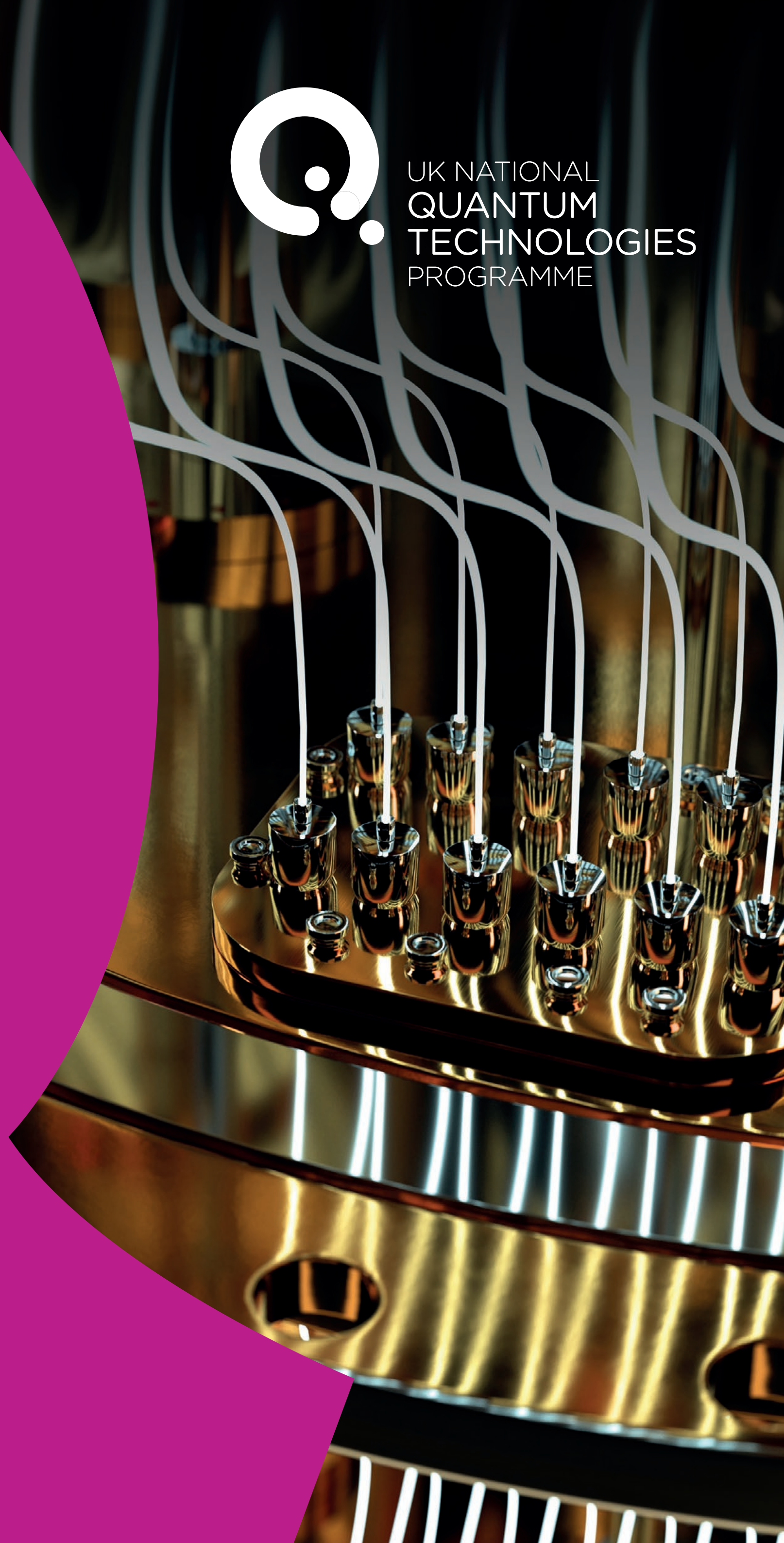
Quantum Computing & Simulation Hub

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

International State of Quantum Information Technologies Research

Part 1: UK, EU Frameworks, France, Germany, Austria, Denmark, Finland, Netherlands, Poland, Spain, Sweden & Switzerland.



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This report was authored by Christopher Noble, Dr Keith Norman and Adi Sheward-Himpson under the guidance of the QCS Hub Leadership team.

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UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Contents

Introduction

International research in quantum computers has developed rapidly over the last decade, with many countries investing heavily to support the development of quantum technologies.

This report is the first of two reports that summarise global activity in quantum technology. It presents a snapshot of activities across Europe, focusing on governmental and large-scale groupings and activities.

