# Quantum technology – a bibliometric analysis of a maturing research field

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August 2019
Max Planck Society

## Introduction and dataset

The present study summarises the results of a bibliometric analysis investigating the research field of "quantum technology". Quantum technology is a maturing field combining knowledge from physics and engineering where quantum effects are utilized for practical applications. The field of quantum technology can be separated into quantum computing, quantum algorithms, quantum networking, quantum communication, quantum cryptography, quantum information science, quantum simulation, quantum metrology, quantum sensing, quantum imaging, quantum control, quantum software, quantum theory, quantum hardware systems, and quantum systems for information processing. Of course, the sub-fields of quantum technology overlap significantly. Since previous speed-ups as described by Moore's law (Moore, 1995) appear to come to an end on the basis of semiconductor technology (Bilal, Ahmed, & Kakkar, 2018; Lau, Fischer, & Acm, 2017; Liu, Wu, & Yi, 2015), quantum computers promise a quantum leap in computational power. Unfortunately, so far, it has only been possible to design quantum computers for very special purposes. New (quantum) algorithms, software, and hardware are necessary to exploit advantages of quantum computing.

Quantum networks allow for transmission of quantum information, usually by entangled qubits (quantum bits). Quantum networks can be used for quantum computing and quantum communication. Quantum processors can communicate over quantum networks. An extended quantum network leads to a quantum internet. Secure communication is essential for quantum networks. This can be accomplished by quantum cryptography. Quantum metrology offers measurement techniques that provide higher precision than the same measurement performed in a classical framework. One well-known example of quantum metrology is the atomic clock (see, e.g., Lyons, 1957). Similarly, quantum sensing promises to develop advanced sensing techniques. Quantum imaging is a new sub-field of quantum optics that exploits quantum correlations such as quantum entanglement of the electromagnetic field in order to image objects with a resolution or other imaging criteria that are beyond what is possible in classical optics.

The approach of the study on quantum technology follows previous studies dealing with research fields such as climate change (Haunschild, Bornmann, & Marx, 2016) and related fields (Marx, Haunschild, & Bornmann, 2017a; Marx, Haunschild, & Bornmann, 2017b, 2018). The bibliometric data used in this study are from two sources: (1) the online version of the Web of Science database provided by Clarivate Analytics (Philadelphia, Pennsylvania, USA) and (2) the bibliometric in-house databases of the Max Planck Society (MPG) and the Competence Centre for Bibliometrics (CCB, see: http://www.bibliometrie.info/). The MPG's database is developed and maintained in cooperation with the Max Planck Digital Library (MPDL, Munich), and the CCB's database is developed and maintained by the cooperation of various German research organizations. Both databases are derived from the Science Citation Index Expanded (SCI-E), Social Sciences Citation Index (SSCI), Arts and Humanities Citation Index (AHCI) , Conference Proceedings Citation Index- Science (CPCI-S), and Conference Proceedings Citation Index- Social Science & Humanities (CPCI-SSH) prepared by Clarivate Analytics.

The analyses considered publications of the document types "Article", "Conference Proceeding", and "Review". The results are based on 43,392 papers published between 2000 and 2016 in the field of quantum technology. Some analyses use the period 2012-2016 to focus on recent developments. The search strings that we used for compiling the dataset including the publications for the different fields of quantum technology can be found in the Appendix. For each of the different subfields, effects of earlier truncation, usage of quotation marks, and different proximity operators were tested. We carefully considered the different result sets. The final set of publications does not comprise all quantum technology publications, nor does it exclude irrelevant publications. One of the most critical topics is quantum simulation because many different simulations of quantum systems are performed by classical means. Therefore, we decided to include publications belonging to the most relevant Web of Science subject categories and containing "quantum simulat*" in the topic. Similarly, quantum theory, the theoretical basis of quantum technology, is a very broad field in itself. We decided to include only publications which contain "quantum theory" and qubit* or "quantum bit*" in the same field of the topic. A 100% clean publication set is not achievable on such a scale. However, following our careful Web of Science search, we are confident that we captured most of the relevant publications while including only very few irrelevant publications within the scope of our study.

We analysed the number of papers (full counting) broken down by year, country, organisation, etc. and the citation impact of these papers. The citation window relates to the period from publication until the end of 2018. The citation impact analyses are based on time- and field-normalized indicators: the number and proportion of papers are reported which belong to the 10% most frequently cited papers in the corresponding publication year and subject area (Bornmann, 2013). This normalised indicator is a standard indicator in bibliometrics (Hicks, Wouters, Waltman, de Rijcke, & Rafols, 2015). Subject areas are defined in this study by sets of journals defined by Clarivate Analytics in the Web of Science database.

# Results

## Results on quantum technology

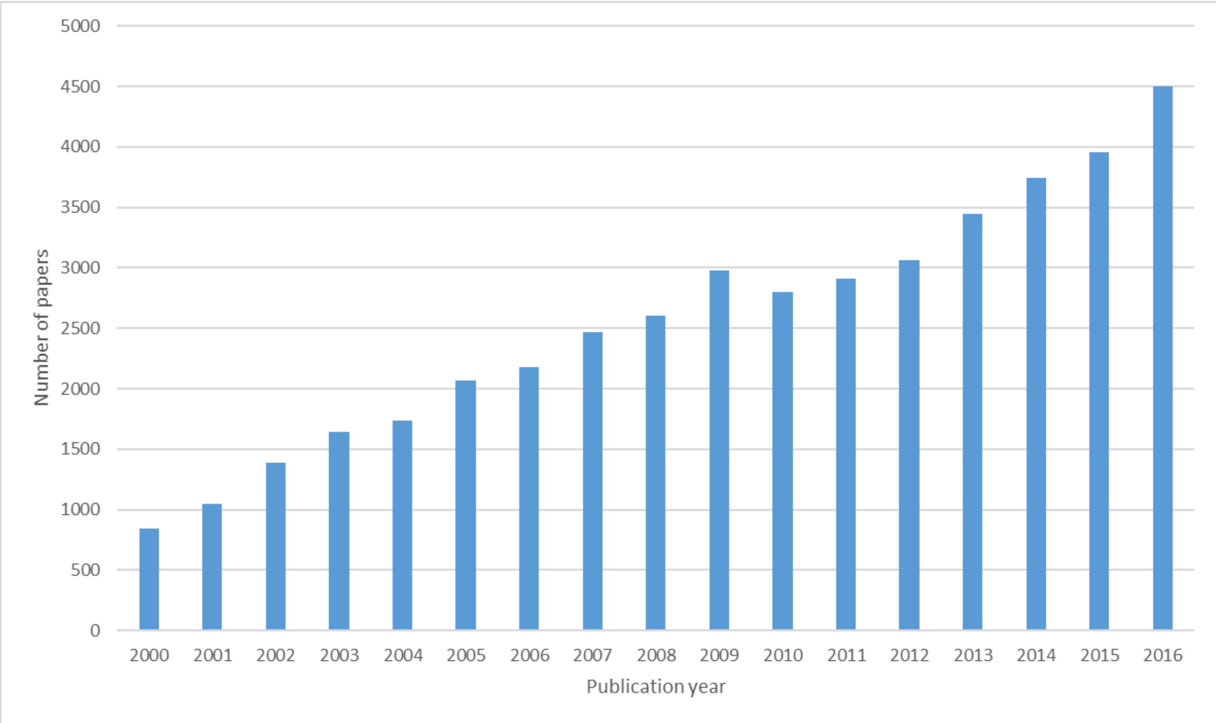


Figure 1. Number of papers published between 2000 and 2016 (database: in-house version)

The annual number of publications in the field of quantum technology has steadily increased from 842 in 2000 to 4502 in 2016 (Figure 1).

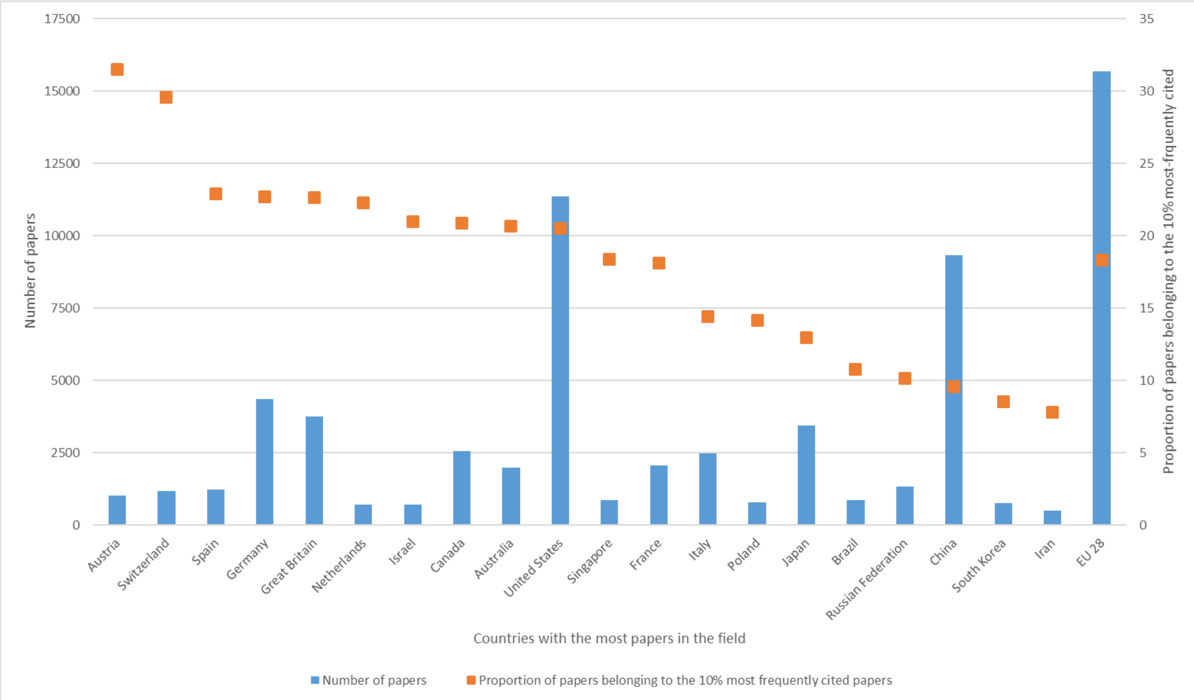


Figure 2. Countries with the most papers published in the field (between 2000 and 2016) and proportion of papers belonging to the 10% most frequently cited papers (including the EU 28). The countries are ordered by the proportion of papers belonging to the 10% most frequently cited papers (database: in-house version).

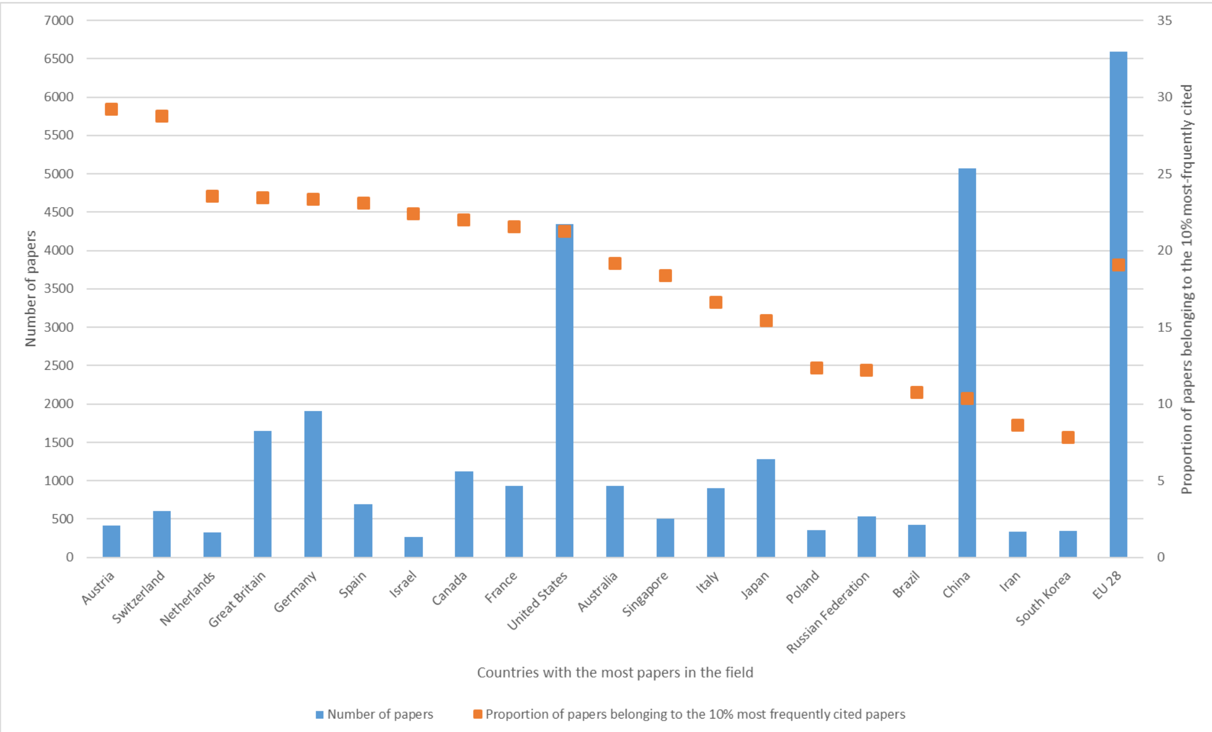


Figure 3. Countries with the most papers published in the field (between 2012 and 2016) and proportion of papers belonging to the 10% most frequently cited papers (including the EU 28). The countries are ordered by the proportion of papers belonging to the 10% most frequently cited papers (database: in-house version).

As Figure 3 shows, among the countries with the most publications in the field of quantum technology between 2012 and 2016 are the EU-28 (6598 publications), China (5070), USA (4343), Germany (1911), United Kingdom (1644), Japan (1278), Canada (1121), France (931), Australia (929), and Italy (906). In Great Britain, Germany, Canada, France, and the USA (and some others), the proportion of publications that are among the 10% most cited is over 20%. In the case of China, the proportion of the 10% most frequently cited publications is only 10%, which corresponds to the global average.

As Figure 4 shows, among the countries with the most publications in 2016 are EU28 (1579), China (1275), and the USA (1067). In 2012, China overtook the USA in the annual number of publications. The EU-28 are clearly at the top here (Germany: 473; Great Britain: 423).

With regard to the number of publications in the field of quantum technology, which are among the 10% most cited in their field (Figure 5), the EU-28 published 294 papers in 2016, the USA 230, and China 123. Here, the EU-28 is thus well ahead of the USA, and the latter well ahead of China (Germany: 102; Great Britain: 98).

