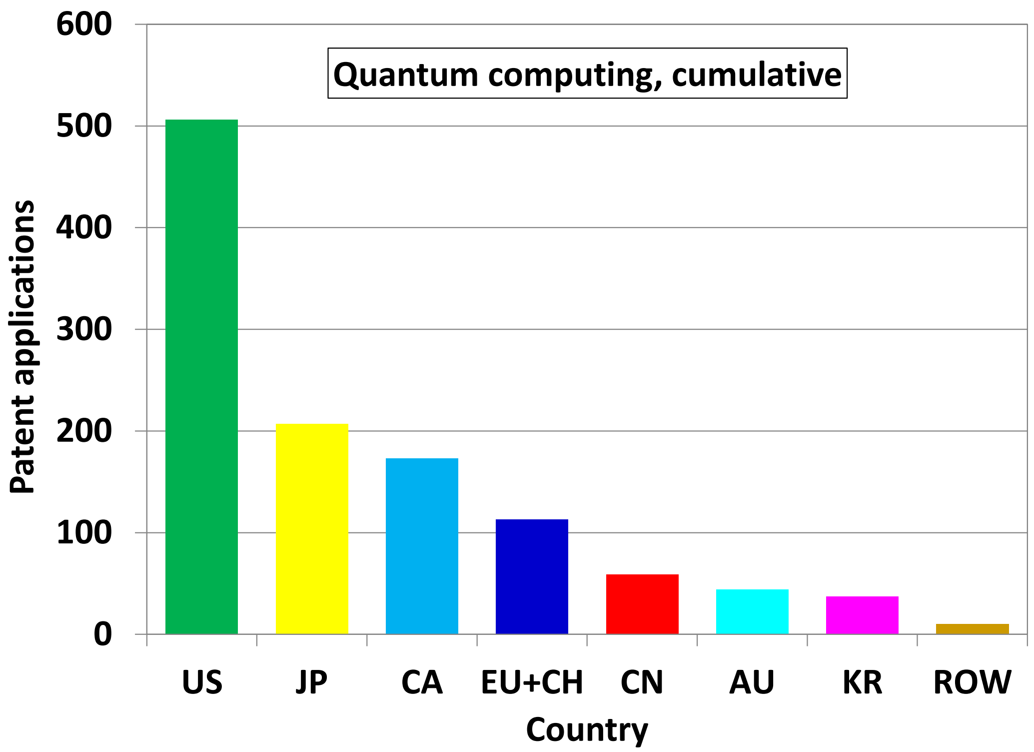

Figure 2: total number of applications, divided by country where applicants are headquartered. Main contributors to EU28 plus Switzerland are United Kingdom, Germany, Italy, France, Netherlands, Austria, Denmark and Finland.

Fig. 3 shows the applicants which filed the highest number of applications. Roughly speaking, they can be divided according to their field of activity in the following way:

Information technology: IBM, Microsoft, Google, HP, Intel

Electronics and telecom: Toshiba, NTT, Hitachi, NEC, ST, Fujitsu

Dedicated startups: Dwave, Rigetti, 1QB, Tucci, MagiQ

Defence and Security: Northrop Grumann, Raytheon, USA Navy/Air Force, NSA

Public research agencies and laboratories: Japan Science & Tech Agency, Korea advanced institute for science and technology, Sandia

Technology consultancies: Unisearch (linked to University of New South Wales, AU)

Universities: Massachussets Institute of Technology, Oxford, Yale, Harvard, Johns Hopkins, Seoul, California, Stanford, University of New South Wales (via QuCor and NewSouth Innovation)