The report shows the scale of activity, and the growing involvement and maturity of the industrial sector. Research Hubs are a common feature of many of the programmes across Europe, showing the continued relevance of rigorous academic research to the mission of developing Quantum Technologies for real-world applications. There are also emerging procurement based programmes, with National Centres acting as customers for first machines, and of course a growing number of efforts that use the commercially available services available through the cloud. Within all these activities there is a high degree of connectivity between nations, with a large number of jointly authored papers, MOUs between states, and trans-national projects.

I am delighted to see this report bring together an overview of the state of quantum computing research in the UK and Europe. I hope it will be a source of encouragement for those active in quantum computing research, and a reinforcement of the need to commit to this research at a national and a global level.

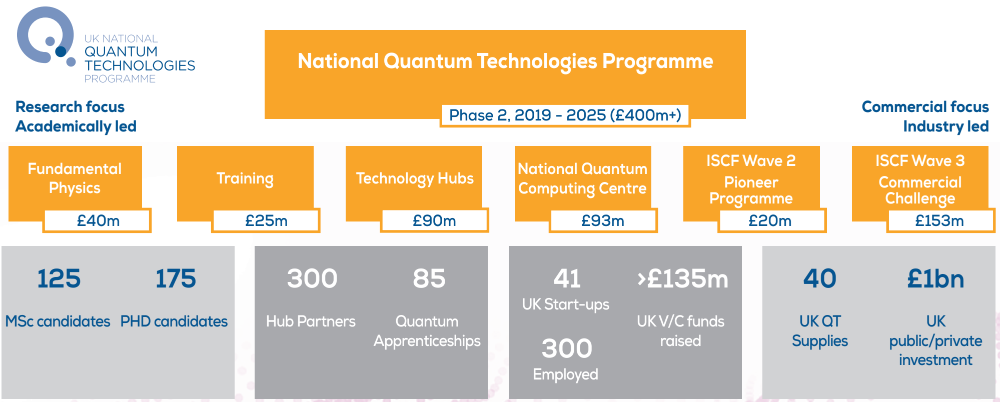
Professor Dominic O'Brien
Director, Quantum Computing and Simulation Hub

United Kingdom

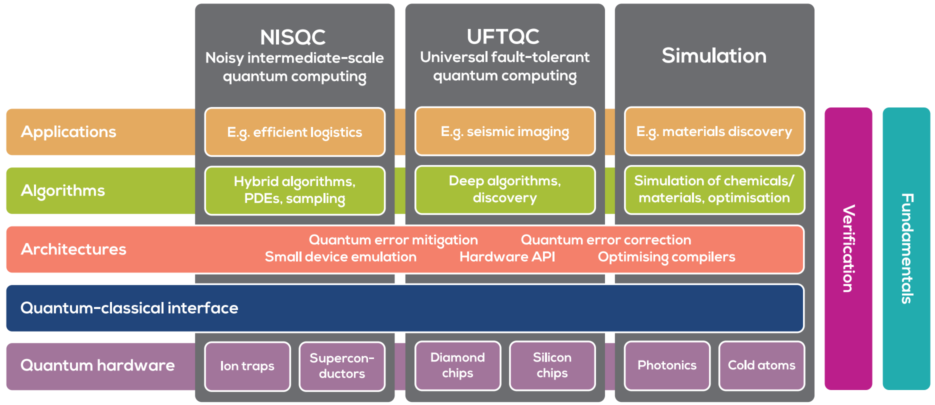
The UK was one of the first countries to initiate a formal national programme in quantum technologies. In 2013, then UK Chancellor George Osbourne made a "commitment to invest in quantum technology" in his Autumn Statement [1], which translated into an initial £270m investment to create a UK National Quantum Technologies Programme (NQTP) [2]. This ultimately grew to £380m over a five-year period, from 2014-19, and included nearly £13m of private funding.

This 'Phase 1' of the UK's national programme included a funding call for dedicated quantum research centres for communications, computing, imaging, sensing, and measurement, leading to four hubs involving close to thirty universities [2] [3]. One of these hubs was Networked Quantum Information Technologies (NQIT), involving nine UK universities, and with the support and engagement of over thirty companies. Some of the achievements of the NQIT Hub in this time include a photonically-connected ion trap architecture with world-leading fidelity, the high-performance emulator QuEST, and the generation of seven spinout companies, such as OQC and Universal Quantum. Separately, there were three skills hubs focussing on training and manpower: Quantum Engineering and Science, Quantum Enterprise, and Innovation in Quantum Business.

The UK programme is sponsored by the UK Department for Business, Energy and Industrial Strategy (BEIS), EPSRC, UKRI, Dstl, GCHQ, KTN, STFC and the MoD), and also supports work at the UK National Physical Laboratory and the Fraunhofer Centre for Applied Photonics.



The National Quantum Technologies Programme is now in its second phase, which includes a £94m refresh of the four technology Hubs funded by the EPSRC [5]. The technology hub for quantum computing, NQIT, evolved into the Quantum Computing and Simulation Hub, made up of seventeen leading UK universities, and with scientific research spanning the full stack of hardware and software.