Looking at the co-authorships of German publications in the field of quantum technology in the period from 2000–2016 (Figure 6), the most frequent cooperation partners are the USA (656), Great Britain (397), Italy (237), Canada (231), Austria (230), Spain (227), France (225), Japan (206), China (204), and Switzerland (164). The proportion of these publications of the 10% most cited is more than 20%. When interpreting this result, however, it must be borne in mind that a larger proportion of publications among the 10% most frequently cited can be expected for publications that have been generated in (international) collaboration than for publications that have not been generated in (international) co-authorship.

In terms of the co-authorships of German publications in the field of quantum technology in the period from 2012–2016 (Figure 7), the most frequent cooperation partners are the USA (325), Great Britain (215), Spain (138), France (128), Italy (113), Canada (112), Japan (111), Austria (97), Switzerland (97), and China (85). The proportion of these publications of the 10% most cited is more than 20%.

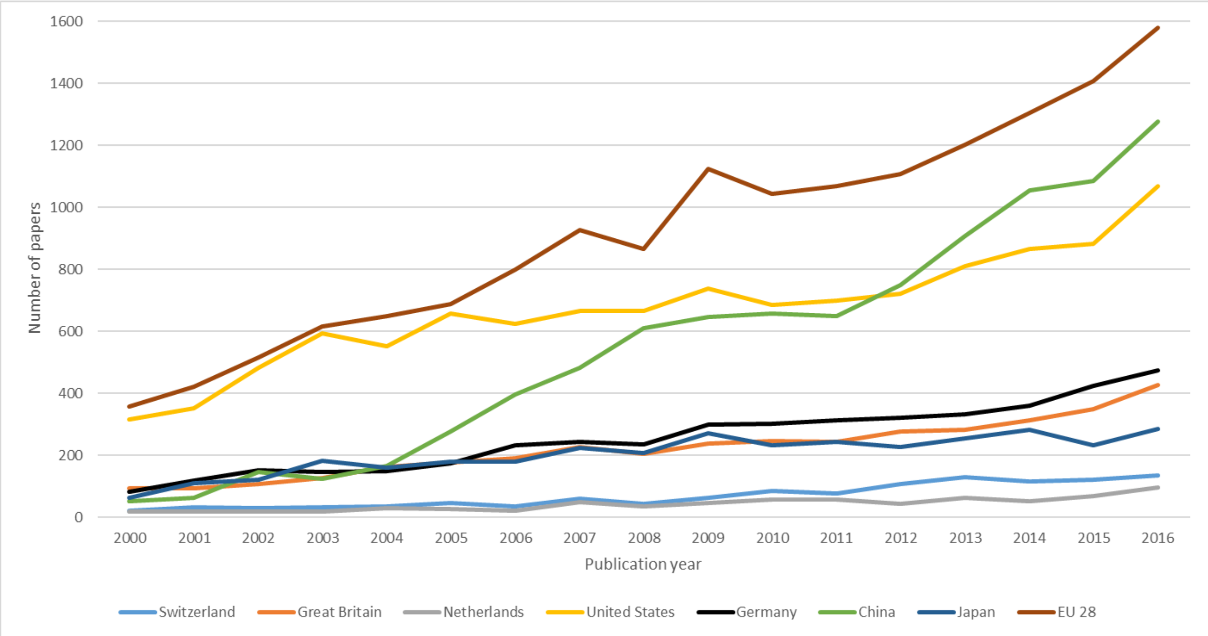


Figure 4. Number of papers published between 2000 and 2016 by selected countries. The EU-28 has been additionally included (database: in-house version).

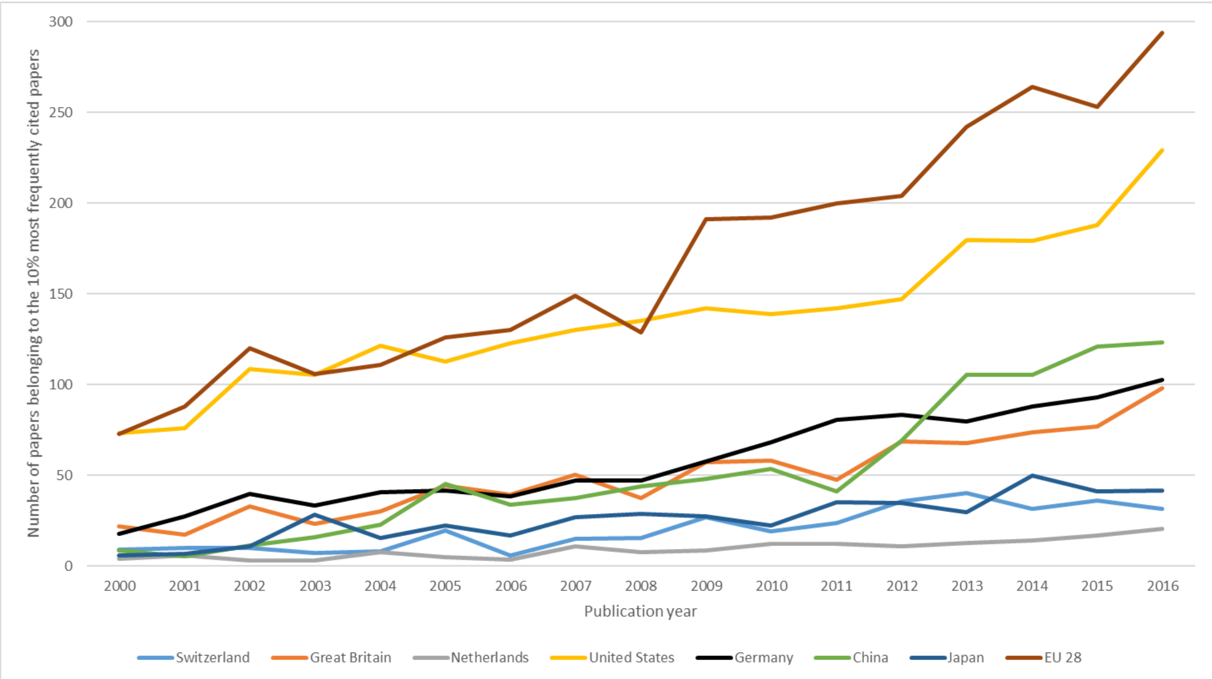


Figure 5. Number of papers belonging to the 10% most frequently cited papers published between 2000 and 2016 by selected countries. The EU-28 has also been included (database: in-house version).

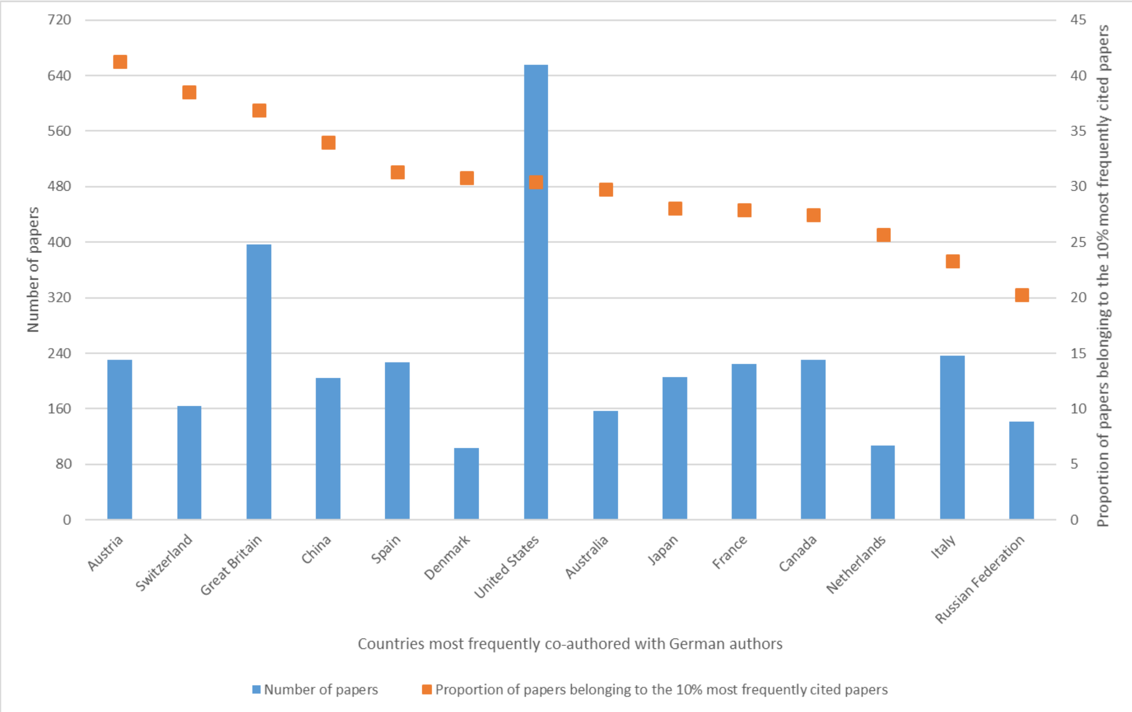


Figure 6. Countries with the most papers published in co-authorship with German authors between 2000 and 2016 and proportion of papers belonging to the 10% most frequently cited papers. The countries are ordered by the proportion of papers belonging to the 10% most frequently cited papers (database: in-house version).

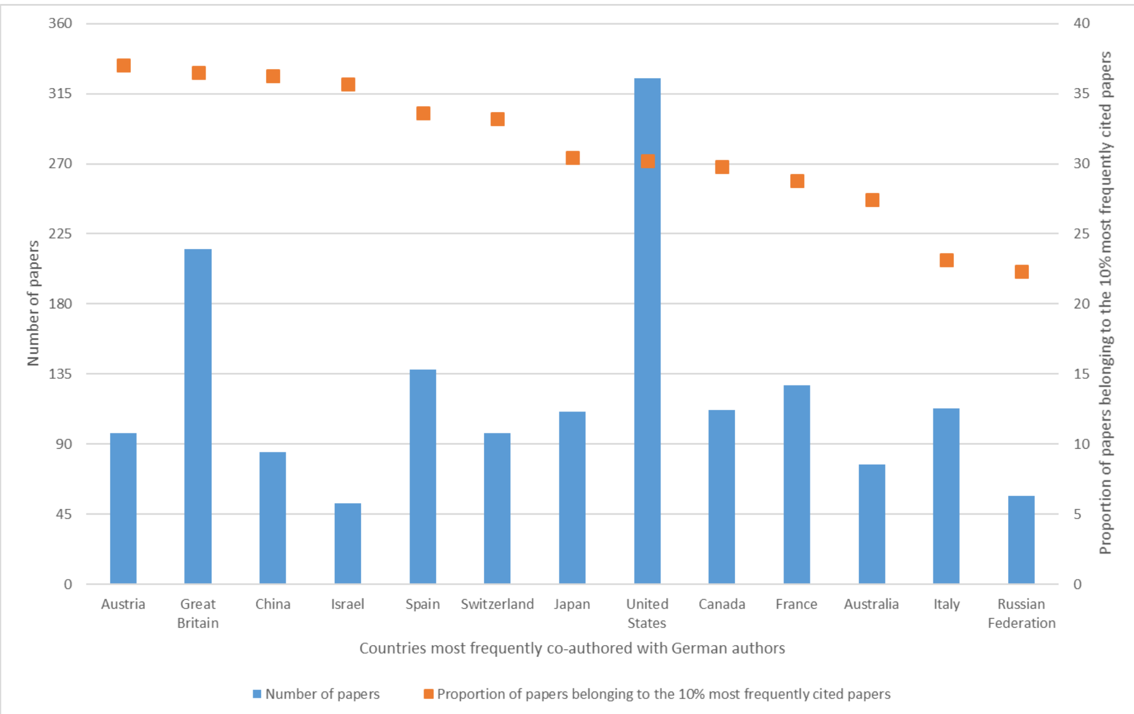


Figure 7. Countries with the most papers published in co-authorship with German authors between 2012 and 2016 and proportion of papers belonging to the 10% most frequently cited papers. The countries are ordered by the proportion of papers belonging to the 10% most frequently cited papers (database: in-house version).

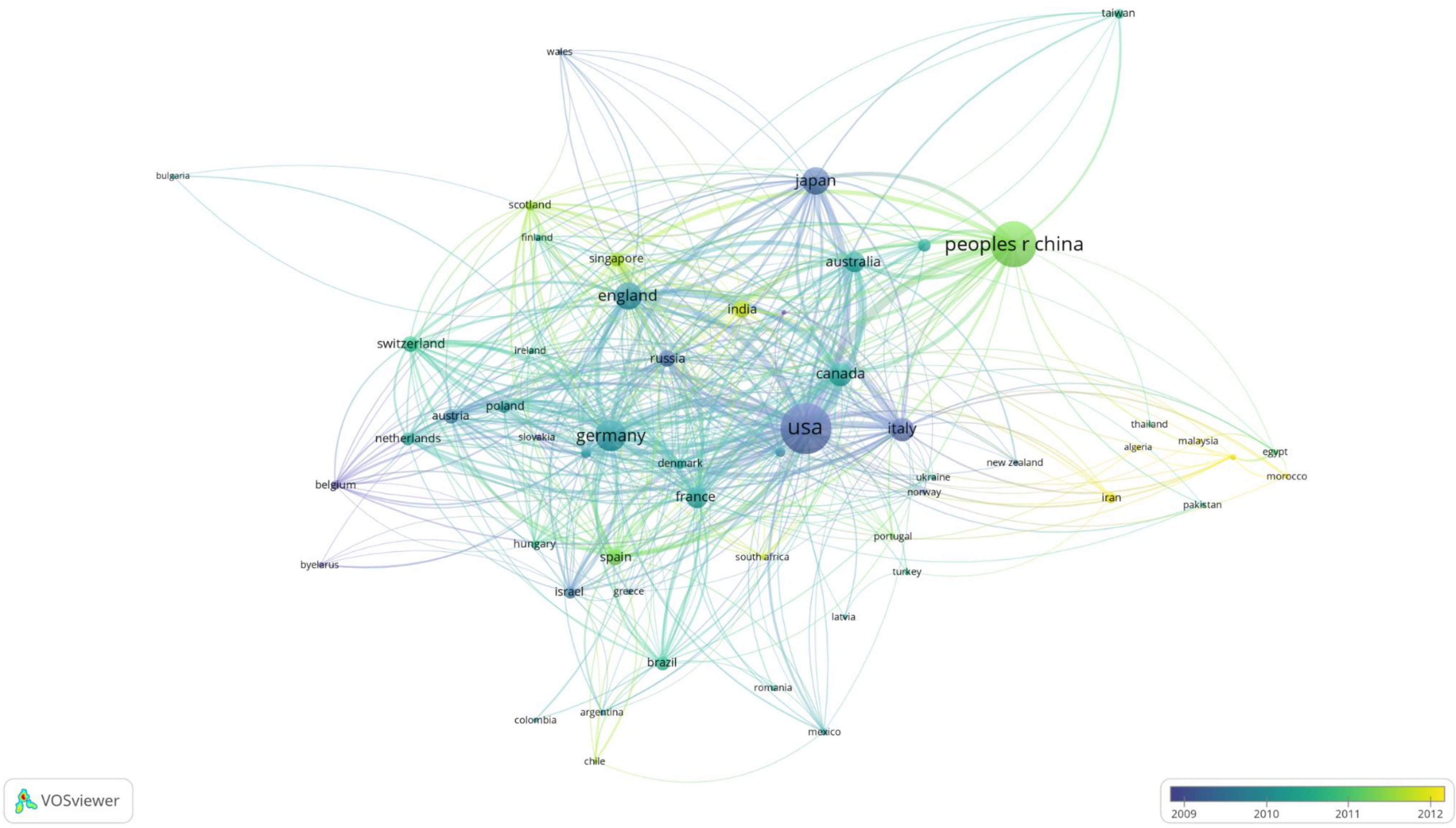


Figure 8. Co-authorship network based on countries with at least 50 papers in the field (published between 2000 and 2016). The colour indicates the average publication year of the country-specific papers (database: online version).