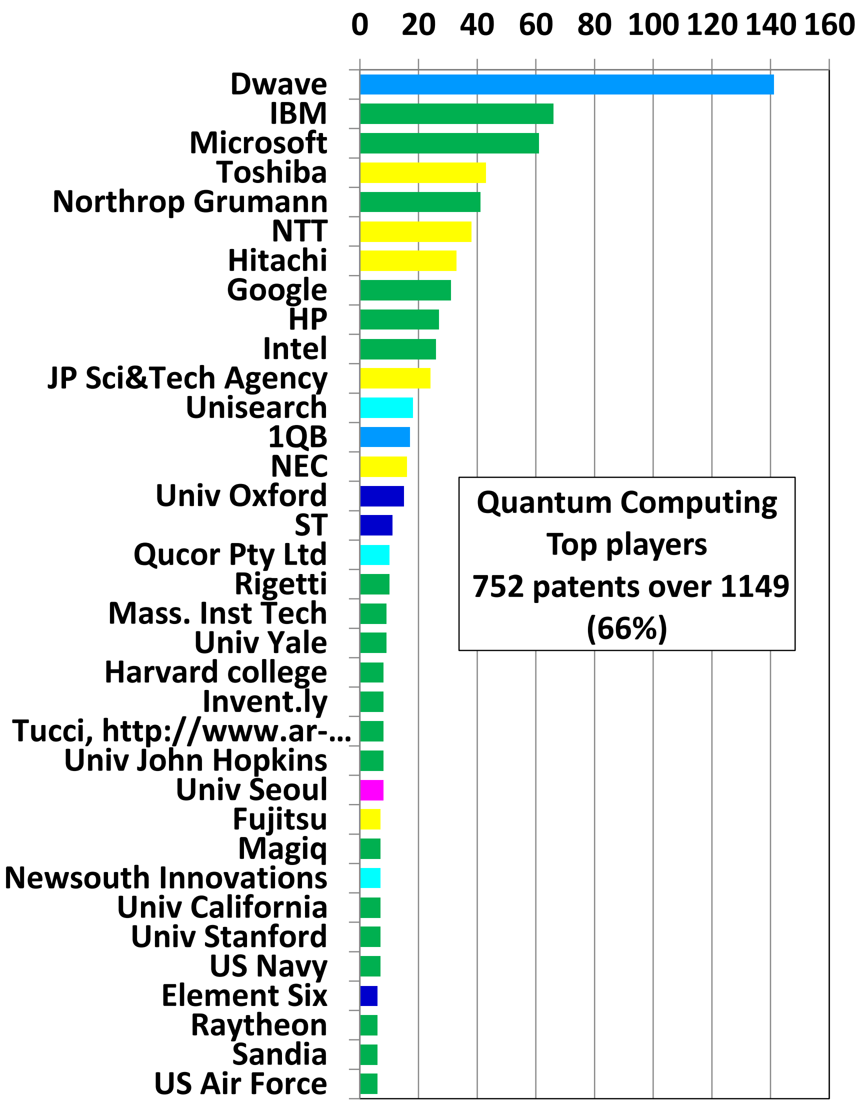

Figure 3: Top applicants in Quantum Computing, color-coded as in Fig. 2 according to the country where they are headquartered.

Most of the patents pertain to the physical platfoms used to implement the qubit, such as superconducting circuits, semiconductor materials, ion traps, quantum dots, color centers in diamond, topological devices. However, there are also several applications on quantum error correction and algorithms, and some are emerging which target specific applications, usually by taking advantage of the optimization capabilities of quantum computation. To give some examples, QCWare (USA) has an application on ”Quantum-Annealing Computer Method for Financial Portfolio Optimization”, Seoul University (SK) has one titled ”Machine vision system using quantum mechanical hardware”, University of Michigan (USA) filed ”Quantum-based machine learning for oncology treatment”. The Chinese Electric Power Company Economic Research Institute has an application on ”Optimizing method of mixed energy accumulation capacity configuration for stabilization wind power fluctuation”, where the optimization step is done by ”using genetic algorithm with chaotic disturbance and quantum computation”. We mention also Invent.ly (USA) with ”Marketing to a community of subjects assigned quantum states modulo a proposition perceived in a social value context”, as an example of a small but significant area where scientific soundness seems to give way to quackery.

It is worth noting that the 34 players with a minimum of 6 patents reported in Fig. 3 represent only 2/3 of all the patents filed in this field. There are more than 500 applicants with a smaller number of applications: most of them are universities (often with their technology transfer agencies), but there are also small corporations and even private citizens. We identified some venture capital investors (e.g. Quantum Valley Investment, Canada) and several large industries (Yamaha, Boeing, Silicon Graphics, Atos, OKI) involved in very different business field, which can be taken as a further confirmation of the widespread interest that quantum computing is raising.

3 Quantum Key Distribution

Among the several CPC codes which can be used to find inventions related to Quantum Key Distribution, we have found that the most suitable are:

H04L9/0852: Quantum cryptography (transmission systems employing electromagnetic waves other than radio waves, e.g. light)

H04L9/0855: involving additional nodes, e.g. quantum relays, repeaters, intermediate nodes or remote nodes

H04L9/0858: details about key distillation or coding, e.g. reconciliation, error correction, privacy amplification, polarisation coding or phase coding

In our searches ([5]) we have tried also some combinations of words, obtaining the following number of applications:

CPC = H04L9/0852 : 451

CPC = H04L9/0855 : 76

CPC = H04L9/0858 :313

WORD = (quantum AND key AND distribution) :711

WORD = (qkd) :261

WORD = (quantum AND cryptography) : 230

The union of all the above results gives a total of 1338 hits. By analysing them we found out that 1161 were pertinent while 177 were not linked to the technique under investigation.

The 1161 application on QKD are distributed in time according to the plot shown in Fig. 4. We can see that after 10 years of slow increase (1992-2002) we had ~10 years of constant patenting activity (2003-2013) with an average of 50 applications per year. After 2013 a steep increase took place, and in 2016 ~150 applications were filed. Applicants based in China are mainly responsible for this increase, and have made of China the most prolific patenting country in QKD.

As made apparent in Fig. 5, China has now surpassed the USA as the country with the highest number of patent applications in QKD. Actually, patenting by players headquartered in the USA seems now to be kept low-key, after the peak reached in ~2005. Japan and Europe come respectively third and fourth, with a steady effort along the years. We have then South Korea (which seems to be accelerating), Malaysia (peaked in 2010, then slowed down), and finally Australia, Russia, and Canada.