UK Quantum Computing and Simulation Hub

Research that the QCS Hub is involved with includes:

- Implementation of ion trap processors, and development of next generation ion traps
- Superconducting gate improvements, and new schemes for annealing
- Diamond Nitrogen vacancy related technologies
- Photonic simulators
- Silicon quantum logic using commercial CMOS
- Cold atom systems for quantum simulation
- Verification, validation and benchmarking of the technologies available in the Hub
- Architectural and control studies, using the technologies available in the Hub, and simulation of technology platforms using QUEST
- Algorithm development for Machine Learning and solving partial differential equations
- Industrial applications
- Fundamental studies of non-classical systems

The national programme now also includes the National Quantum Computing Centre, launched by the then Science Minister Amanda Solloway at London Tech week in 2020, [6]. Based at the Harwell Science Campus in Oxfordshire, the NQCC is a £93m investment by UKRI over 5 years [7], with the facility due for completion in 2023 [8]. The NQCC's strategic intent includes the creation of a UK sovereign capability, which will catalyse the UK supply chain in the sector.

Some notable activities for NQCC since its foundation include the signing of a Memorandum of Understanding with the QCS Hub, a collaboration with OQC [10], and the launch of its SparQ Applications Discovery Programme [11]. It has also published a Quantum Readiness Survey in conjunction with EY. This survey found that 81% of senior UK executives expect quantum computing to play a significant role in their industry by 2030 [12].

Outside of this, a new Hartree National Centre for Digital Innovation was announced in June 2021. Quantum computing forms part of a wider programme to enable UK businesses to explore and adopt innovative digital technologies. UKRI will invest £172 million in the centre over five years, with an additional £38 million in-kind contribution from IBM [13].

Separately, the related Quantum Communications Hub has made major contributions to quantum networking, which is likely to be an enabling technology for QIT. In consortium with BT and Toshiba Europe Ltd, the Quantum Communications Hub has implemented an extended quantum network from Cambridge Science Park to BT's Research and Innovation Labs Campus [ref : https://www.quantumcommshub.net/industry-government-media/collaboration-opportunities/case-studies/bt/]

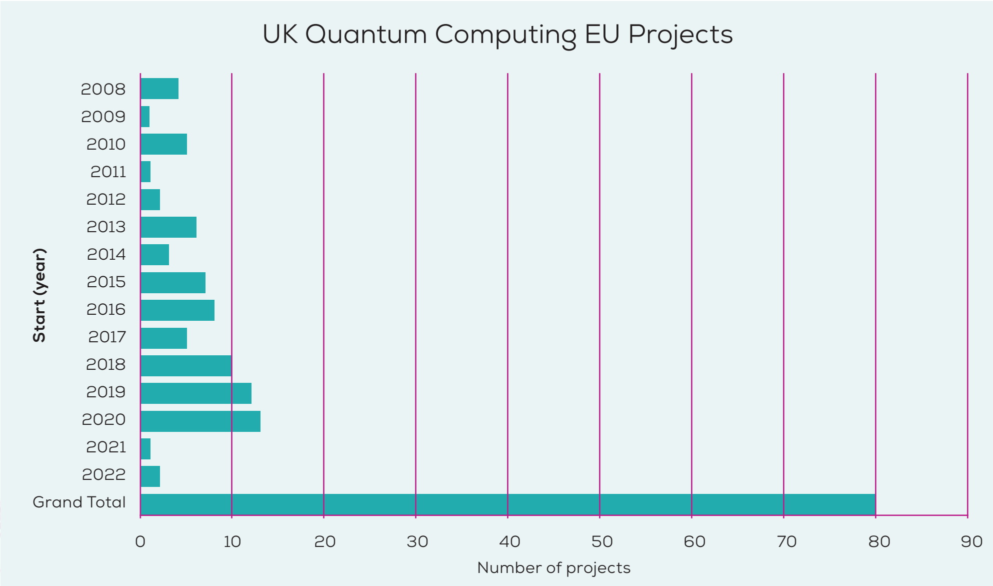
Innovate UK have also run and Quantum Commercialisation Challenge, investing £153 million, supported by £205 million from industry, to develop new products and technologies based on advances in quantum science [ref: https://www.ukri.org/what-we-offer/our-main-funds/industrial-strategy-challenge-fund/artificial-intelligence-and-data-economy/commercialising-quantum-technologies-challenge/].

Collaborations

European Union

The UK has had significant involvement in projects funded by European Union (EU) mechanisms, primarily through the FP7 and Horizon 2020 funding programmes – these are covered in more depth in the following EU section in this report. The terms of UK involvement in the EU's latest funding programme, Horizon Europe, were agreed in December 2020, however this association has not been finalised [14].The UK government has since launched the Horizon Europe guarantee, with the last legal grant signature date before the end of December 2022. [14] In the event of being unable to associate, the UK has set out its alternative, which includes funds for bottom-up collaborations with researchers in partner countries around the globe, multilateral and bilateral collaborations, and continued funding for UK researchers to join Horizon Europe consortia as third country participants [15].