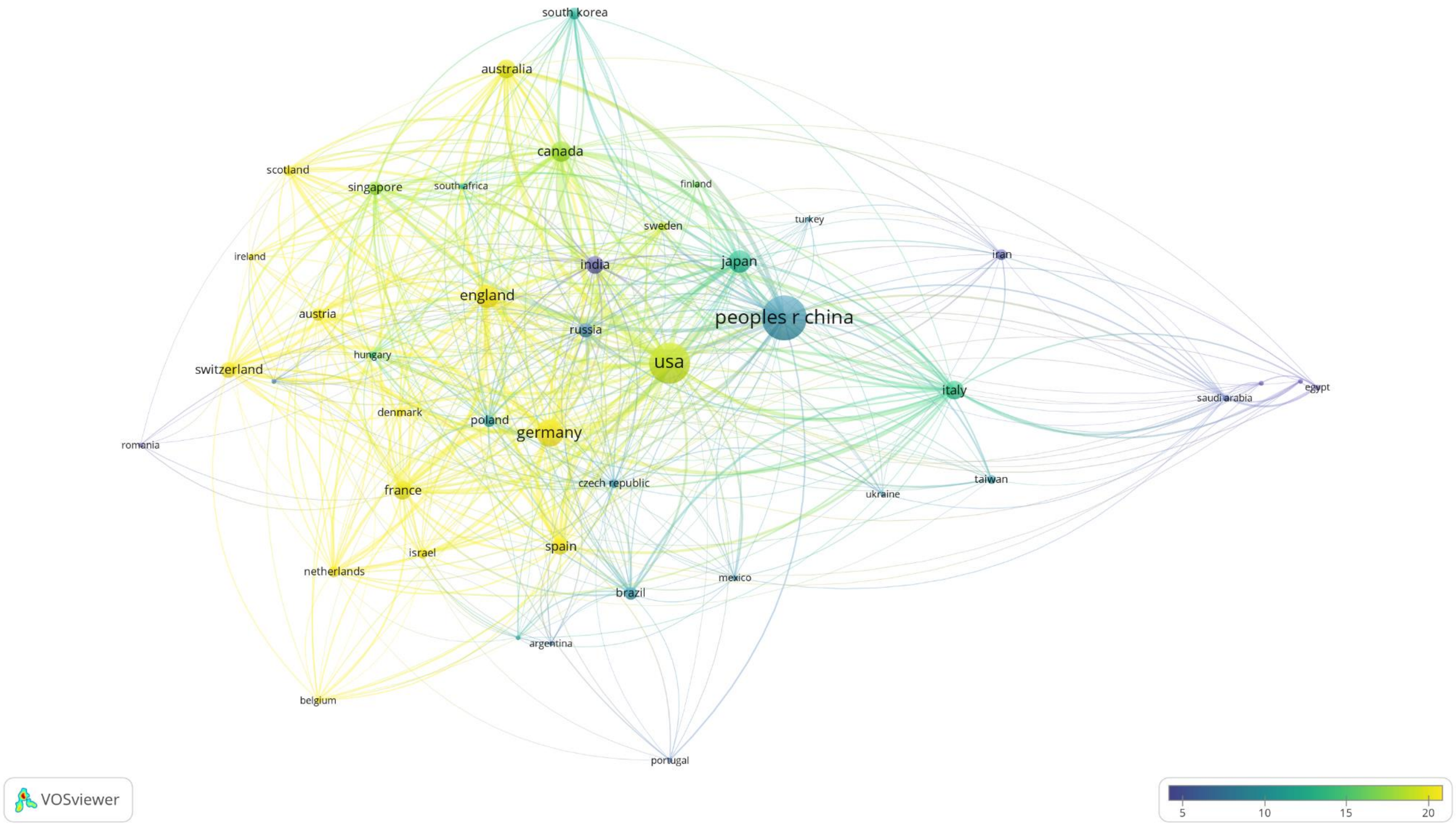


Figure 9. Co-authorship network based on countries with at least 50 papers in the field (published between 2012 and 2016). The colour indicates the average citation rate of the country-specific papers (database: online version).

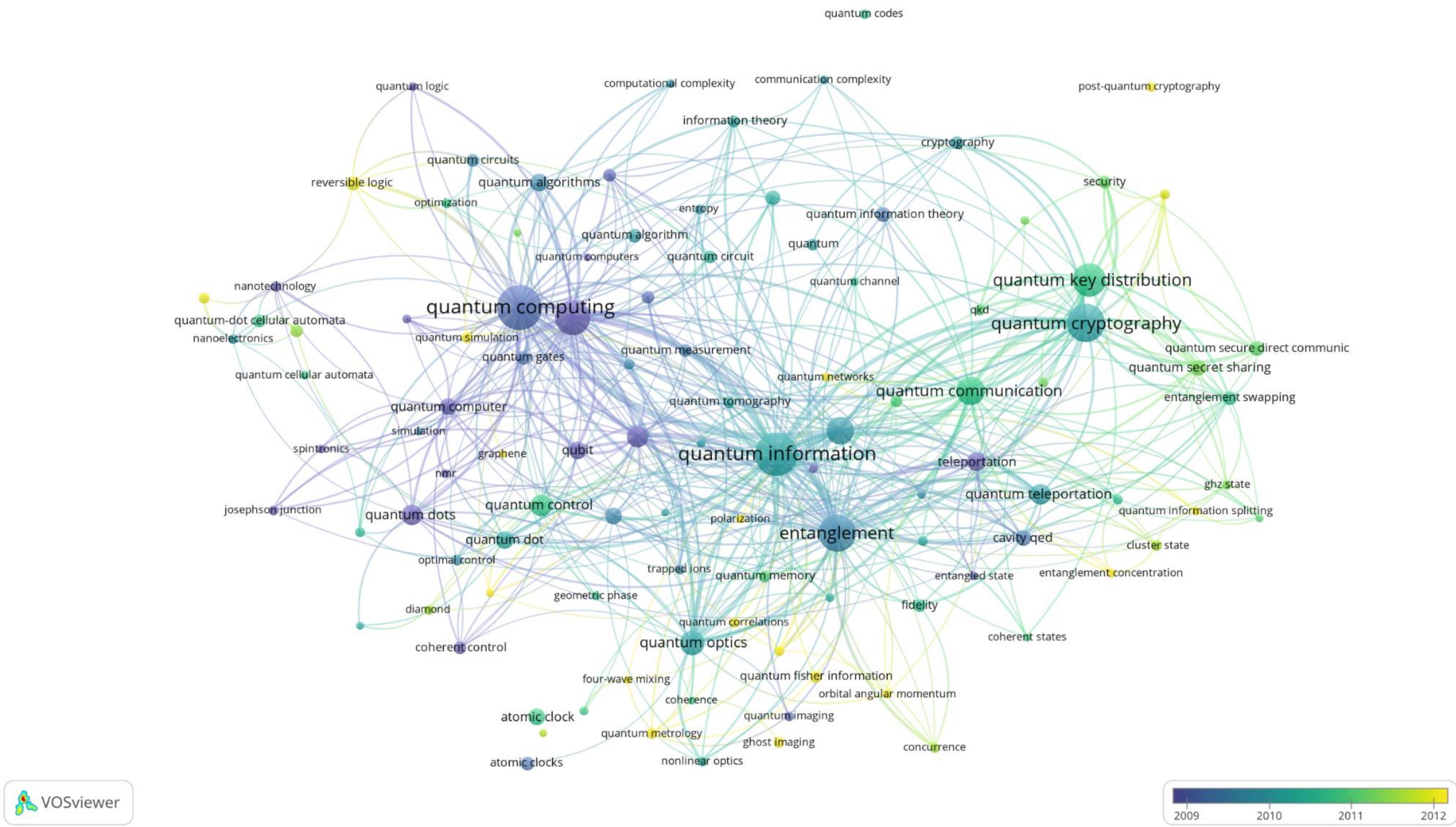


Figure 10. Co-occurrence network of keywords provided by authors in quantum technology (papers published between 2000 and 2016). The colour indicates the average publication year of the keyword-specific papers (database: online version).

Figure 8 shows the co-authorship network for publications in the field of quantum technology in the period from 2000–2016 broken down by country. The size of a circle corresponds to the number of joint publications with other countries; the colour indicates the average publication year of the country-specific publications. Countries coloured dark blue have been publishing in this area for longer than countries coloured yellow.

Figure 9 shows the co-authorship network for publications in the field of quantum technology in the period from 2012–2016, broken down by country. Nations with at least 50 publications in the period were taken into account. The size of a circle corresponds to the number of joint publications with other countries; the colour indicates the average citation rate for the publications of a country. Dark blue coloured countries have a low citation rate (five citations per publication); yellow coloured countries a rate of about 20 citations per publication. Almost all European countries are coloured yellow.

Figure 10 shows the network of keywords that appear together in publications and that originate from the authors of the respective publications. The size of a circle indicates the frequency with which a keyword appears together with other terms in publications; the colour indicates the average year of publication of those publications containing the keyword. Terms coloured in dark blue have been mentioned in publications for longer than items coloured in yellow.

In the network, it can be seen that the terms *quantum computing, quantum computer, quantum dots* are mentioned as keywords for longer than the terms *quantum information, quantum communication, quantum key distribution, quantum cryptography, entanglement (Verschränkung), quantum optics.* Terms with an even younger average age in each case are *quantum metrology, ghost imaging, quantum correlations, entanglement concentration, quantum fisher information.*

As Figure 11 shows, in the period from 2000–2016, most of the publications published worldwide in the field of quantum technology came from the following research organisations in descending order: The Chinese Academy of Science (CAS, 2037), Centre national de la recherche scientifique (CNRS, 1337), University of California System (1116), University of Science and Technology of China (1080), MPG (1010), National Institute of Standards and Technology (NIST, 833), University of Waterloo (777), Massachusetts Institute of Technology (MIT, 772). The MPG is thus one of the five most active research organisations in the field of quantum technology. As Figure 12 shows, in the period from 2012–2016, most of the publications published worldwide in the field of quantum technology came from the following research organisations in descending order: CAS (1074), CNRS (662), University of Science and Technology of China (508), University of California System (446), National University of Singapore (431), MPG (413), University of Waterloo (395), Tsinghua University (356), NIST (329), US Department of Energy (324), MIT (322). During this period, the MPG is one of the six most active research organisations in the field of quantum technology worldwide.

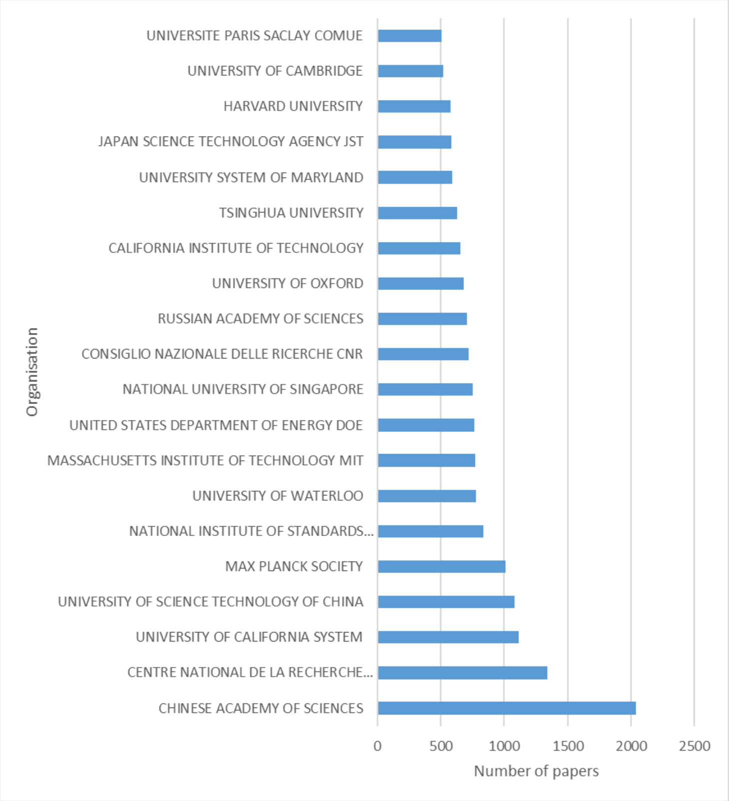


Figure 11. Organisations with the most papers published between 2000 and 2016 (database: online version)

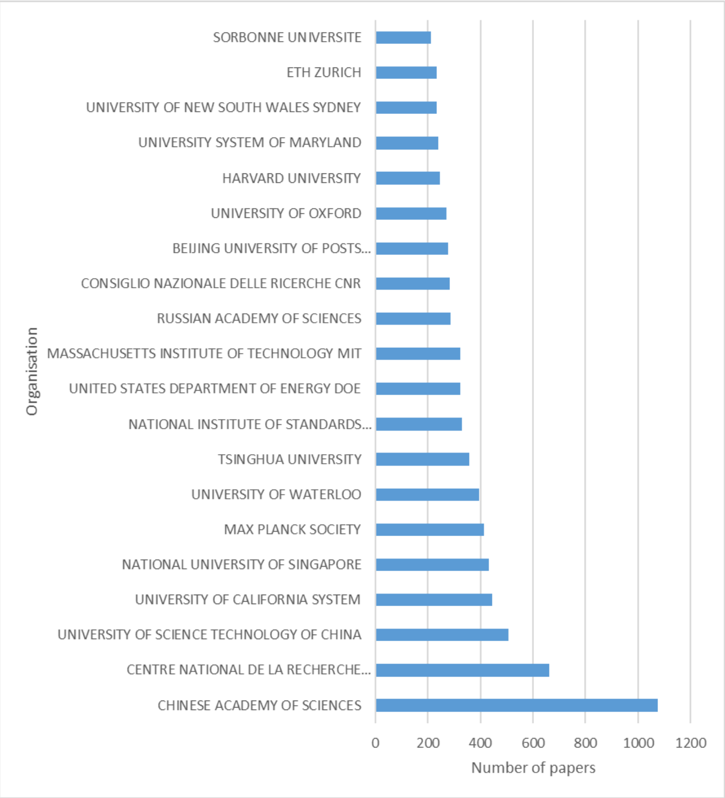


Figure 12. Organisations with the most papers published between 2012 and 2016 (database: online version)