([5]) Searches done in July/August 2018, using the EPO GPI database

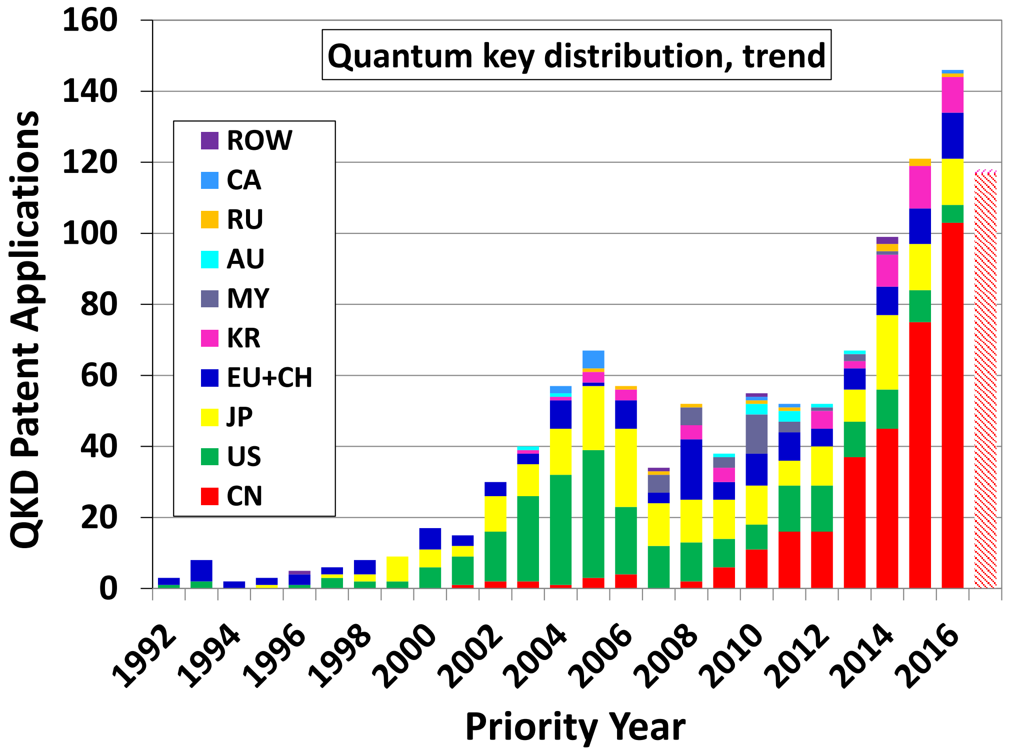

Figure 4: number of patent applications on Quantum Key Distribution per year, according to the country where the applicant is headquartered. The bar for year 2017 is shaded, to highlight that results are provisional because of the optional 18-month confidentiality period between filing and disclosure.

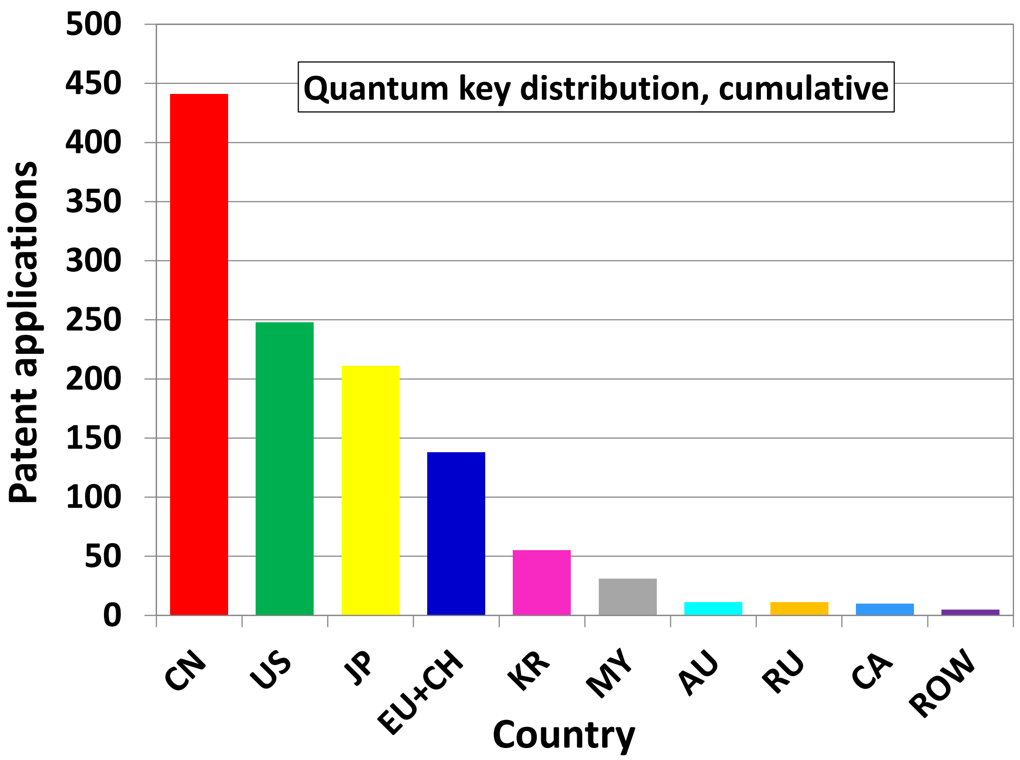

Figure 5: total number of applications in QKD, divided by country where applicants are headquartered. Main contributors to EU28 plus Switzerland are United Kingdom, Switzerland, France, Germany, Italy, and Finland. Some patents also from Spain, Austria, Belgium, and other EU countries.

Fig. 6 shows the most prolific applicants, which allow identifying the following areas of business:

Electronics and telecom: here we have mostly Japanese firms (Toshiba, NEC, Mitsubishi, NTT, Hitachi), but also European ones (British Telecom and Nokia, now Nokia Bell Labs) and South Korean (SK Telecom).

Defence and Security: we have mostly USA players (Magiq, BBNT, Los Alamos Labs, Boeing, US army), but also European ones (Qinetiq) and the Chinese People Liberation Army (PLA).

Information technology: Hewlett Packard (USA), Alibaba (China)

Dedicated firms: in this category we have very prolific Chinese players (Anhui Qasky, Zhejiang QTEC, QuantumCtek, Zhejiang Shenzhou Liangzi), but also the Switzerland firm IdQuantique. It is to be noted that IdQuantique and QTEC formed a joint-venture named IQQ-QTEC in December 2016, and that SK Telecom bought a majority share of IdQuantique for $65 million in February 2018.

There are also public research laboratories and R&D organizations (e.g. Mimos Berhad from Malaysia, the Korea Institute for Science and Technology), and several universities (especially from China but also Europe, notably the University of Geneva).

The vast majority of patents is dedicated to technological developments. There is however a minority which target specific use-cases, such as mobile commerce, infrastructure protection (in particular electric grids), payment authentication, and video conference systems. We add that several among the patent applications retrieved with our searches do not regard QKD in a strict sense: we have e.g. applications on devices (such as optical sources and detectors), quantum random number generators, data processing methods, communication networks. However, all of them mention QKD as a driver for the invention (e.g. a single photon source to be used for QKD) or highlight that the invention is compatible with QKD (e.g. a network topology particularly well suited to QKD deployment over it). The abundance of such applications can be considered as an indication that QKD is starting to exert some pull in other domains.