We have analysed the UK involvement in EU quantum computing projects – We have analysed the UK involvement in EU quantum computing projects, covering activity in both FP7 and Horizon 2020. 80 projects were funded in total, one of the highest such figures in Europe, with the projects' start dates distributed as shown.



United States

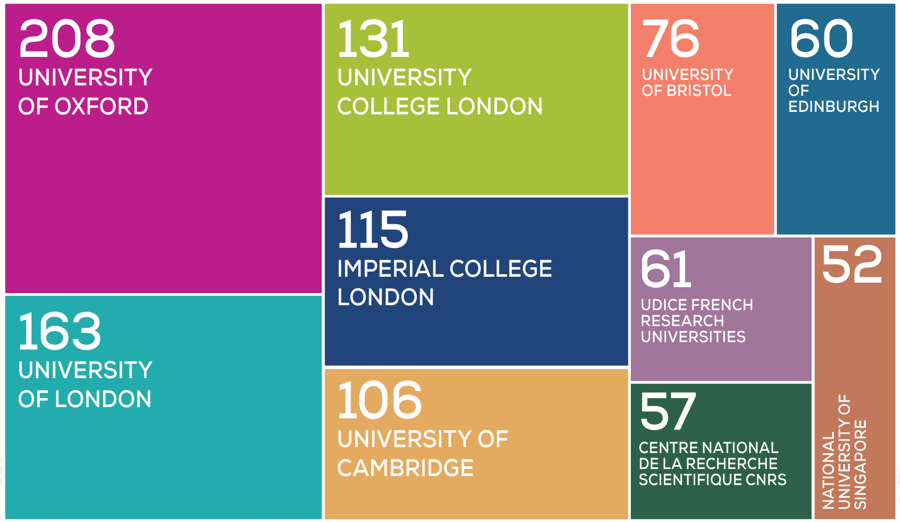
A joint statement between the UK and the USA was published in November 2021, with the intent of enhancing cooperation on quantum information science and technology. The joint statement facilitates continued collaboration between the US National Institute of Standards and Technology and the UK National Physical Laboratory. Furthermore, an enhanced partnership between the US National Science Foundation and UKRI is intended to enable additional collaboration on research in QIS. [16]

Grants and Publications

The report will now examine UK grants and publications relating to QIT. In this analysis, and elsewhere in this report, we have used a standard search terminology as follows: "`quantum computing`" OR "`quantum computation`" OR "`quantum computer`" OR "`quantum error`" OR "`quantum circuit`" OR "`quantum simulation`" OR "`quantum architecture`" OR "`quantum compile`" OR "`quantum software`".

In July 2022, we analysed active UKRI grants encompassing research grants, studentships and CR&D Bilaterals. In terms of an overall count of participant involvement (at an institutional level), the UK's top collaborators are USA (65), Germany (24), Canada (16), Switzerland (14, primarily through IBM Research GmbH), Japan (12), France (9) and Australia (8).

Through Clarivate's Web of Science, we analysed papers published from 2018 onwards, where some or all of the authors were based in UK institutions. Note that UK author involvement in a paper does not mean the lead institution is UK based. A visualisation of the top ten funding bodies for these pieces of work, in terms of number of papers allocating their funder, is shown below – UKRI/EPSRC funding dominates, along with funding from European sources. There is also activity from Australia, China and the USA.



1,113 papers involving UK authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of papers
PHYSICAL REVIEW A	99
PHYSICAL REVIEW LETTERS	63
PHYSICAL REVIEW RESEARCH	39
QUANTUM SCIENCE AND TECHNOLOGY	39
NEW JOURNAL OF PHYSICS	38
PHYSICAL REVIEW B	37
QUANTUM	33
NPJ QUANTUM INFORMATION	29
PRX QUANTUM	27
NATURE COMMUNICATIONS	25

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 600 times between them. The overall number of citations can provide an indication on the strength and scientific merit of the papers.

The number of citations on a country-by-country basis can provide an insight into levels of activity, as well as crosslinks and collaborations between the country in question and the originator of the paper. The USA tops the list, followed by the UK, and China, Germany and the Netherlands some distance behind.

Journal	Number of citations
Australia	21
Austria	9
Belgium	5
Brazil	2
Canada	5
China	34
Czech Republic	2
Denmark	11
Finland	1
France	3
Germany	32
Hungary	1
Iceland	1
Israel	3
Italy	9

Journal	Number of citations
Japan	12
Luxembourg	1
Malaysia	1
Mexico	2
Netherlands	31
Pakistan	2
Poland	5
Russia	2
Spain	11
Switzerland	8
Thailand	1
UK	163
USA	222
Grand Total	**600**

Again, note that a paper's lead author may be based outside of the UK, with one or more of the other named authors based at a UK institution. The lead author's institutional country for these fifty papers is shown.