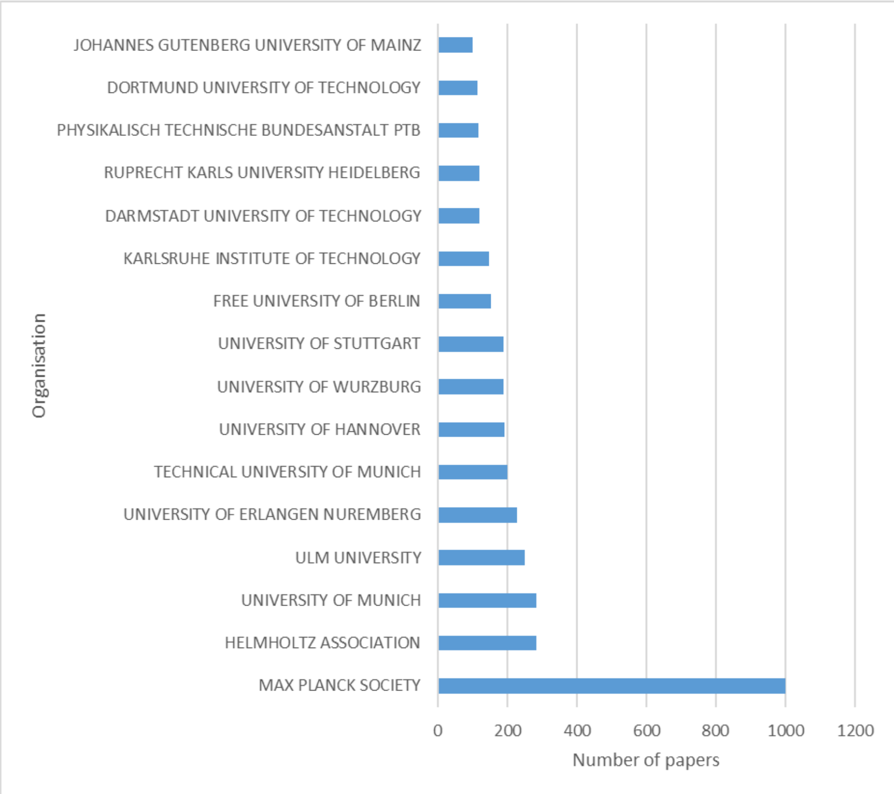


Figure 13. Organisations in Germany with the most papers published between 2000 and 2016 (database: online version)

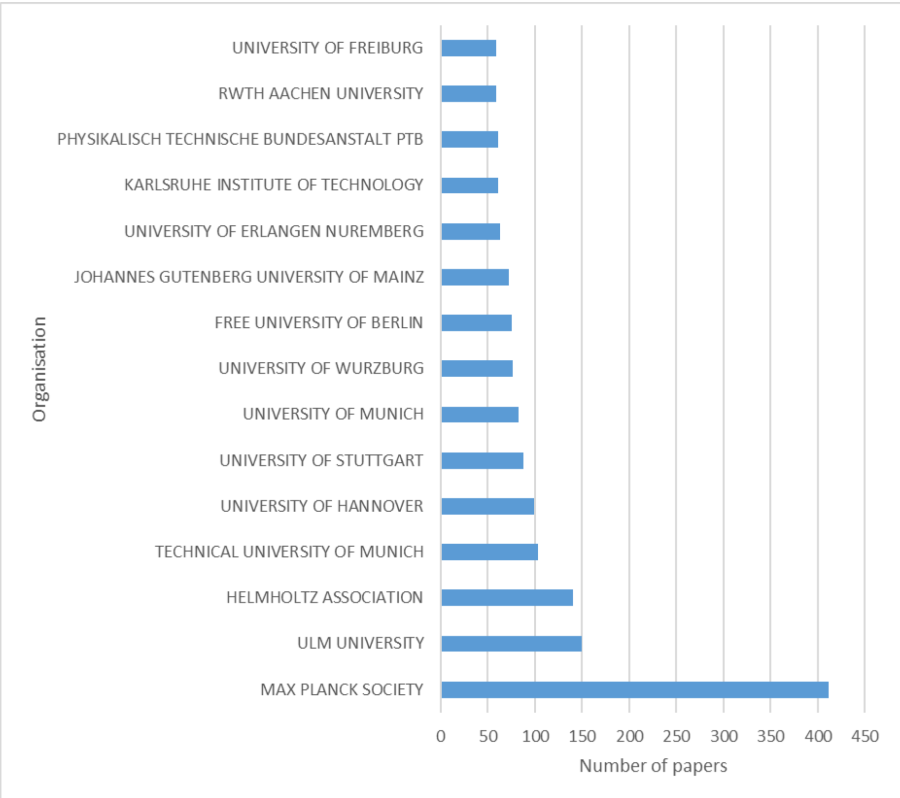


Figure 14. Organisations in Germany with the most papers published between 2012 and 2016 (database: online version)

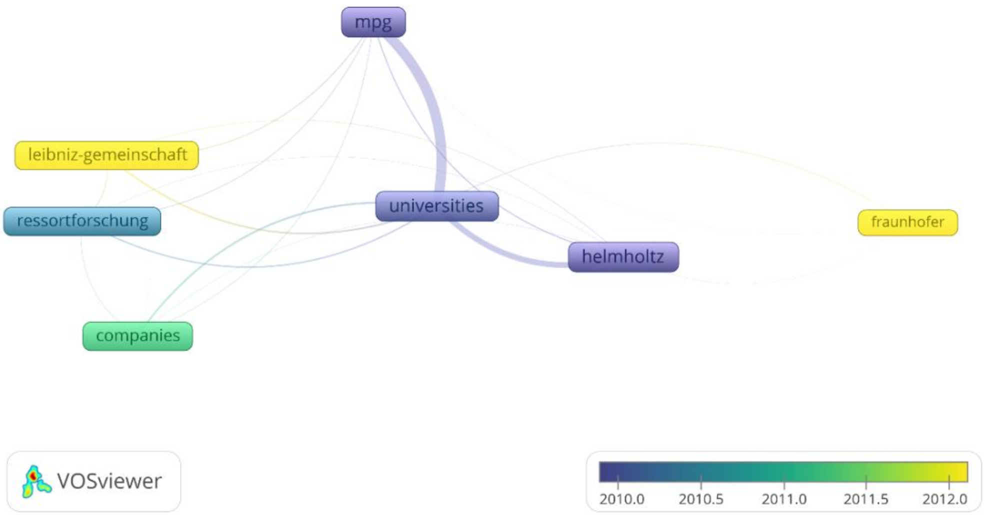


Figure 15. Cooperation network between non-university research organisations, universities, "Ressortforschung" (governmental research institutes), and companies in Germany. The colour indicates the average publication year of the organisation-specific papers (published between 2000 and 2016) (database: in-house version).

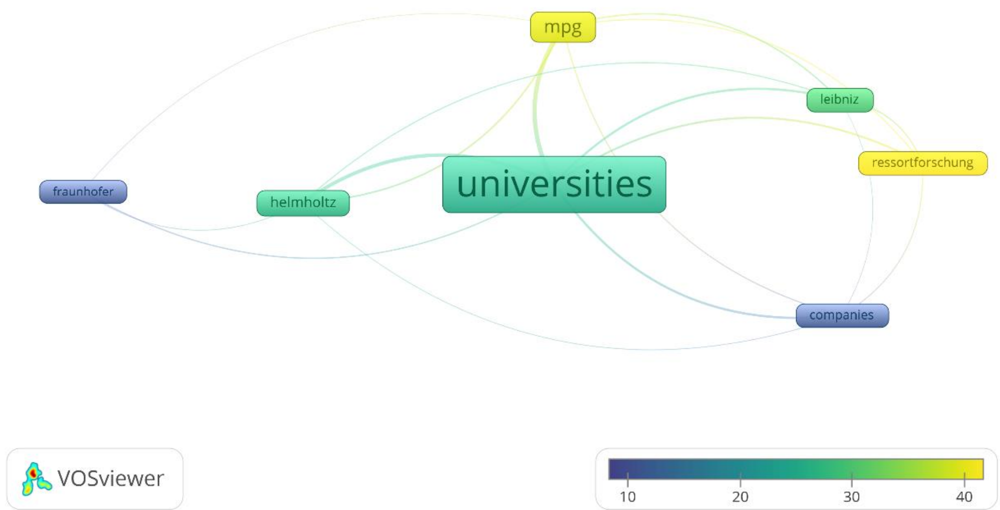


Figure 16. Cooperation network between non-university research organisations, universities, "Ressortforschung" (governmental research institutes), and companies in Germany. The colour indicates the average citation rate of the organization-specific papers (papers published between 2012 and 2016) (database: in-house version).

As Figure 13 shows, in the period from 2000–2016, most of the publications published in Germany in the field of quantum technology came from the following research organisations in descending order: The MPG (1002) leads by a large margin. This is followed by Helmholtz Association (HGF, 285), Ludwig-Maximilians-University Munich (LMU, 285), the University of Ulm (251), the University of Erlangen-Nurnberg (228), TU Munich (202), the University of Hanover (192), the University of Wurzburg (191), and the University of Stuttgart (190). In the period from 2012 to 2016 (Figure 14), most of the publications published in Germany in the field of quantum technology come from the following research organisations: the MPG (411) leads by a large margin. This is followed by the University of Ulm (150), HGF (140), TU Munich (103), the University of Hannover (99), the University of Stuttgart (88), LMU (83), the University of Wurzburg (77), the Free University of Berlin (76), the University of Mainz (72), the University of Erlangen-Nurnberg (63), KIT (61), and Physikalisch-Technische Bundesanstalt (National Metrology Institute of Germany, PTB, 61).

Looking at the collaboration between the stakeholders mentioned here in the period from 2000–2016 (Figure 15), all non-university research organisations (MPG, HGF, Leibniz Association, and Fraunhofer Society) cooperate with the universities. Collaborations with companies are still weakly developed. The frame colour indicates the average publication year of the respective stakeholders. Stakeholders coloured dark blue have been publishing in this area for longer than organisations coloured yellow. Under the collective term company, most publications are cumulated with EADS Deutschland (17), Menlo Systems (8), Bruker (8), ADVA Optical Networking (5), Infineon Technologies (5), Siemens (4), Carl Zeiss (4), Philips Deutschland (4), and Kayser-Threde GmbH (4). Looking at the collaboration between the various stakeholders in the period from 2012–2016 (Figure 16), all non-university research organisations cooperate with the universities. Collaborations with companies also are weakly developed. Here, the colour indicates the average citation rate for the publications of the respective stakeholders. Dark blue coloured stakeholders show an average citation rate of about 10 per publication; yellow coloured stakeholders show an average citation rate of 40 or more. The MPG and governmental research institutes (especially the PTB) show very high citation rates.

Figure 17 shows the network of co-authorships between the research organisations in Germany in the field of quantum technology in the period from 2000 to 2016. The size of the circles indicates the number of collaborations; the colour indicates the average publication year of the organisation-specific publications. Organisations coloured dark blue have been publishing in this area for longer than organisations coloured yellow. The map clearly shows the most active research organisations identified in Figure 13.

Figure 18 shows the same network as Figure 17 with a restriction to the period from 2012–2016. Bodies with at least five publications in the period were taken into account. The map clearly shows the most active research organisations identified in Figure 14. Here, the colour indicates the average citation rate for the publications of the respective organisations. Bodies coloured in dark blue show an average citation rate of 10 or less; bodies coloured in yellow show a citation rate of 30 or more.

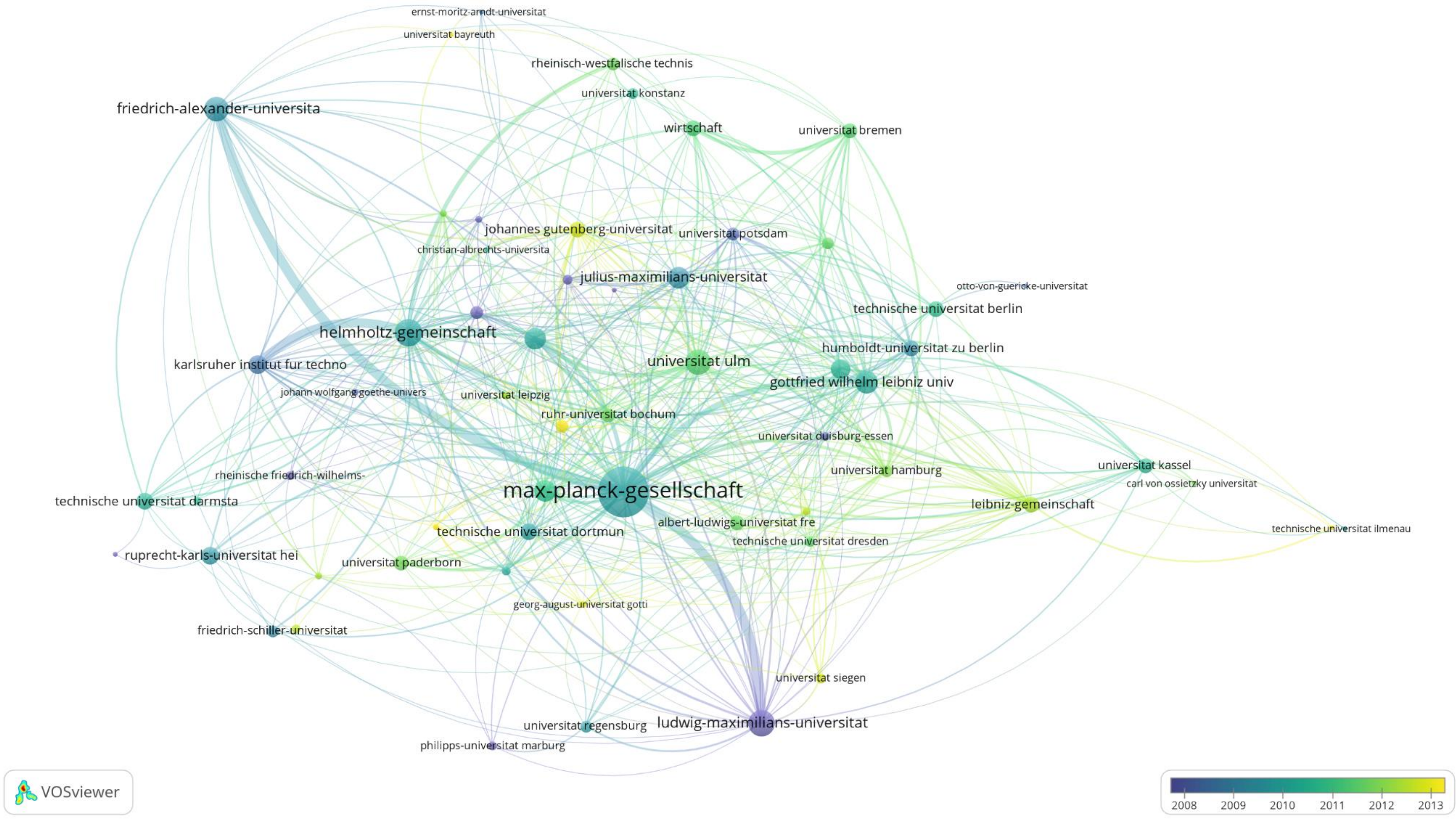


Figure 17. Co-authorships between institutions in Germany. The colour indicates the average publication year of the organisation-specific papers. Each institution has published at least five papers (papers published between 2000 and 2016) (database: online version).