It is also to be noted that if we make a search for the "applicant" field, we usually end up with a number of patents higher than the one retrieved for this applicant by using the CPC codes and the WORD strings related to QKD. For example, by inserting "Zhejiang Shenzhou Quantum Network Tech Co Ltd" in the "applicant" field of the Espacenet smart search tool we find 22 hits, each of them related to the use of quantum phenomena for communications security. But in our list of 1161 pertinent patents, only 12 have "Zhejiang Shenzhou Quantum Network Tech Co Ltd" as applicant. This is due to the fact that some of the patents filed by this applicant do not fall in the commonly-used definition of QKD: to clarify, we mention as an example the application "Multi-party quantum digital signature method without trusted center". Including such applications would entail enlarging the query to a wider domain, which could be loosely defined as "quantum technologies for communications security". We have performed some searches, gaining the insight that such an enlargement would increase the patenting lead of China. However, the boundaries of this larger technological domain are blurred, preventing any clear-cut conclusion. We decided therefore to limit our searches to the well-defined QKD technique.

As a further note, we note that in Chinese applications it is very common to find different names for same company, and conversely different companies with very similar names. However, only three companies seem to have commercial products, namely

ANHUI QASKY QUANTUM SCIENCE AND TECHNOLOGY CO LTD, www.qasky.com

QUANTUMCTEK CO LTD, http://www.quantum-info.com/English

ZHEJIANG QTEC INFORMATION TECH CO LTD, http://www.qtec.cn

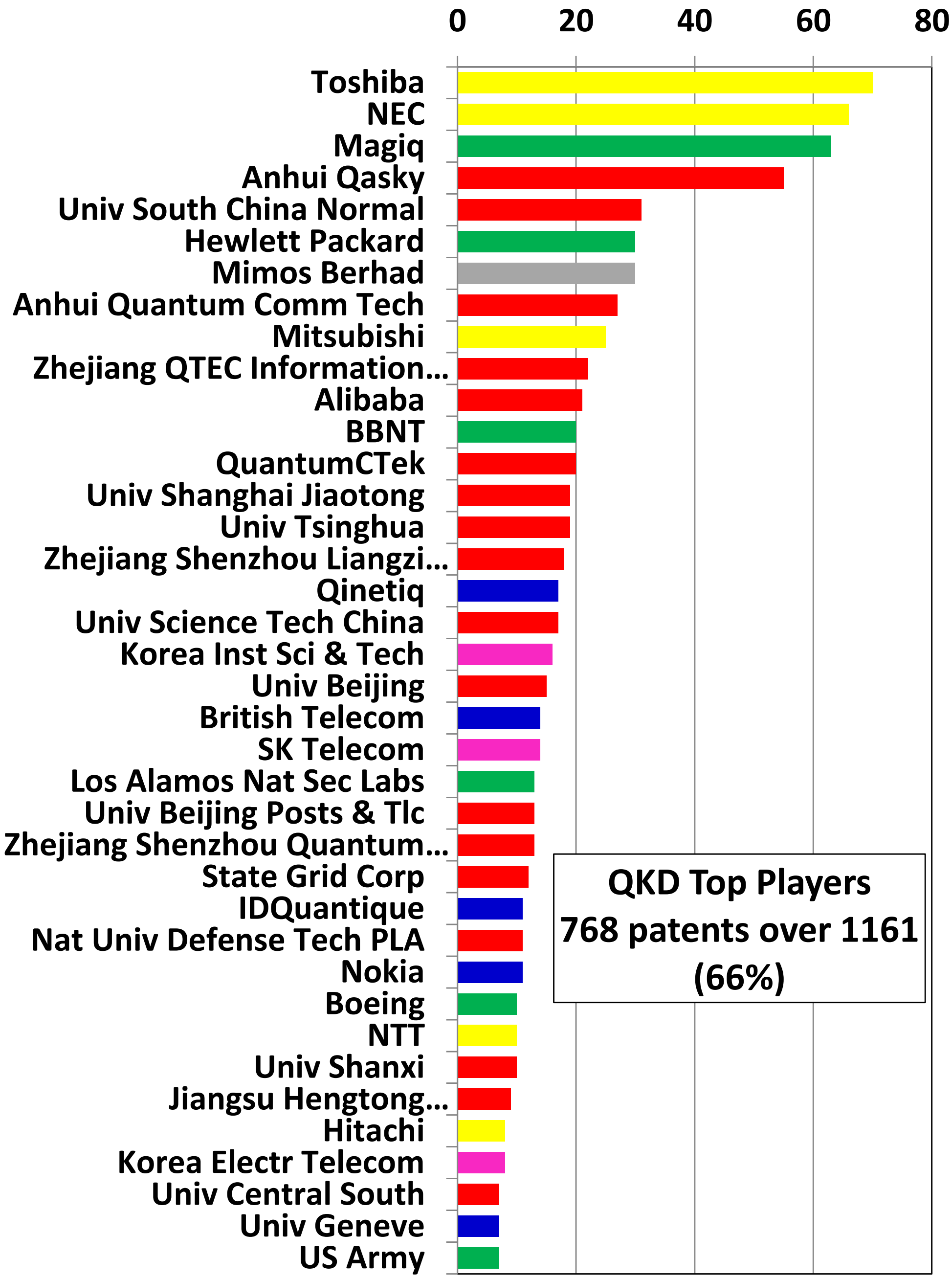

Figure 6: Top applicants in Quantum Key Distribution, color-coded as in Figure 5 to indicate the country where they are headquartered.