Journal	Number of papers
Australia	1
Austria	1
China	2
Germany	2
Japan	3
Netherlands	4
Pakistan	1
Spain	1
UK	27
USA	8
Grand Total	**50**

European Union

A number of member states of the European Union (EU) are covered in more depth individually later in this report, however there has been a concerted effort by the EU as a whole which will be detailed here.

Quantum Flagship

The Quantum Flagship is the third large-scale research and innovation initiative of its kind, after the Graphene Flagship and the Human Brain Project. It is funded by the European Commission and consists of a set of research and innovation projects selected through a peer-review process. It started in October 2018. [17]

The Flagship has a budget of €1 billion and a duration of 10 years, and is designed to bring together research institutions, academia, industry, enterprises, and policy makers, in a joint and collaborative initiative. [18]

Quantum Flagship in a nutshell.

- 01 — **1b€** Quantum Technologies will be funded with at least one billion Euro by the European Commission
- 02 — **10+ yrs** Flagship's timescale
- 03 — **5000+** Researchers residing in all EU and associated countries
- 04 — **140** Research and Innovation Action (RIA) proposals of the first Quantum Flagship call

The Quantum Technologies Flagship conducts research and development activities in the key domains of quantum computing and simulation, quantum communication, and quantum sensing. Projects related to quantum computing and simulation in the Flagship are listed below.

Name	Description	Participants	Total Cost €
AQTION	Advanced Quantum computing with Trapped IONs. AQTION focuses on the scalability, availability, and Advanapplicability aspects of trapped-ion quantum computers, tackling the transition from current laboratory-based experiments to industry-grade quantum computing technologies.	The project consists of 7 academic partners – at the Universities of Innsbruck, Mainz, Oxford, and Complutense de Madrid, ETH Zurich, Forschungszentrum Jülich and Fraunhofer IOF – and 3 industrial partners, TOPTICA Photonics AG, Bull SAS, AKKA DSW GmbH.	9,588,000
NEASQC	NExt ApplicationS of Quantum Computing The goal is to prepare the next applications of quantum computing, bringing together academic experts and industrial end-users to investigate and develop a new breed of Quantum-enabled applications that can take advantage of NISQ (Noise Intermediate-Scale Quantum) systems in the near future.	Atos, (coordinator, France) AstraZeneca AB (Sweden) CESGA (Fundación Publica Gallega Centro Tecnológico de Supercomputación de Galicia (Spain) Electricité de France (EDF (France) HQS Quantum Simulations GmbH, (Germany) HSBC Bank Plc, (United Kingdom) Irish Centre for High-End Computing (ICHEC), Leiden University, through its Leiden Institute of Advanced Computer Science (Netherlands) TILDE SIA, (Latvia) TOTAL S.E (France) Universidade da Coruña – CITIC (Spain) VUniversité de Lorraine, through the LORIA lab) (France).	4,671,332.50
OpenSuperQ	An Open Superconducting Quantum Computer. The overall vision of the OpenSuperQ project is to build a hybrid high-performance open quantum computer of up to 100 qubits and to sustainably make it available at a central site for external users.	The project consists of ten partners across five European countries. Within Germany are Saarland University, EURICE (European Research and Project Office GmbH) and Forschungszentrum Jülich. Spain has the University of the Basque Country, whilst Sweden has Chalmers University of Technology and Low Noise Factory. Switzerland has both ETH Zurich and its spinout Zurich Instruments, whilst Finland has the VTT Technical Research Centre of Finland and Bluefors.	10,334,392.50

Name	Description	Participants	Total Cost €
QLSI	Quantum Large Scale Integration in Silicon The project aims to demonstrate that silicon spin qubits are a compelling platform for scaling to very large numbers of qubits.	CEA, TUD, CNRS, IMEC, TNO, Fraunhofer IPMS, Univ. of Copenhagen, UCL, Forschungszentrum Jülich, Univ. of Basel, Univ. of Twente, Hitachi, Univ. of Konstanz, IHP, ATOS, STMicrolectronics, Infineon Dresden, Quantum Motion, Soitec.	14,666,159
PASQuans	Programmable Atomic Large-Scale Quantum Simulation. A next generation platform for quantum simulation with cold atoms will be developed, with the goal to build the largest programmable quantum simulator, at more than 500 atoms.	Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. (Germany)Institut d'optique théorique et appliquée IOTA - SupOptique (France) Ruprecht-Karls-Universität Heidelberg (Germany) Centre national de la recherche scientifique CNRS (France), Österreichische Akademie der Wissenschaften (Austria), Università degli Studi di Padova (Italy), University of Strathclyde (United Kingdom) Freie Universität Berlin (Germany), My Cryo Firm (France) Bull SAS (France) Muquans (France) Azur Light Systems (France) TOPTICA Photonics AG (Germany) Forschungszentrum Jülich GmbH (Germany)	9,659,515

The European Commission has a Digital Decade strategy in place, the aim of which is for the EU to become digitally sovereign in an interconnected world. Quantum technologies are seen as a key element of this digital sovereignty, of global strategic importance.