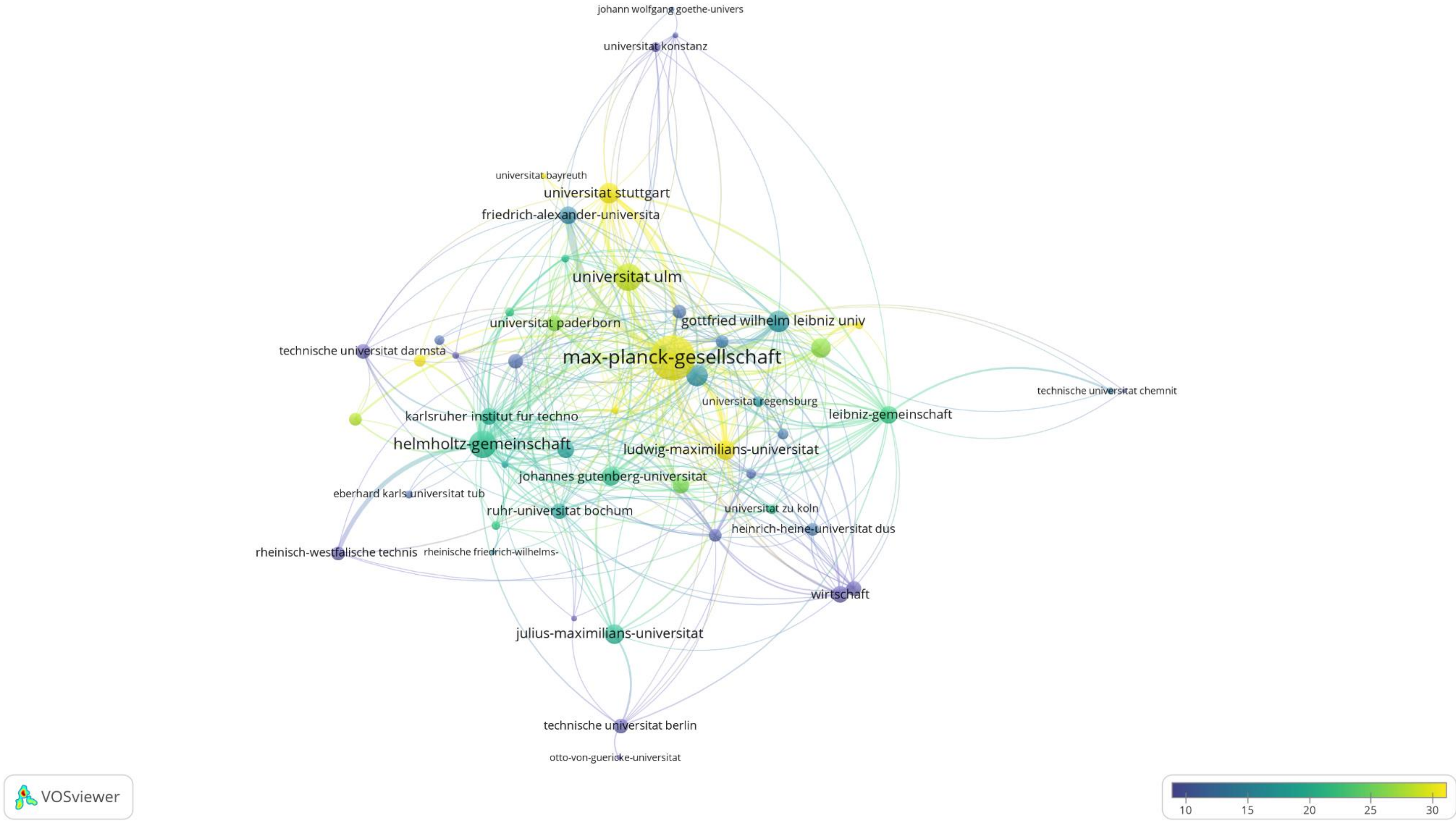


Figure 18. Co-authorships between institutions in Germany. The colour indicates the average citation rate of the institutional papers. Each institution has published at least five papers (papers published between 2012 and 2016) (database: online version).

This is followed by bibliometric analyses on various sub-areas of quantum technology.

**Results on quantum computing**

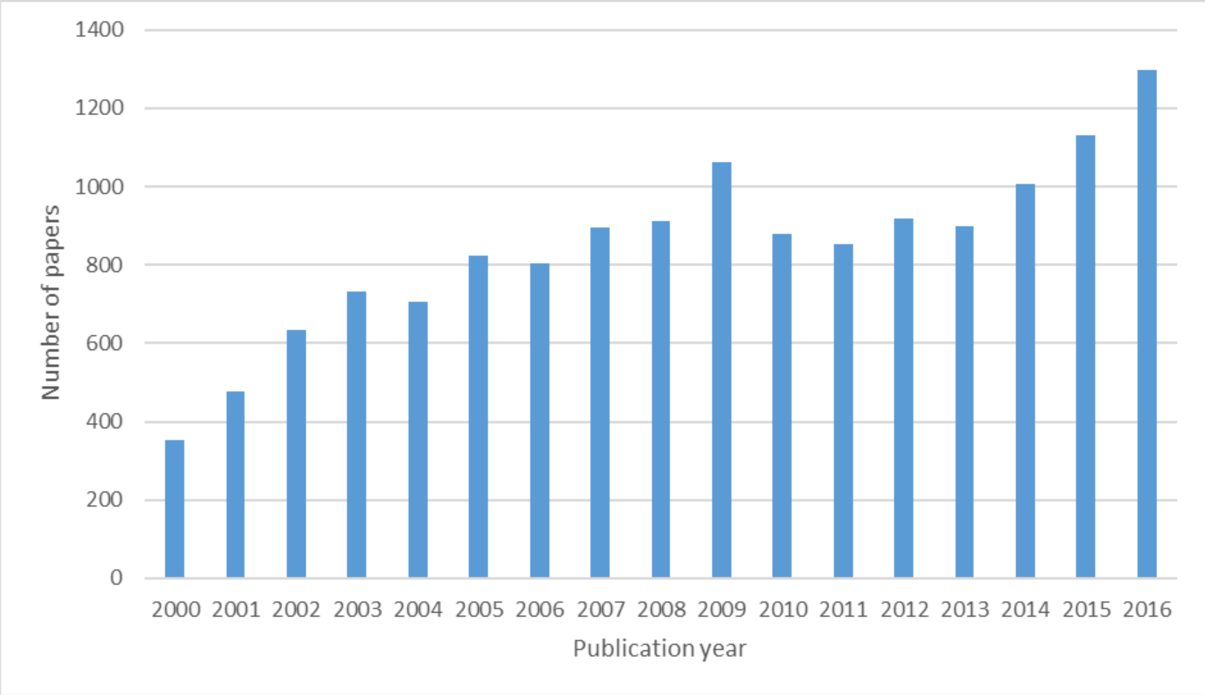


Figure 19. Number of papers published between 2000 and 2016 in quantum computing (database: online version)

Figure 19 shows the annual number of papers in quantum computing published between 2000 and 2016.

Figure 21 names the most active publishing research organisations worldwide for the period from 2012–2016. As the most active organisation in Germany, the MPG ranks 11th internationally in this respect.

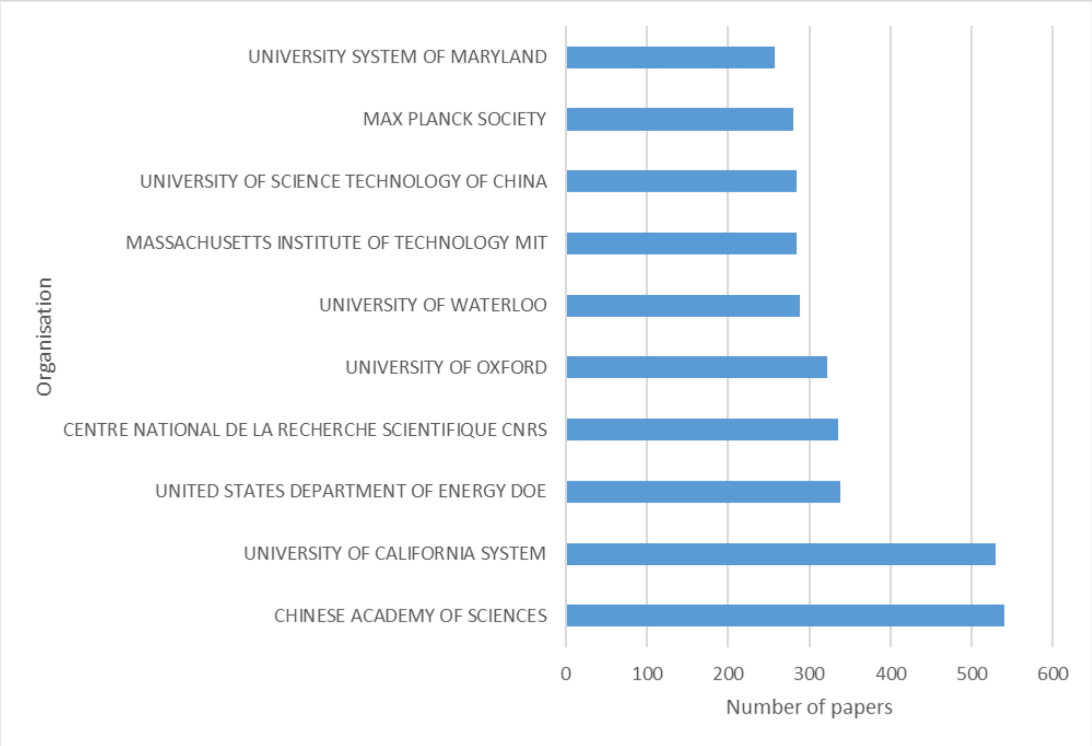


Figure 20. Organisations with the most papers published between 2000 and 2016 in quantum computing (database: online version)

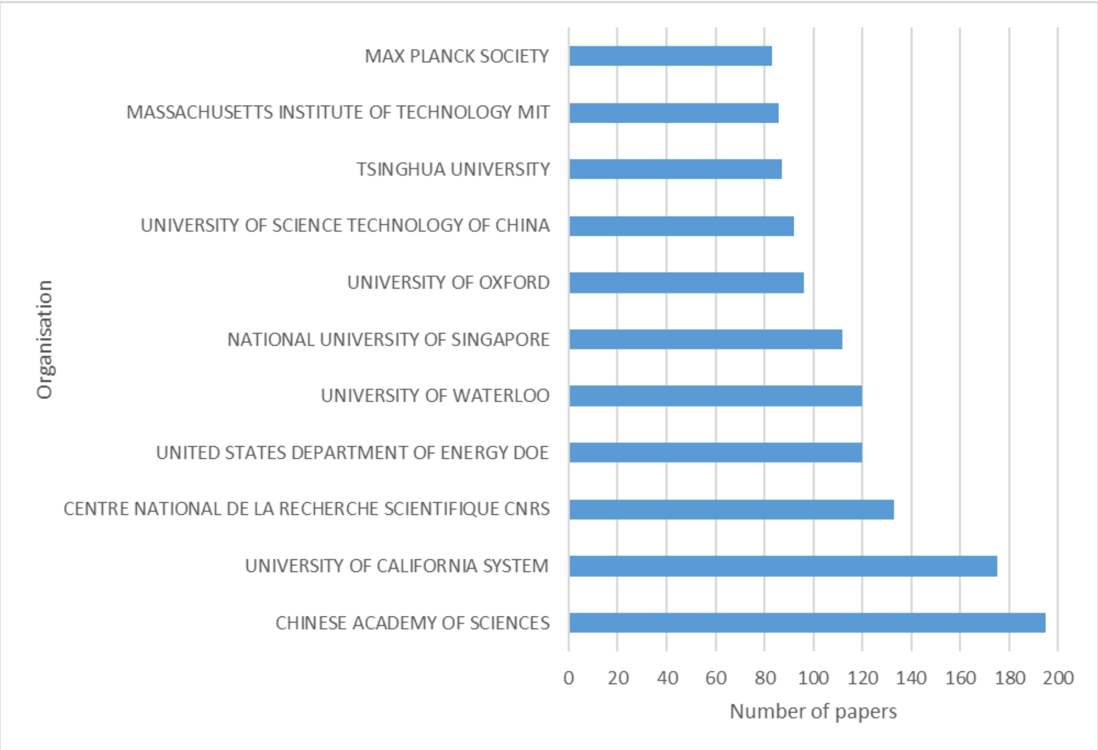


Figure 21. Organisations with the most papers published between 2012 and 2016 in quantum computing (database: online version)