4 Entanglement

Since entanglement is widely considered one of the peculiar quantum phenomena which define the "second quantum revolution", we have conducted some searches ([6]) on patent applications based on it. In the absence of dedicated CPC codes, only text strings can be used. In a first example, we have used the following query:

word = (photon or photons or photonic) and (entangled or entanglement or entangling or entangle)

This query retrieves 337 patent applications, and by analysing them we found 4 false positives. The 333 remaining applications are distributed in time according to the graph shown in Fig. 7. There is not a discernible overall increase trend in the last ten years, but a clear increase in contributions from China. As a consequence (see Fig. 8 overleaf) China is now at the second place after the USA, with Japan a close third and EU a distant fourth.

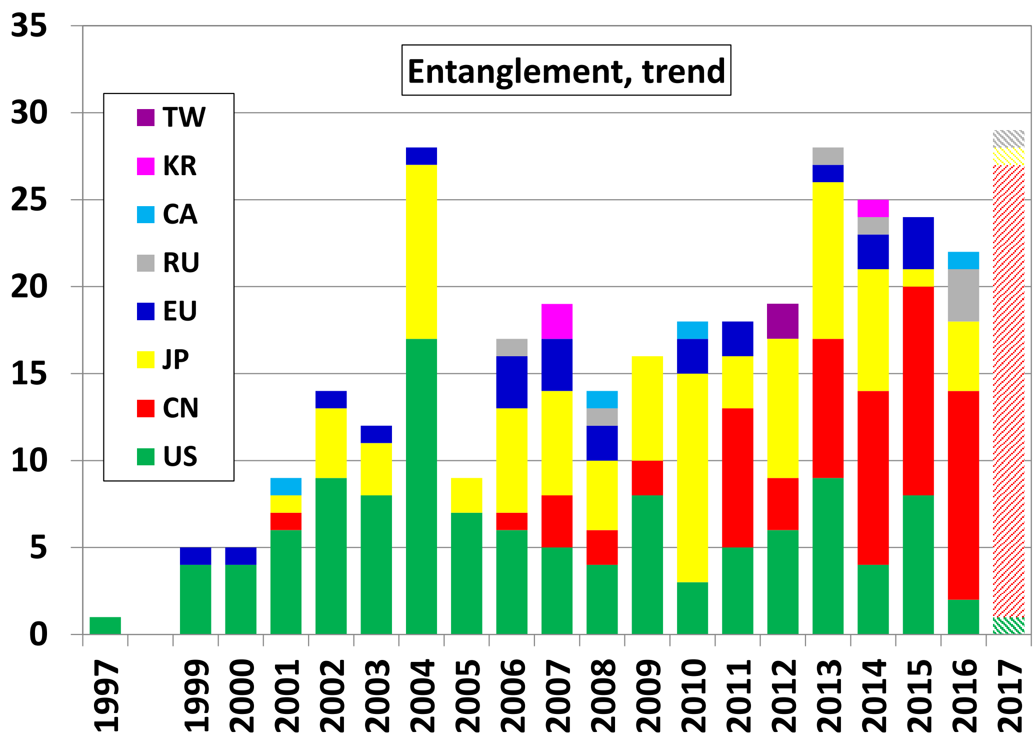

Figure 7: number of patent applications exploiting quantum entanglement per year, according to the country where the applicant is headquartered. The bar for year 2017 is shaded, to highlight that results are provisional because of the optional 18-month confidentiality period between filing and disclosure.

([6]) In October 2018, on the EPO GPI database

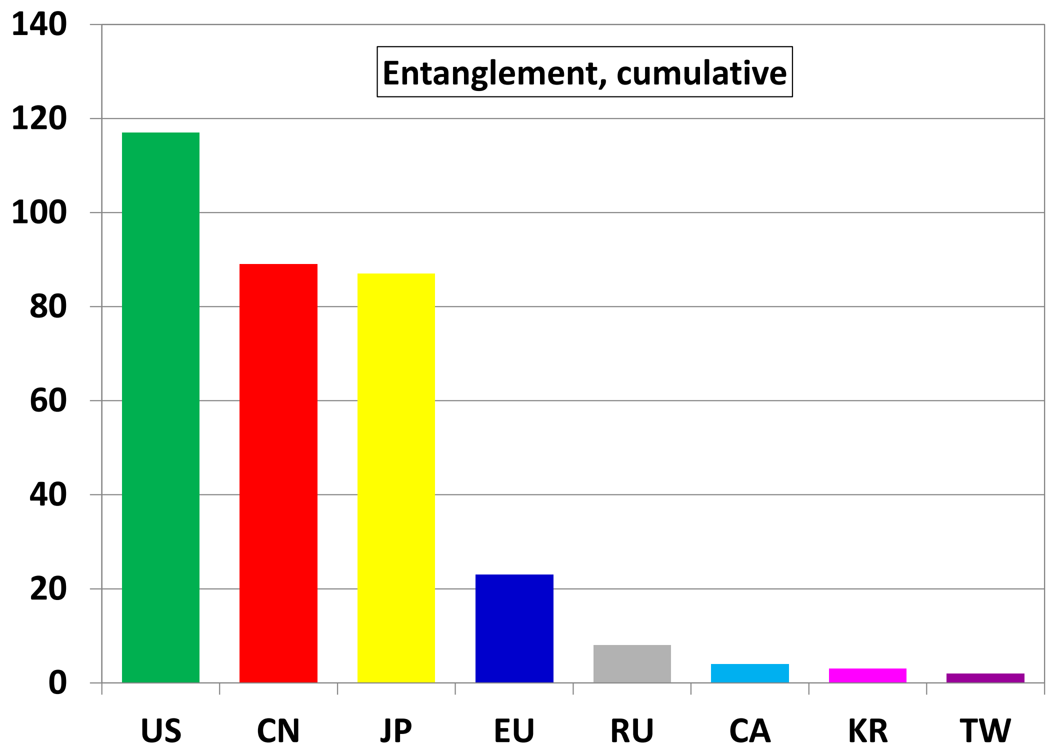

Figure 8: total number of patent applications since 1997 quoting photon entanglement, divided by country where applicants are headquartered. Main contributors to EU28 are United Kingdom, Germany,France, and Italy.