The Flagship will contribute to world-leading quantum computers and simulators that will be ultimately acquired by the European High Performance Computing Joint Undertaking – a joint initiative between the EU, European countries and private partners to develop a world-leading supercomputing ecosystem in Europe. This is central to the Digital Decade goal of having a first computer with quantum acceleration by 2025, with a view to being at the cutting edge of quantum capabilities by 2030. [19] When examining international partnerships for the Digital Decade, quantum is listed as a potential area of collaboration, though it is worth noting that the European Flagship programme is partly based on an ambition to reduce or remove the dependency on the USA and China to meet the fundamental technological needs of European citizens and companies. [20]

A newly introduced "Coordination and Support Action" (CSA) called QUCATS (2022-2025) aims to strengthen the foundations of the Flagship and related initiatives, via maintenance and development of the strategy, and aiming to grow all quantum technologies. This is supported by €6.5m funding for 3 years by the European Commission.

Funding Mechanisms

The EU's most noticeable research and innovation funding programme is Horizon Europe, with a budget of €95.5 billion and due to run until 2027. It follows on from Horizon 2020, and the earlier Framework Programmes (FP) for Research and Technological Development. Quantum has featured increasingly in these programmes – of the UK's 80 EU quantum-related projects in FP7 and Horizon 2020, 58 were funded through the later Horizon 2020. In Horizon Europe, quantum features within Cluster 4 - Destination 4: Digital and Emerging Technologies for Competitiveness and Fit for the Green Deal. There is a clear link to the Quantum Flagship, being listed as its own topic in the destination, with the objective "to further develop quantum technologies and their applications in the areas of quantum computing, simulation, sensing and communication, in order to strengthen European technological sovereignty in this strategic field and achieve first-mover industry leadership." [21]

A prominent example of a programme receiving funding is QuantERA, which received funding through Horizon 2020. QuantERA is a European network of 39 research funding organisations from 31 countries, which supports research and innovation in quantum technologies. QuantERA also funds projects itself, to the level of €89M across 77 projects.

The Programme's goals are as follows:

- Successfully providing the European quantum community with Calls for Proposals in QT
- Promoting excellent research in QT
- Encouraging transnational collaborations in QT
- Networking research funders in QT
- Mapping national, regional & European public policies in QT
- Spreading research excellence across the European Research Area (ERA).

QuantERA aims to enhance cooperation between academia & industry, recently issuing guidance for the public sector engaging with industry. QuantERA cooperates with the European Quantum Technologies Flagship to bridge academic research with engineering endeavours, and joint efforts are directed towards speeding up knowledge and technology transfers. [23]

Non EU Institutions

There are several Europe-based intergovernmental institutions which are not part of the EU that have active Quantum Technology programmes, notably the European Space Agency (ESA) and CERN [ref https://home.cern/news/press-release/knowledge-sharing/cern-quantum-technology-initiative-unveils-strategic-roadmap]

France

In January 2021 France announced its Quantum Plan, a €1.8 billion investment over 5 years. French President Emmanuel Macron outlined two focus areas for the plan: "The first is global and integrated technological development, from fundamental research to industrialization. The second is the strengthening of the French innovation ecosystem in its European environment, in particular by developing human capital and by recruiting, training and attracting the best both in public research and in industry," [24]. A commitment of €1bn by the French government sees annual spending to rise from €60 million to €200 million, described at the time as putting France in third place in this metric after the United States and China. The remaining €800 million will come from commitments made by industrial players (€500 million), European funding (€200 million), and investors in the French startup ecosystem (€100 million) [24].

The plan allocates nearly €800 million to computers alone, divided into work on simulators and partially quantum machines (€350 million) and towards universal fault-tolerant devices (€430 million). The other funds will be devoted to sensors (€250 million), post-quantum cryptography (€150 million), quantum communications (€320 million) and related technologies which facilitate the development of quantum equipment (cryogenics, for example, €300 million) [25] [26]. As part of this plan, in January 2022 the creation of a new quantum computing platform was announced. The platform has a total budget of €170 million, and aims to make the technology accessible to as many people as possible, including the scientific community and French and EU start-ups. The intent is to ensure France does not miss out on the major advances quantum computing could make in the decades to come. [22] Secretary of State for Digital, Cédric O, remarked: "By mid-2022, we will open a procedure [...] for the purchase of two to three quantum hardware machines that are integrated into the platform."