**Results on quantum cryptography**

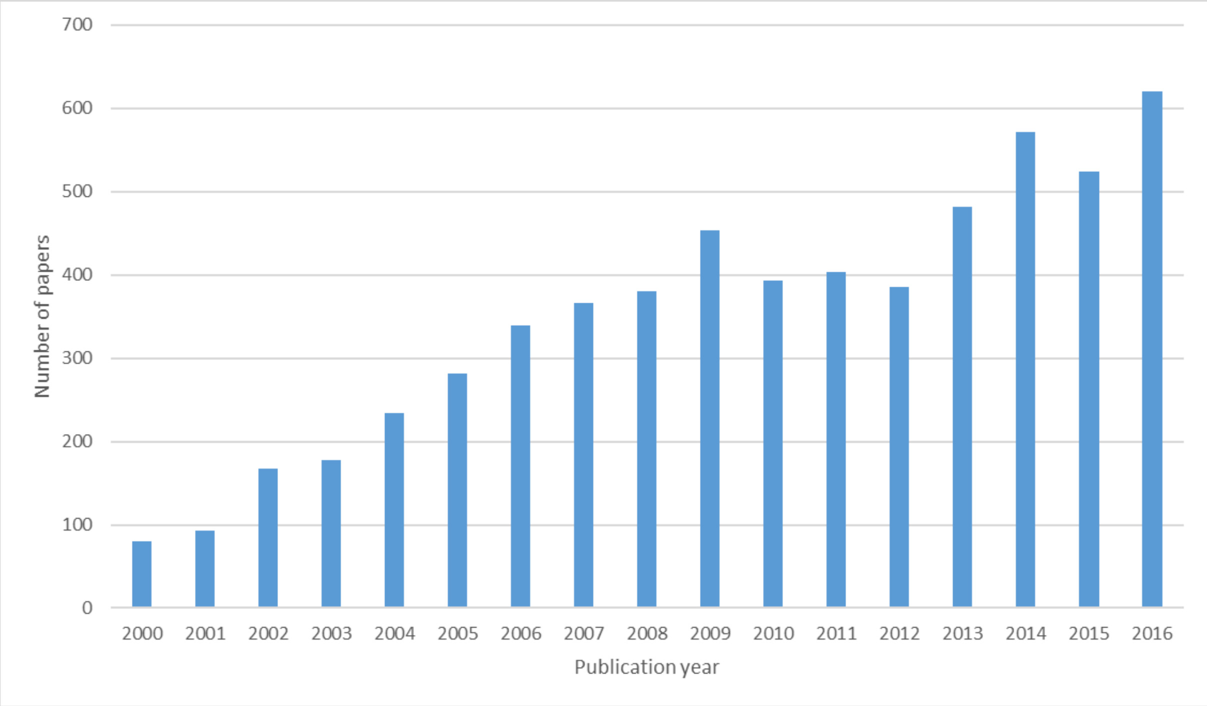


Figure 22. Number of papers published between 2000 and 2016 in quantum cryptography (database: online version)

Figure 22 shows the annual number of papers in quantum cryptography published between 2000 and 2016.

Figure 24 names the 10 most active publishing research organisations worldwide for the period from 2012–2016. Six organisations from China are represented here in the first through fourth as well as the ninth and tenth places. As the most active German organisation, the MPG ranks eighth internationally and is almost on par with the CNRS.

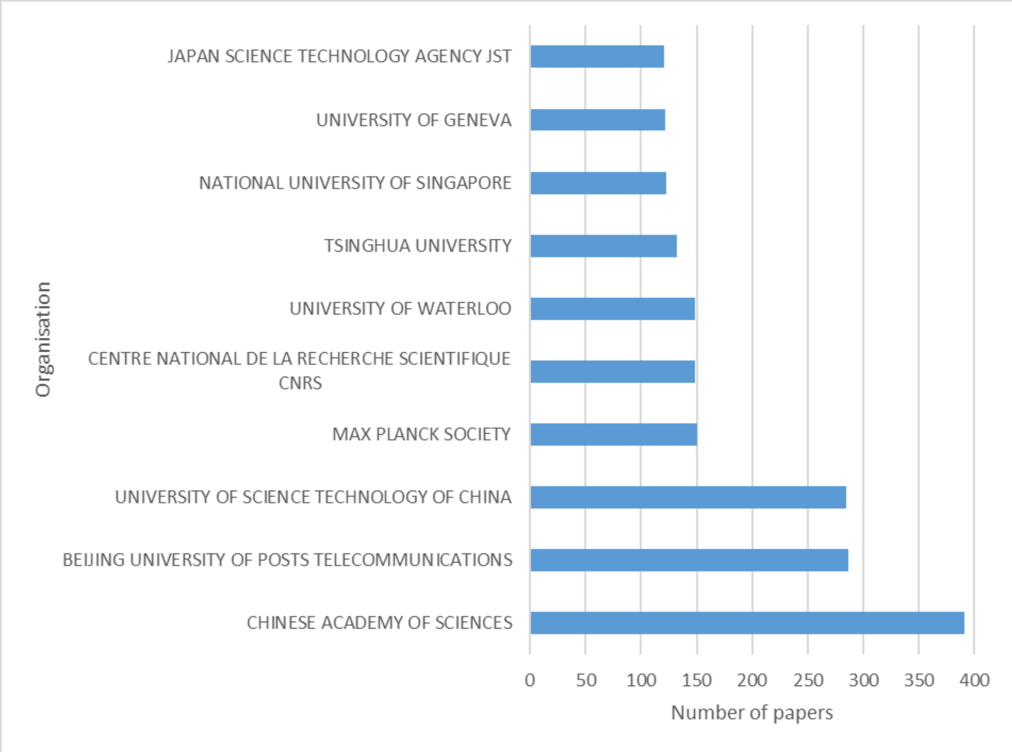


Figure 23. Organisations with the most papers published between 2000 and 2016 in quantum cryptography (database: online version)

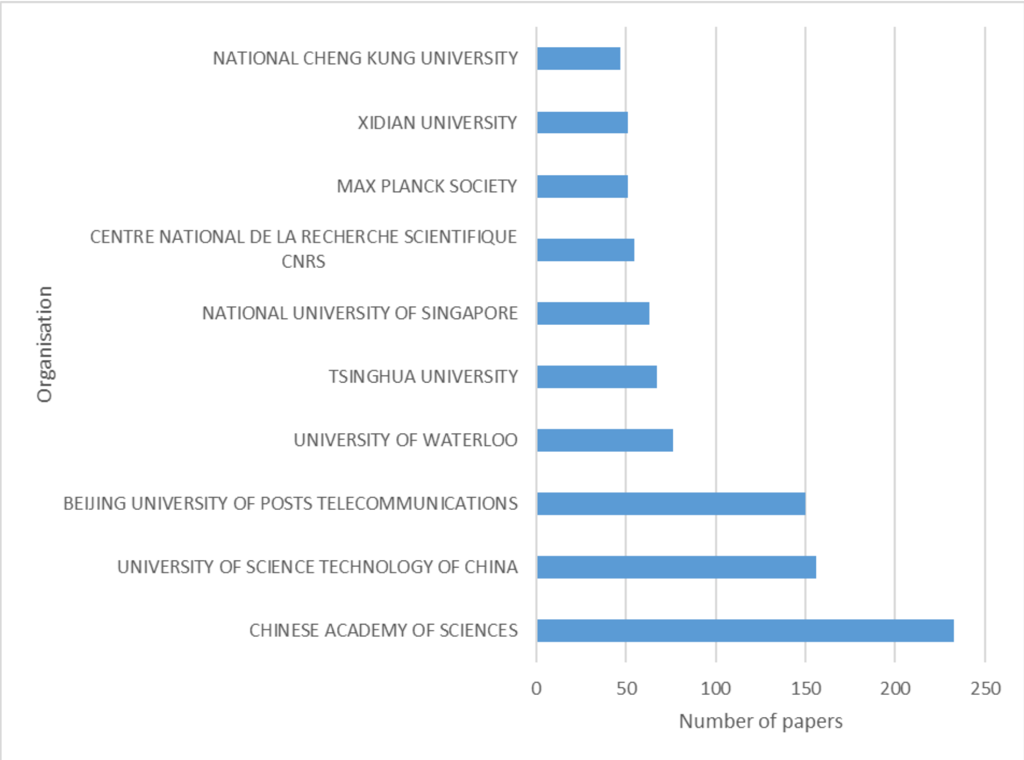


Figure 24. Organisations with the most papers published between 2012 and 2016 in quantum cryptography (database: online version)

**Results on other subfields in quantum technology (annual number of papers)**

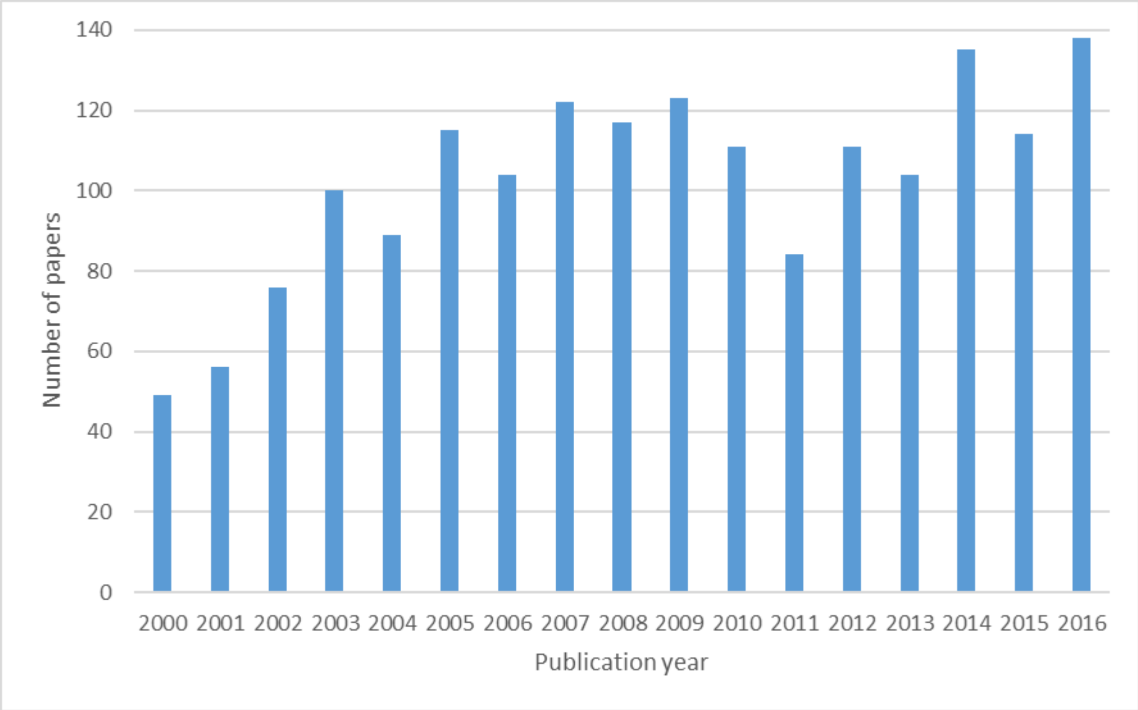


Figure 25. Number of papers published between 2000 and 2016 in quantum algorithms (database: online version)

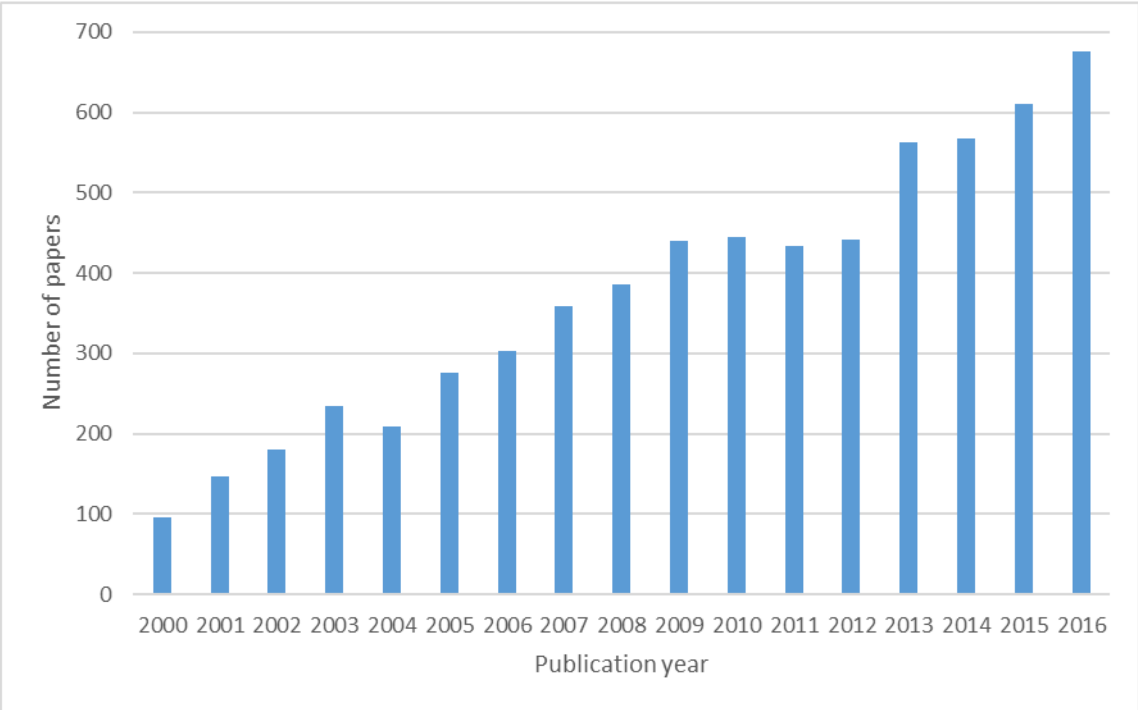


Figure 26. Number of papers published between 2000 and 2016 in quantum communication and networking (database: online version)