Patent applications can be broadly divided in two categories, aiming respectively at technological developments (around 130) and at practical applications (around 200). Technological development is mostly focused on sources of entangled photons, but there are also some patents on quantum repeaters and quantum memories, and a few on fabrication processes. In the application category, the largest fraction of patents regards communications (around 110 applications, with the great majority dedicated to communications security). We have then applications in the sensing domain (~70 patent families), then computing, and the exploitation of entanglement for manufacturing (e.g. quantum lithography).

We present here a brief overview on sensing applications of entanglement. The following areas seem to be receiving most of the attention:

Target detection:

- "Quantum radar and target detection implementing method thereof", Air Force Academy, China, 2017
- "HOM interference principle-based range finder", Beijing Inst. Aerospace Control Devices, China, 2016
- "System and method for authenticated interrogation of a target with quantum entanglement", Raytheon, USA, 2015
- "System and processor implemented method for improved image quality and generating an image of a target illuminated by quantum particles", US army, USA, 2011
- "Systems and methods for quantum illumination detection for optical communications and target detection", Raytheon, USA, 2010
- "Entangled-photons range finding system and method", General Dynamics Advanced Information Systems, USA, 2004

Imaging:

- “Cerebral function imaging and brain tissue component detection method and device”, Borui Taike Tech Co Ltd, China, 2017
- “Pure phase object imaging system based on photon orbit angular momentum”, Harbin Inst. of Technology, China, 2017
- “Compressed-sensing-based entangled light imaging device and imaging method against background of strong interference”, Univ. Xidian, China, 2015
- “Imaging system”, BAE, UK, 2014
- “Terahertz-stokes two-photon entangled imaging device of spherical wave pump”, Univ. Northwester, China, 2013
- “Entanglement imaging system and method based on dual-compression coincidence measurements”, Space Science and Research, CAS, China, 2013
- “Two-photon entanglement-based terahertz wave imaging device”, Univ. Northwester, China, 2012
- “Angular resolution of images obtained using photons having non-classical states”, Boeing, USA, 2012
- “Entangled quantum communications and quantum imaging, US army, USA, 2003
- “Imaging with nondegenerate frequency-entangled photons”, Boeing, USA, 2007
- “Method and system for quantum and quantum inspired ghost imaging”, US army, USA, 2003

Navigation:

- “Quantum Imaging for Underwater Arctic Navigation”, US Navy, USA, 2014
- “Navigation and distance measurement system on basis of quantum entanglement light and method for implementing navigation and distance measurement system”, Univ. Shanghai Jiaotong, China, 2013
- “Method and system for realizing all-weather aircraft landing or carrier landing by quantum entangled-state light”, Xi An Optics Precision Mech, China, 2011
- “Method for detecting underwater object by relevance imaging”, Univ. Guilin, China, 2009
- “System and method for improving the resolution of an optical fiber gyroscope and a ring laser gyroscope”, Larry Fullerton, USA, 2007

Satellite ranging:

- “Inter-satellite ranging method based on quantum light sources on satellites and reflector”, Beijing Inst. Aerospace Control Devices, China, 2014
- “System for improving location accuracy of dipper satellite navigation system”, Xi An Optics Precision Mech, China, 2011
- “Method and system for improving positional accuracy of Beidou navigation system”, Xi An Optics Precision Mech, China, 2011
- “Satellite-ground dual-optical-path alignment system”, Shanghai Engineering Centre for Microsatellites, China, 2017

Clock synchronization:

- “Satellite clock bias measurement device”, PLA Air Force Engineering Academy, China, 2016
- “Quantum synchronization for classical distributed systems”, Raytheon, USA, 2013
- “Method and device for synchronizing and acquiring twin photons for a quantum cryptography process”, Elsag, Italy, 2004
- “System and method for clock synchronization and position determination using entangled photon pairs”, Univ. Maryland, USA, 2004

Microscopy:

- “Method for distinguishing microscopic organisms on basis of quantum correlated imaging technologies”, Chongqing Inst. for green & intelligent technology, CAS, China, 2017
- “Supercontinuum microscope for resonance and non-resonance enhanced linear and nonlinear images and time resolved microscope for tissues and materials”, Alfano Robert, USA, 2009
- “Microscope using quantum-mechanically entangled photons”, Toshiba, JP, 2004
- “Optical microscope using an interferometric source of two-color, two-beam entangled photons”, Battelle, USA, 2001
- “Entangled-photon microscope”, Leica, Germany, 2000
- “Entangled-photon microscopy, spectroscopy, and display”, Univ. Boston, USA, 1997

Other sensing applications:

- “Chemical sensing using quantum entanglement between photons”, Halliburton, USA, 2015
- “Quantum entanglement teleportation-based spinal cord injury nerve signal relay system and method”, Univ. Xi An Posts & Tlc., China, 2013
- “Magnetic field detection apparatus and magnetic field detection method”, NTT, JP, 2013
- “Method and apparatus for detecting chemical & biological weapon components using Raman spectrum”, Juliano Michel, USA, 2004
- “Method and apparatus for performing in-vivo blood analysis using Raman spectrum”, Juliano Michel, USA, 2004
- “Entangled-photon Fourier transform spectroscopy”, General Dynamics Advanced Inf. Systems, USA, 2004
- “Multi-photon imaging and quantum lithography”, Univ. Maryland, USA, 2001
- “Lithography using quantum entangled particles”, Caltech, USA, 1999

To highlight the risk of false positives, we show a second example of a possible search on quantum entanglement, now based on the query:

word = (spin or spins) and (entangled or entanglement or entangling or entangle)

Such a search should target patents on quantum memories, which usually rely on atomic or nuclear spin. Among the 104 hits, we have 80 false positives, with examples such as: “Tennis racket string and method for making the same”, “Entanglement preventive device for laundry in washing machine”, “Direct spin-draw process for polyester fiber”. The 24 patents actually referring to quantum entanglement do not reveal any new research areas with respect to those already described above.