In March 2022, ten selected projects were announced during the launch of the €150M Quantum Priority Research and Equipment Programme (PEPR) over 5 years. The Quantum PEPR is an acceleration programme, aiming at supporting research activity ranging from basic science to proofs of concept (TRL 1 to 4), and is co-driven by the French National Centre for Scientific Research (CNRS), the French Alternative Energies and Atomic Energy Commission (CEA), and the French National Institute for Research in Digital Science and Technology (INRIA) [27].

A selection of these relating to quantum computing are shown below:

The **PRESQUILE** project is to help identify and overcome the scientific and technological obstacles to integrating spin qubits within well-established CMOS technology.

The **RobustSuperQ** project aims to accelerate French R&D relating to superconducting and hybrid qubits protected against decoherence. In 5 years, the project should demonstrate a high-fidelity quantum processor that is controllable and measurable.

The **QubitAF** project is to improve cold-atom platforms for quantum simulation by increasing the number of manipulated atoms, certifying results, and detailing the performance of these platforms.

- The **QAFCA** project seeks to develop compact and transportable cold-atom sensors to measure gravitational fields, with applications in climate change analysis and the anticipation of natural disasters, and even in civil engineering and CO_2 storage.

- **e-DIAMANT**, which is closely connected to industry, deals with NV centres in diamonds, aiming to create the entire chain necessary for the manufacture of these defects and their exploitation.

- The **NISQ2LSQ** project will study in-depth the different correction strategies for random errors through the quantum aspect of qubits. Correction codes will be tested in experiments on superconducting and photonic platforms.

- The **EpiQ** project will study all the logical building blocks needed for a quantum processor to function properly (compilation, manipulation, optimization, intermediary languages, certification, etc.), by identifying constraints and better simulating actual machines, in an effort to develop new algorithms that can surpass today's capacities

Quantum Centres

There are several notable hubs for quantum in France:

Paris Centre for Quantum Computing (PCQC)

The PCQC was established in 2014, with the long-term objectives of: high impact, interdisciplinary research; international visibility for the quantum research in Paris and in France; the dissemination of quantum research via workshops/visits and students exchange; and the collaboration with industry for the commercialization of end-to-end quantum solutions.

PCQC is a research federation made up of the CNRS, the University of Paris, Sorbonne University, and later enlarged to include INRIA and PSL Research University. Its research areas, including quantum computing and the foundations of quantum information, are shown [28].

Computing

- Quantum Algorithms and Complexity
- Error Correction and Fault Tolerance
- Distributed Quantum Computing
- Quantum Metrology and Memories

Security

- Theoretical Quantum Cryptography
- Device-Independence and Security in Realistic Conditions
- Quantum Key Distribution
- Cryptography beyond QKD

Communications

- Quantum Games
- Quantum Communication Complexity
- Hybrid Quantum Networks and Entangled Photon Sources
- Delegation of Computation and Multipartite Resources

Foundations of Quantum Information

- Entanglement Theory and Quantum Correlations
- Non-locality
- Quantum Axiomatics
- Philosophy of Quantum Mechanics

Members of the PCQC are involved in a number of European projects related to quantum computing, including both the aforementioned PASQuans and QuantERA [29].

Quantum Engineering Grenoble programme (QuEnG)

Quantum Engineering Grenoble aims to develop a highly connected ecosystem for quantum technologies, through fostering interfaces between different areas of knowledge and creating synergies between academia and industry. Six work packages are contained within QuEnG, including several directly or indirectly related to quantum computing, as shown. A fundamental ambition of our project is to train the next generations of quantum engineers, and hence QuEnG hosts two PhD programmes: The QuEnG doctoral programme funded by the Idex-UGA, and the GreQue doctoral programme funded by the Marie-Sklodowska Curie Actions within Horizon 2020 [30].

Work packages include:

- Quantum processors and simulators
- Architecture and software
- Qubit – photon interfaces
- Quantum sensing
- Energetics of quantum computing
- Philosophical and societal challenges of quantum technologies

In addition, QuEnG has a Quantum Algorithmic Group, which investigates topics including architectures of quantum computers, quantum error correction, quantum programming language and compilation, computation models based on quantum phenomena, and applications. The labs involved within this group are shown in Table 1.