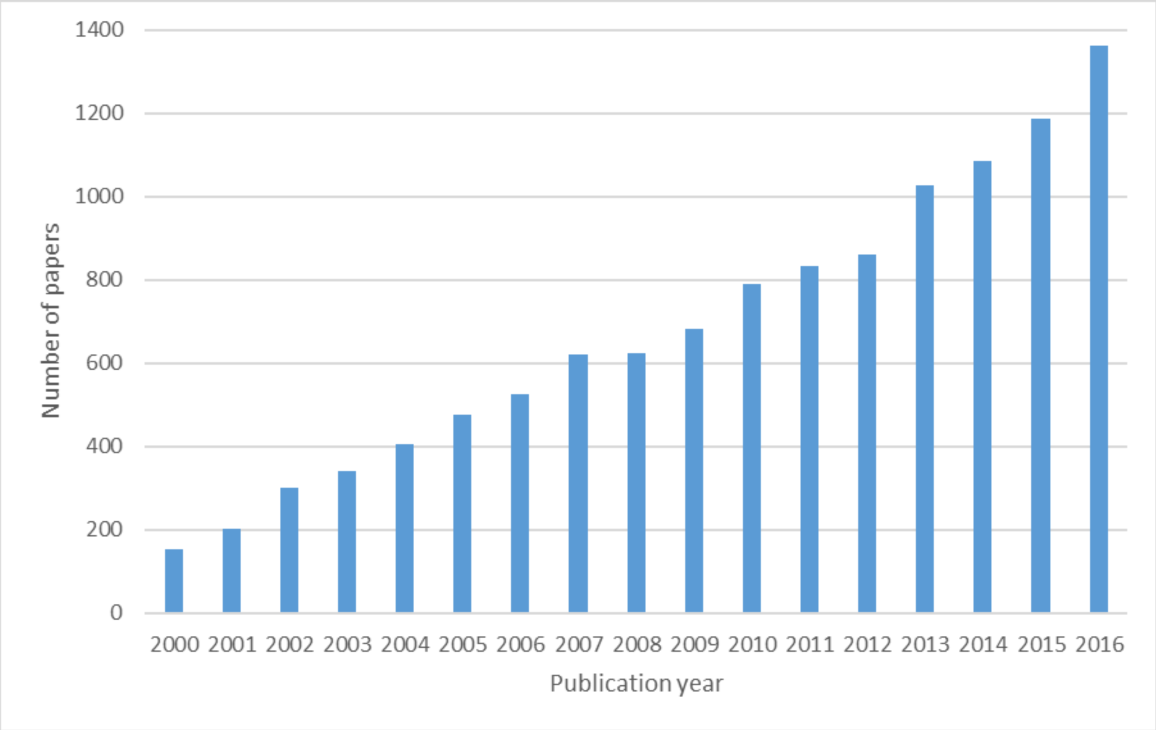


Figure 27. Number of papers published between 2000 and 2016 in quantum information science (database: online version)

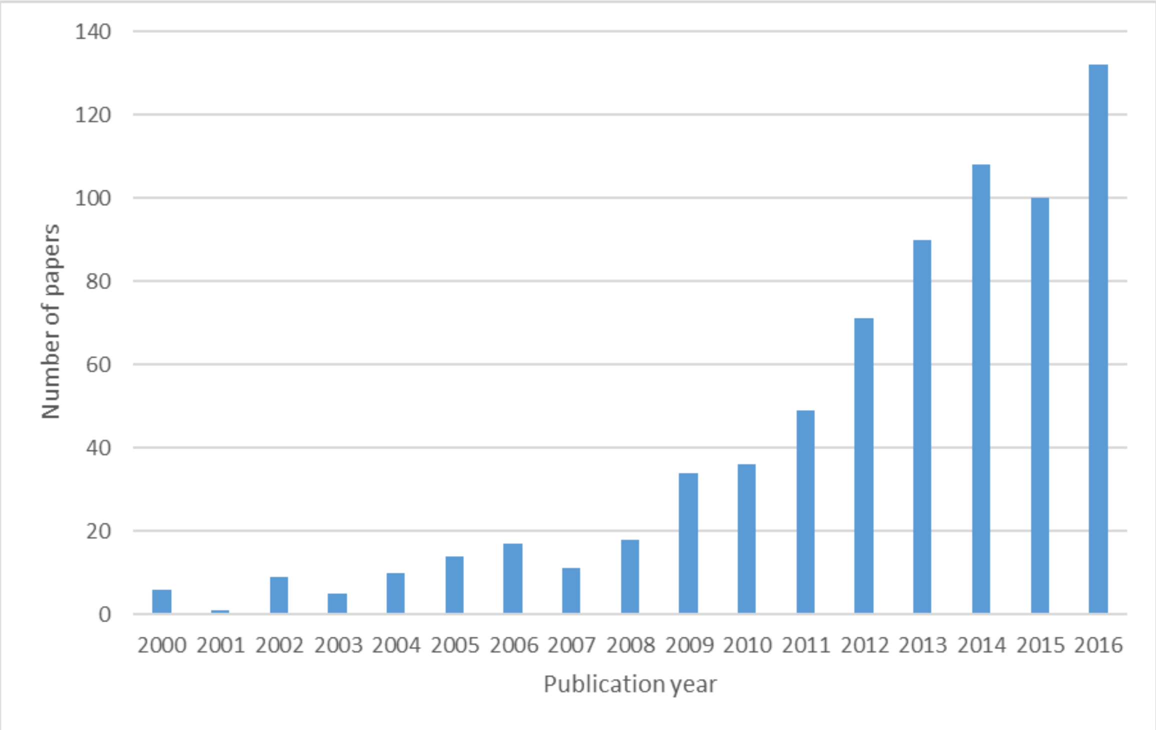


Figure 28. Number of papers published between 2000 and 2016 in quantum simulation (database: online version)

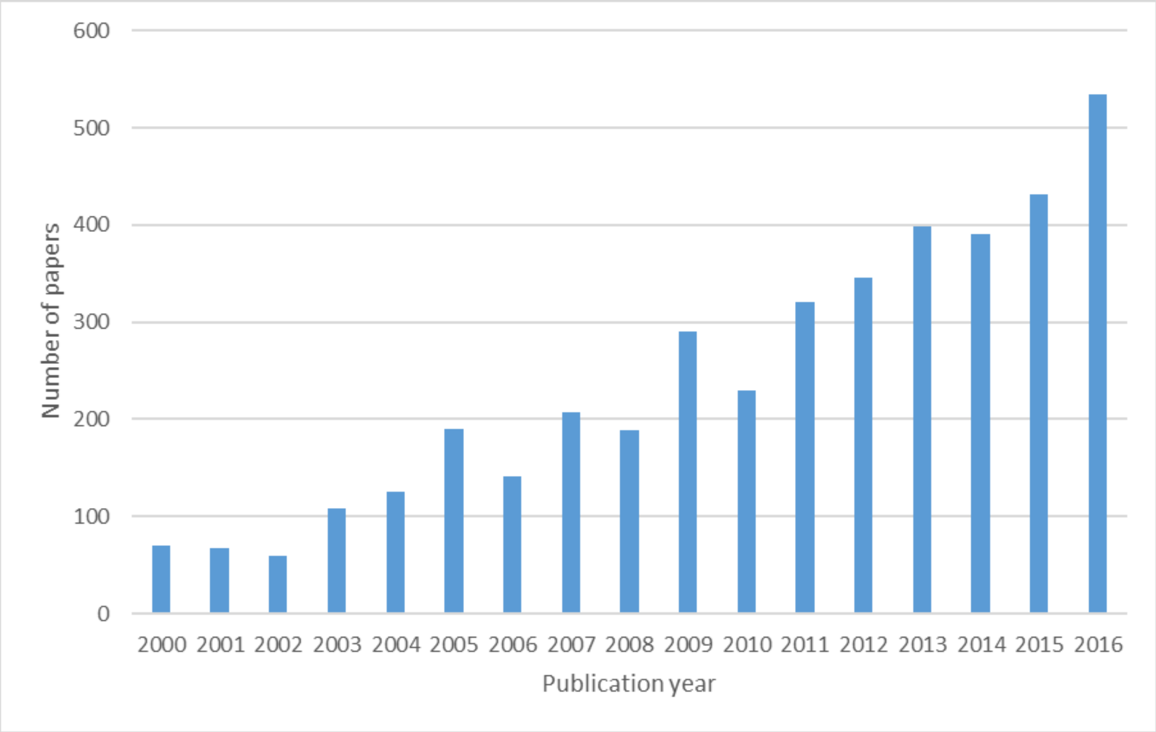


Figure 29. Number of papers published between 2000 and 2016 in quantum metrology (database: online version)

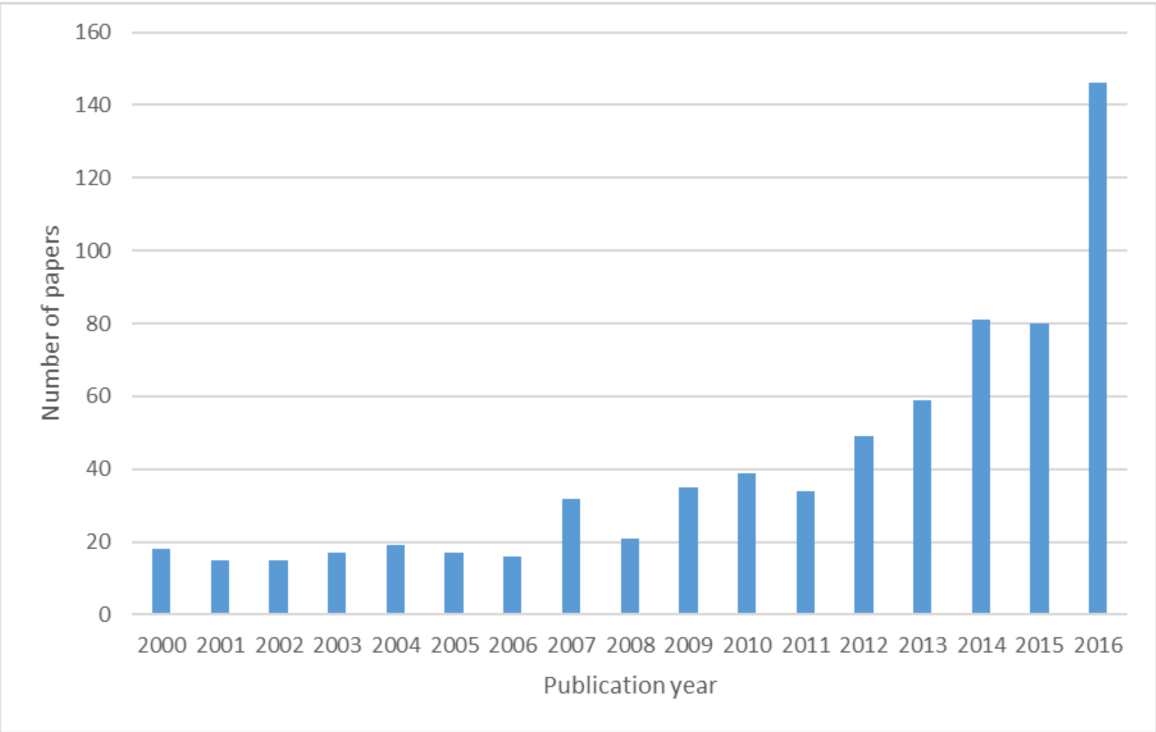


Figure 30. Number of papers published between 2000 and 2016 in quantum sensing (database: online version)

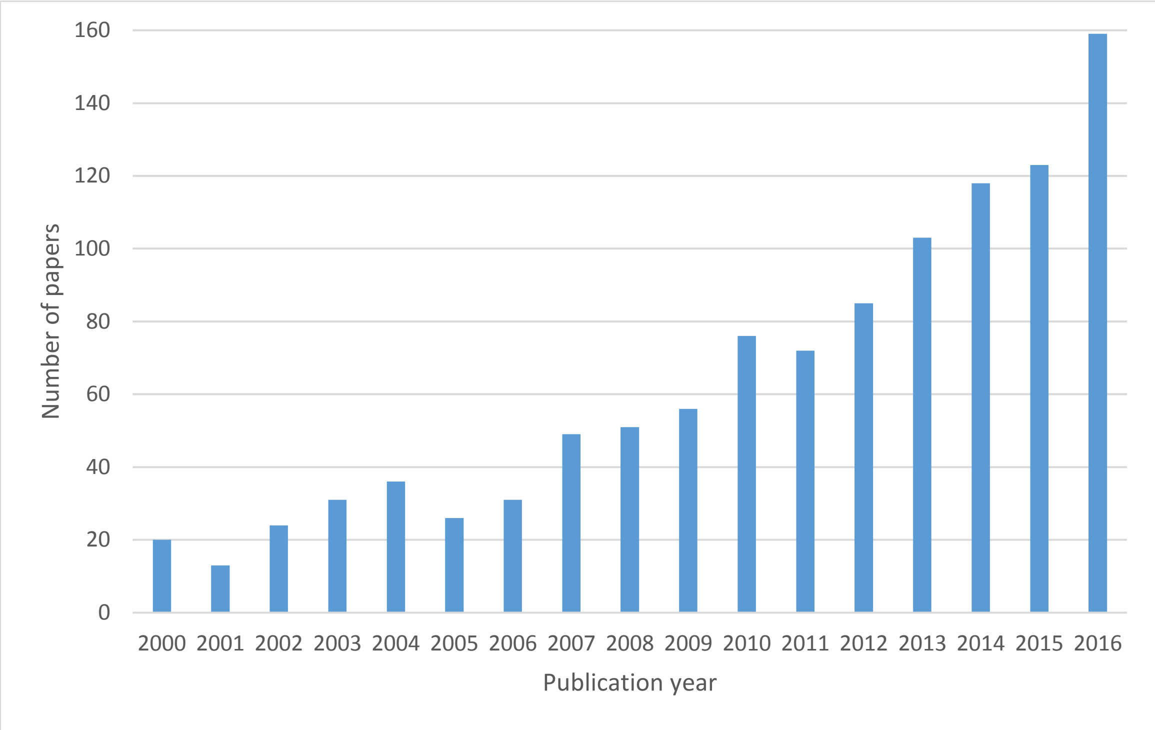


Figure 31. Number of papers published between 2000 and 2016 in quantum imaging (database: online version)

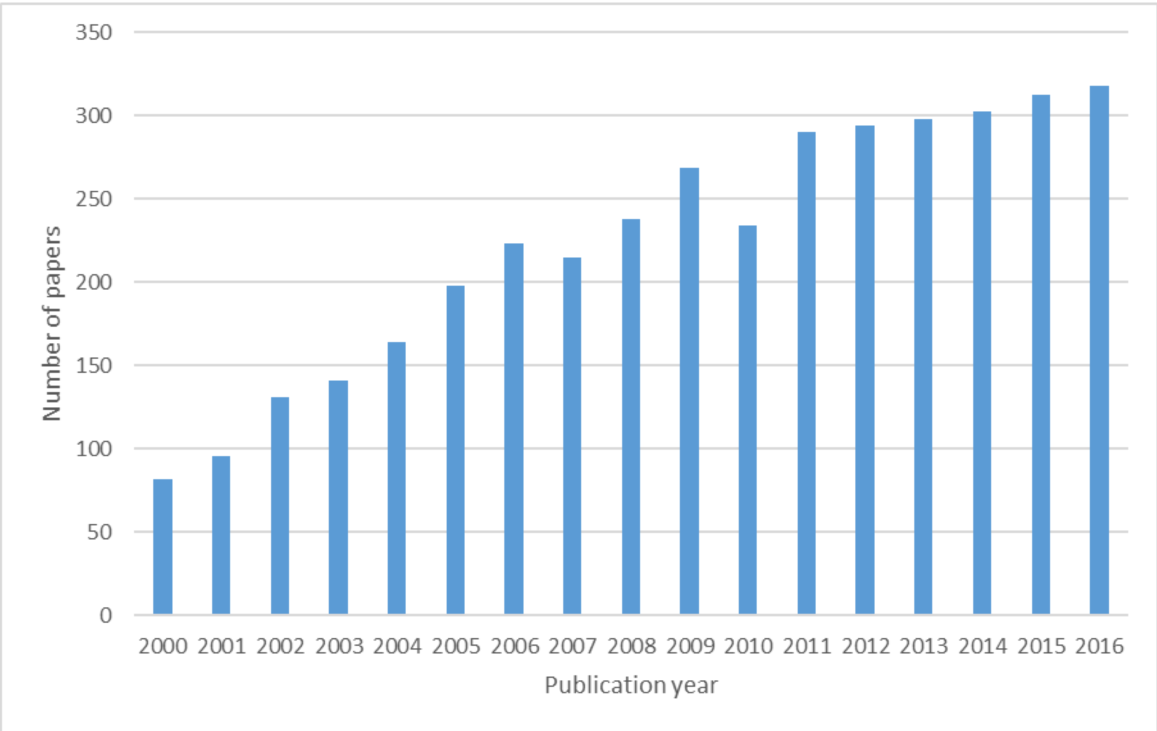


Figure 32. Number of papers published between 2000 and 2016 in quantum control (database: online version)