5 Cold atom interferometry

Cold atom interferometry exploits interference between matter waves, typically for sensing purposes. Numerous different search strategies can be adopted to analyze this area, and several attempts allowed us concluding that it is very easy to incur a significant fraction of false positives. One of the queries least affected by false positives is

word = ("cold atom") or ((atom or atoms or atomic) and (interferometer or interferometry))

which gives 263 hit ([7]). Among these, 72 are false positives. Among the remaining 191 pertinent applications, we have 41 inventions which actually refer to enabling technologies (laser, electronics, microwave devices, thermal or vibration control): most of them are from Chinese applicants, and have been filed in the last three years. We decided not to exclude them, since (i) they are a measure of the driving force that cold atom interferometry is exerting, spurring innovation in other areas (ii) they often mention the particular application area for which the invention has been introduced, therefore providing useful information. Conversely, it could be argued that the existence of a high fraction of patents which actually pertain to unrelated technologies but still mention atomic interferometry shows that applicants are exploiting a policy drive in favour of quantum technologies to attract interest and funding for the research they are actually carrying out in other domains.

The remaining 150 application which can strictly be considered as part of the atomic interference area describe both technology developments (eg. new design for magnetic trap, atomic chip, beam control, etc.) and possible applications. Among them, the main ones are:

- Gravity sensors (gradiometry in particular)
- Gyroscopes
- Angular speed and acceleration sensors
- Clocks (also in space)
- Electric field sensors
- Magnetic field sensors

By far the most common applications are gravity sensors and devices to be used for positioning and navigation. Clocks enter in this analysis only tangentially, since, although they can make use of cold atoms, they usually do not exploit matter interferometry.

Most of the applicants are universities, but we found also a limited number of dedicated start-ups (Aosense, Muquans, Coldquanta), national laboratories (Sandia from US, 717th Research Institute and Flight Automatic Control research Institute from China, CNRS from France), and some large corporations – especially from the defence sector. In particular the following defence players are note of mention:

National University for Defense Technology of the People Liberation Army (China)

Defense Agency (South Korea)

US Navy and Air force / Charles Draper Labs / Honeywell / Northrop Grumman / Lockheed Martin (US)

Onera / Thales / Sagem – Safran (FR)

We mention ENI (Italy) and Halliburton (US), two important players from the energy sector, which hold patent on gravity meters to be used for hydrocarbon prospecting.

([7]) In November 2018, on the EPO GPI database

In the following Fig. 9 and Fig. 10 we show the evolution along the years in the number of patent application, and the final number accumulated by players headquartered in the various countries. With respect to the technologies analysed in the previous section, it is worth noticing that Japan does not seem to play a significant role. However, this can be an indication that our search failed to capture a complete picture of the field.

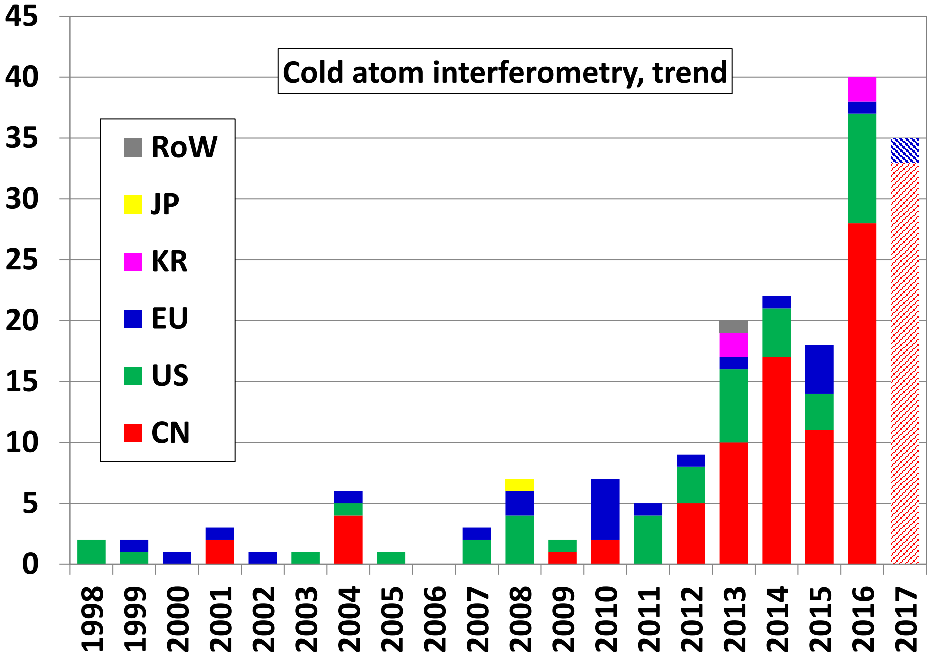

Figure 9: number of patent applications on cold atom interferometry per year, according to the country where the applicant is headquartered. Patenting actually began earlier: we found an application on a ”Matter wave interferometric apparatus” filed in 1972, and another one on a ”Rotation, acceleration, and gravity sensors using quantum-mechanical matter-wave interferometry with neutral atoms and molecules” in 1987. The bar for year 2017 is shaded, to highlight that results are provisional because of the optional 18-month confidentiality period between filing and disclosure.