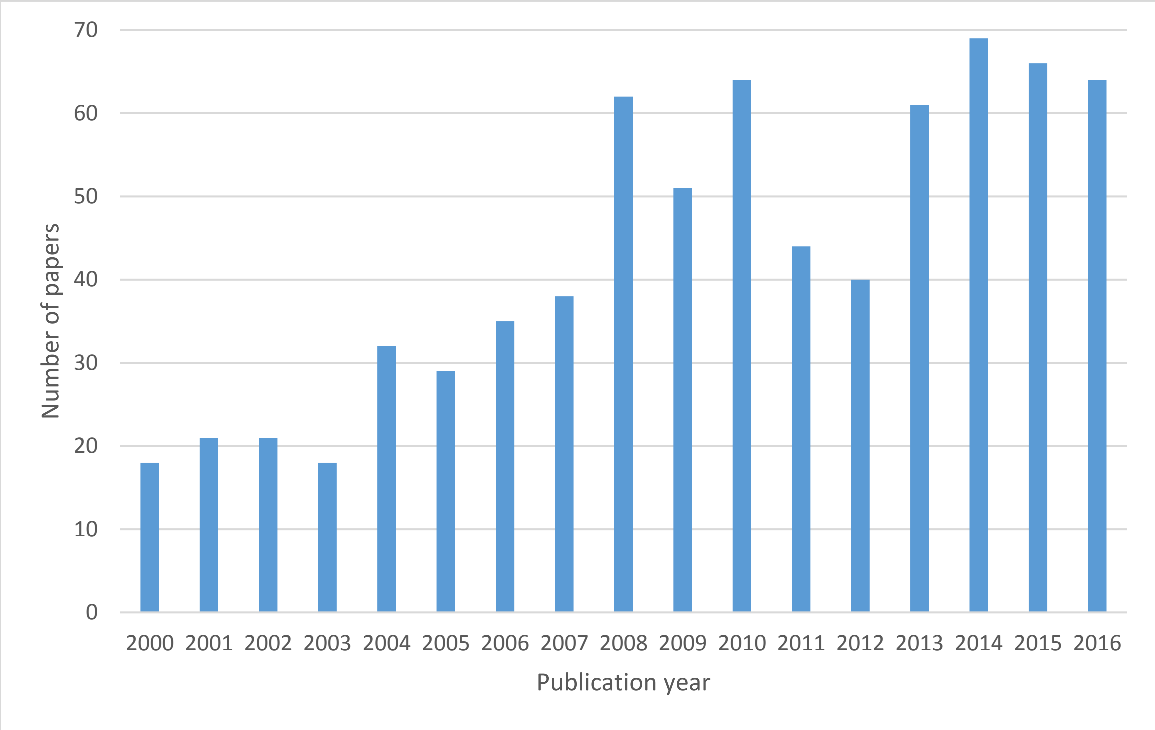


Figure 33. Number of papers published between 2000 and 2016 in quantum software (database: online version)

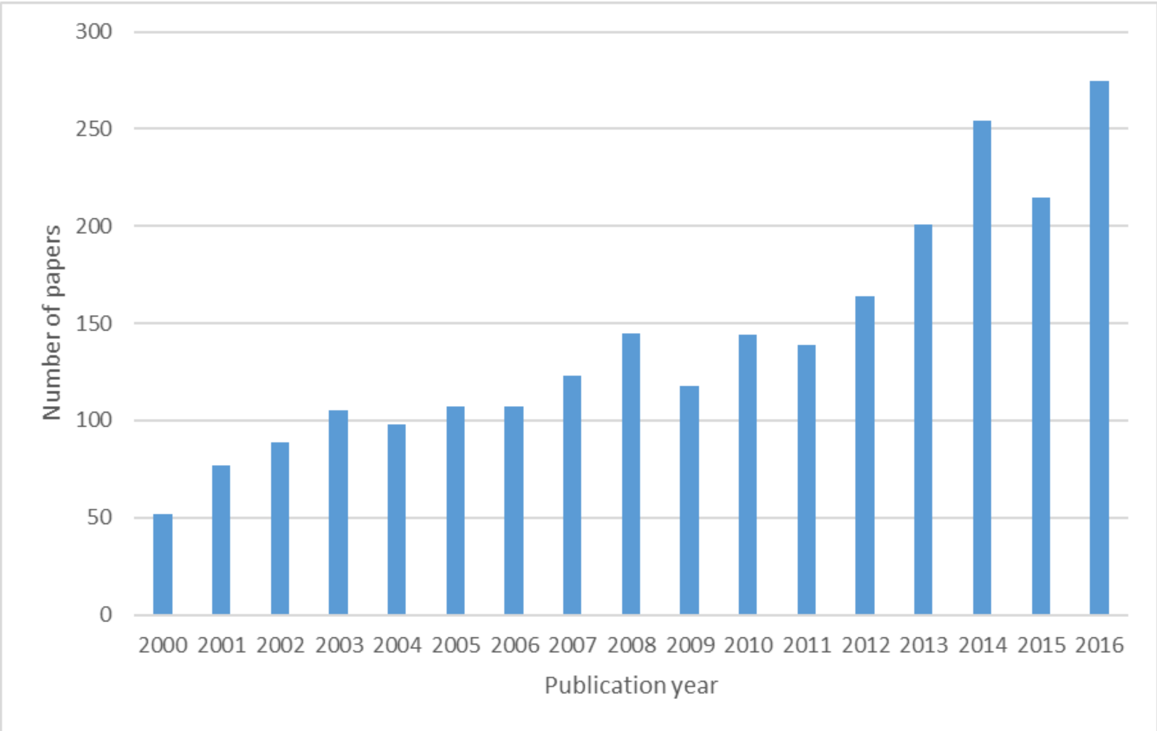


Figure 34. Number of papers published between 2000 and 2016 in quantum hardware systems (database: online version)

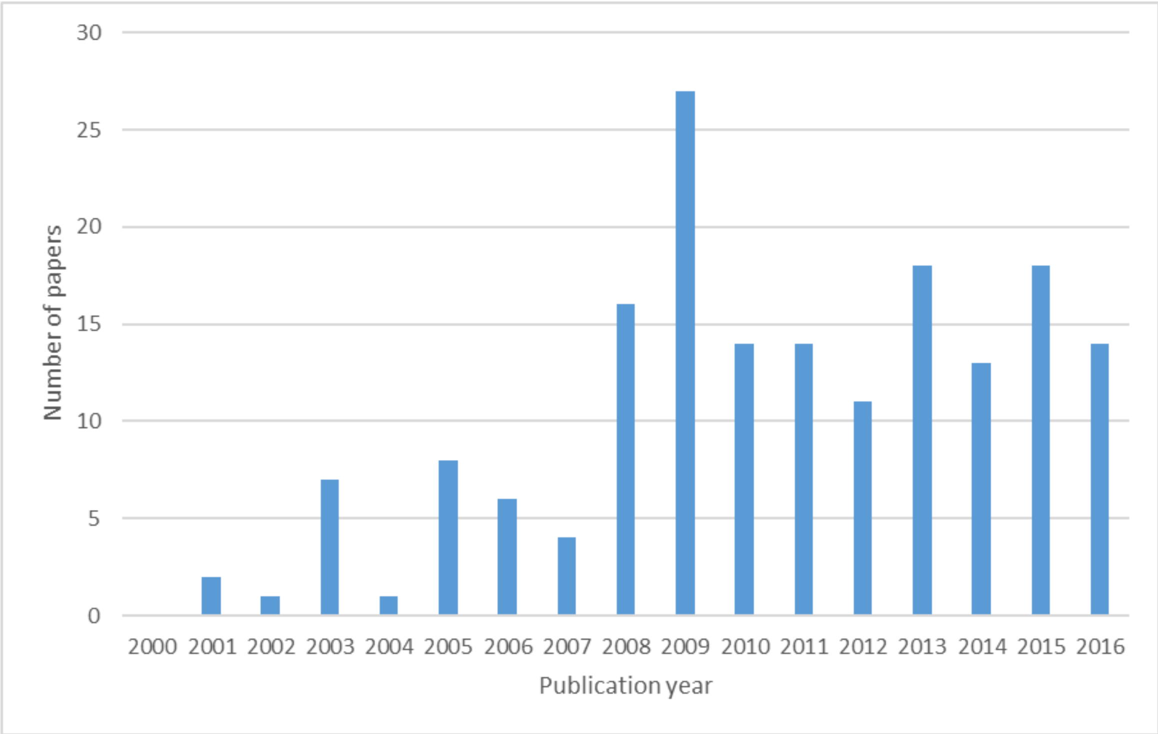


Figure 35. Number of papers published between 2000 and 2016 in quantum theory related to qubits (database: online version)

## References


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# Appendix

The following search strings are separate topic searches for the different fields of quantum technology:

# 1 Quantum technology (in general)

```
ts=(quantum NEAR/2 technolog*)
```

# 2 Quantum computing

```
ts=("quantum comput*" OR "quantum supremacy" OR "quantum error
correction" OR "quantum annealer" OR (quantum NEAR/2 (automata
OR automaton)) OR "quantum clon* machine*")
```

# 3 Quantum algorithms

```
ts="quantum algorithm*"
```

# 4 Quantum communication and networking

```
ts=("quantum communication*" OR "quantum network*" OR "quantum
optical communication" OR "quantum state transmission*" OR (
("quantum memor*" OR "quantum storage*") NEAR/5 photon*) OR
"quantum repeater*" OR "quantum internet" OR ("quantum
teleport*" AND ("qubit*" OR "quantum bit*" OR "entangle*")))
```

# 5 Quantum cryptography

```
ts=("quantum crypto*" OR pqcrypto* OR "quantum key
distribution" OR "quantum encrypt*" OR ( ("quantum secur*" OR
"quantum secre*") NOT ("quantum secreted" OR "quantum
secretion") ))
```

# 6 Quantum information science

```
ts=("quantum information*" OR "von Neumann mutual information"
OR "quantum mutual information" OR "quantum fisher
information")
```

# 7 Quantum simulation

```
ts=("quantum simulat*" AND (qubit* OR "quantum bit*" OR
"quantum comput*") OR "quantum simulator*" ) OR (ts="quantum
simulat*" AND wc=(quantum science technology OR computer
science theory methods))
```

# 8 Quantum metrology

```
ts=( (quantum NEAR/10 metrology) OR (quantum NEAR/1
tomograph*) OR "atomic clock*" OR "ion clock*" OR "quantum
clock*" OR "quantum gravimeter*")
```

# 9 Quantum sensing

```
ts=( (Quantum NEAR/1 Sensing) OR (Quantum near/1 Sensor*) )
```

# 10 Quantum imaging

```
ts=(("quantum imag*") OR "ghost imag*")
```

# 11 Quantum control

```
ts=("quantum control*" OR "control* of quantum" OR "control
over quantum" OR "quantum optimal control" OR "quantum state
control" OR "control* quantum" OR "control* the quantum" OR
"quantum coherent control")
```

# 12 Quantum software

```
ts=("quantum software" OR "quantum cod*" OR "quantum
program*")
```

# 13 Quantum hardware systems

```
ts=("quantum hardware" OR "quantum device*" OR "quantum
circuit" OR "quantum processor*" OR "quantum register*")
```

# 14 Quantum theory in relation to qubits

```
ts=("quantum theory" same (qubit* OR "quantum bit*"))
```

The following search string combines the separate topic searches for the different fields of quantum technology:

```
ts=("quantum theory" SAME (qubit* OR "quantum bit*")) OR
ts=("quantum hardware" OR "quantum device*" OR "quantum
circuit" OR "quantum processor*" OR "quantum register*") OR
ts=("quantum software" OR "quantum cod*" OR "quantum
program*") OR ts=("quantum control*" OR "control* of quantum"
OR "control over quantum" OR "quantum optimal control" OR
"quantum state control" OR "control* quantum" OR "control* the
quantum" OR "quantum coherent control") OR ts=(("quantum
imag*") OR "ghost imag*") OR ts=( (quantum NEAR/1 sensing) OR
(quantum NEAR/1 sensor*) ) OR ts=( (quantum NEAR/10 metrology)
OR (quantum NEAR/1 tomograph*) OR "atomic clock*" OR "ion
clock*" OR "quantum clock*" OR "quantum gravimeter*") OR
ts=("quantum simulat*" AND (qubit* OR "quantum bit*" OR
"quantum comput*") OR "quantum simulator*" ) OR (ts="quantum
simulat*" AND wc=("quantum science technology" OR "computer
science theory methods")) OR ts=("quantum information*" OR
```

```
"von Neumann mutual information" OR "quantum mutual
information" OR "quantum Fisher information") OR ts=("quantum
crypto*" OR pqcrypto* OR "quantum key distribution" OR
"quantum encrypt*" OR ( ("quantum secur*" OR "quantum secre*")
NOT ("quantum secreted" OR "quantum secretion") )) OR
ts=("quantum communication*" OR "quantum network*" OR "quantum
optical communication" OR "quantum state transmission*" OR (
("quantum memor*" OR "quantum storage*") NEAR/5 photon*) OR
"quantum repeater*" OR "quantum internet" OR ("quantum
teleport*" AND ("qubit*" OR "quantum bit*" OR "entangle*")))
OR ts="quantum algorithm*" OR ts=("quantum comput*" OR
"quantum supremacy" OR "quantum error correction" OR "quantum
annealer" OR (quantum NEAR/2 (automata OR automaton)) OR
"quantum clon* machine*") OR ts=(quantum NEAR/2 technolog*)
```