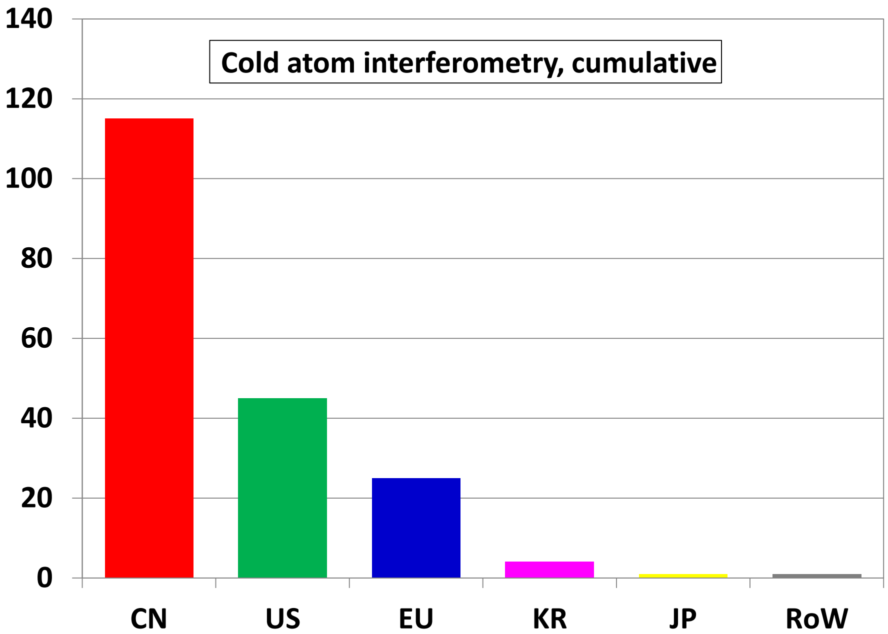

Figure 10: total number of patent applications quoting cold atom interferometry, divided by country where applicants are headquartered. Contributors to EU are France (17), United Kingdom (5), and Italy (3).

6 Conclusions

Overall, our analysis of the examined Quantum Technologies areas shows that patenting activity has been rising since ~2012, following 10 years in which it had been stagnating. Numbers are still limited, applications per year range in the few hundreds, and the accumulated total is in the lower thousands. Simplifying, the increasing trend follows from the following reasons:

In quantum computing, we have newcomers to the field headquartered in the US (e.g. Microsoft and Google) which are progressively matching more established firms such as HP and IBM. Relentless is also the effort of a Canadian firm, Dwave, which is the only one actually selling a quantum computer, albeit of a special kind with only specialized capabilities. Japan and European players seem to be maintaining a constant patenting rate, while China is slowly stepping up its efforts, starting from a very low basis.

In quantum key distribution the increase in patenting is fully to be ascribed to China, where a public-funded effort to establish extensive quantum-secured networks is taking place. Chinese universities and specialized quantum communications firms are filing most of the patents, but the telecom giant Huawei has recently joined the race. European and Japanese players are maintaining their pace, while US firms seem to have lost appetite, having peaked around 2004.

The Rate of patent applications exploiting photon entanglement is steady overall, with China progressively supplanting the USA as the main player. To a certain extent, this is due to the fact that entanglement is an important resource for quantum-safe communications. However, interesting sensing applications have also emerged, some of which may have a significant impact for defence: here French companies are clearly visible.

Finally, we have examined cold atom interferometry. Although first patents were awarded in the 70's, the number of filings per year remained confined to single digit until 2012. China is responsible for the increase in the last 5 years, but a significant fraction of patents actually regards enabling technologies such as photonics and electronics. Gravity sensing based on cold atom interferometry has matured to the point that commercial products do exist, and a significant effort in navigation is taking place, sustained in particular by defence players.

To summarize, the data here presented show that the renewed interest which QTs have been experienced in the last 5-10 years should be mainly ascribed to (i) public-funded technology push initiatives, especially by China in quantum-secured communications (ii) long-term, high-risk investment in Quantum Computing, especially by USA-based IT and internet corporations. Commercial products are starting to emerge in niche sectors of sensing, where both dedicated start-ups and large defence companies are active. Markets pull for QTs appears to be still limited, in part because of insufficient technological maturity and in part because of the lack of clear business cases: indeed, most of the patents do not target specific applications, and are rather directed at improving technologies.

Overall, our analysis shows that it is too early to assess the actual impact that technologies at the core of the "second quantum revolution" will have in the foreseeable future.

Appendix 1: Patent analyses

PatInformatics

Quantum Information Technology Patent Landscape Reports – Innovation at the speed of light (2017), https://patinformatics.com/quantum-computing-report/

- "Quantum Information Technology (QIT): A Patent Landscape Report"
- "Quantum Computing Applications: A Patent Landscape Report"
- "Practical Quantum Computing: A Patent Landscape Report"

UK Intellectual Property Office

- "Quantum Technologies: a patent overview for the Engineering and Physical Sciences Research Council (EPSRC)", 2013 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/312693/informatics-quantum.pdf
- "Eight Great Technologies: Quantum Technologies - A patent overview", (2014) https://www.gov.uk/government/publications/new-eight-great-technologies-quantum-technologies

"Analysis of patent activity in the field of quantum information processing", by R. Winiarczyk, P. Gawron, J. A. Miszczak, Ł. Pawela, Z. Puchała, Polish Academy of Sciences (2012), https://arxiv.org/pdf/1212.2439.pdf

A collection of IPC and CPC codes related to Quantum Technologies can be found at http://www.martinaulbach.net/physics/quantum-information/57-patent-activity

Appendix 2: Market analyses

- https://www.octimine.com/patents-of-quantum-computing-companies/
- https://www.rhtiassets.com/leadership/overview-patenting-quantum-computers
- https://www.reddie.co.uk/2017/04/24/patenting-quantum-realm/
- https://www.statista.com/statistics/693578/worldwide-quantum-computing-patent-applications-by-country/
- https://www.idgconnect.com/abstract/29673/which-companies-leading-quantum-race
- https://relecura.com/wp-content/uploads/2018/03/Quantum_Computing_Relecura_Report_20180104.pdf

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