Néel	Institut Néel
LPMMC	Laboratoire de Physique et Modélisation des Milieux Condensés
INAC	Institute for Nanosciences & Cryogenics
LETI	Laboratoire d'électronique et de technologie de l'information
LIG	Grenoble Informatics Laboratory
PACTE	Laboratoire des sciences sociales
L'Institut Fourier	Laboratoire de mathématiques
PPL	Philosophie, pratiques & langages

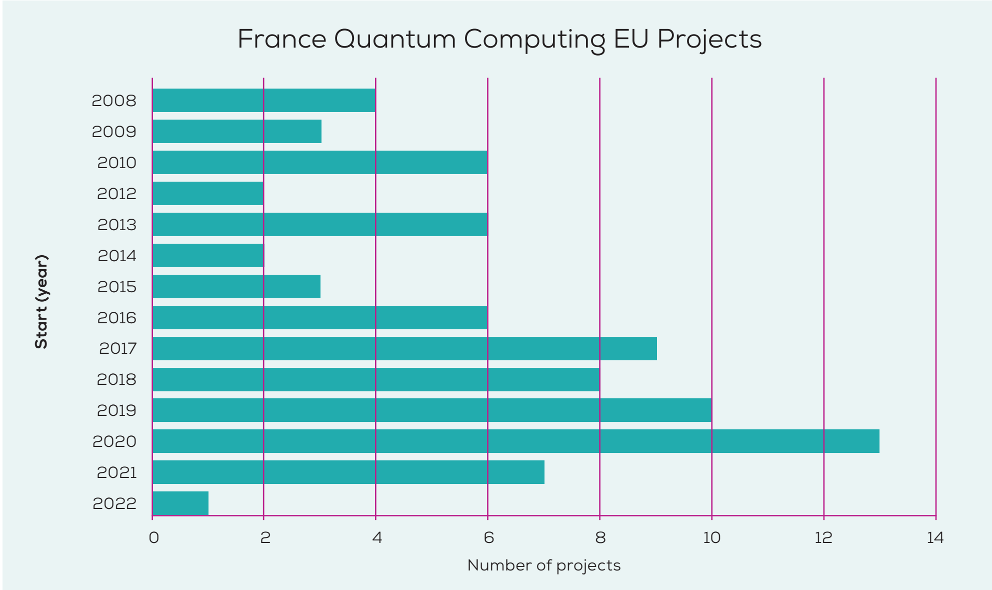
Collaborations

In 2018, the then Prime Minister of Australia, Malcolm Turnbull, and the President of France, Emmanuel Macron, announced plans for a new French-Australian collaboration between Australia's first quantum computing company, Silicon Quantum Computing (SQC), and the French research and development organisation, the Commissariat à Énergie Atomique et aux Énergies Alternatives (the CEA). The Memorandum of Understanding (MoU) outlines steps to form a joint venture in Silicon CMOS quantum computing technology to accelerate technology development and create commercialisation opportunities [31]. In August 2021, a joint statement between France and the Netherlands was signed, strengthening bilateral cooperation in quantum technologies. [32] The then Dutch secretary of state for economic affairs and climate policy, Mona Keijzer, described a European quantum ecosystem, and noted that "The Netherlands and France have been leaders in this field for years, and in order to maintain this international lead, it is necessary to cooperate at the European level."

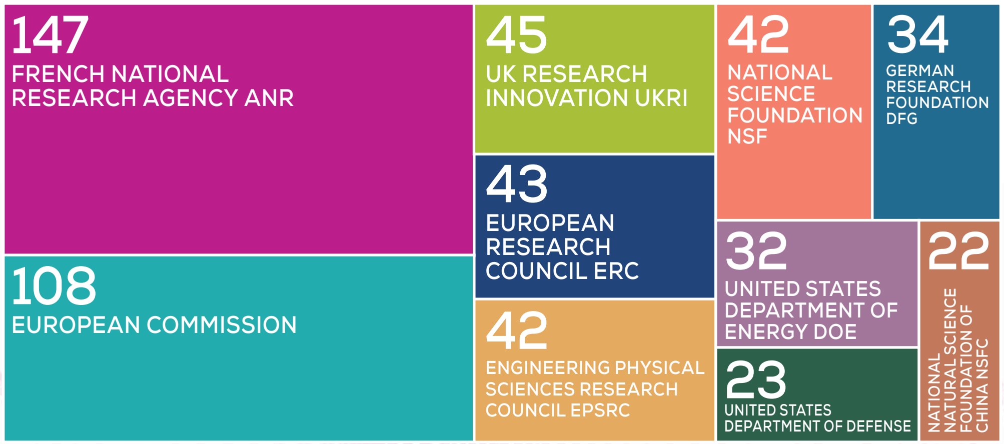
At an institutional level, France's research lab CNRS has expanded its presence in Canada with the creation of the Quantum Frontiers Lab with l'Université de Sherbrooke. THE collaboration was initially part of the 'Quantum Circuits and Materials Laboratory' (LCMQ) International Research Project (IRP), which was created in 2017 between the Physics Department of l'Université de Sherbrooke and multiple laboratories in France. Based on the success of this collaboration, the IRP has now become an International Research Laboratory (IRL) with quantum circuits and devices one of its major research focuses. Its goal is to conduct cutting-edge collaborative international research, to promote exchange between researchers and students from l'Université de Sherbrooke and France, and to promote emerging projects between the scientific communities of France and Quebec [33].

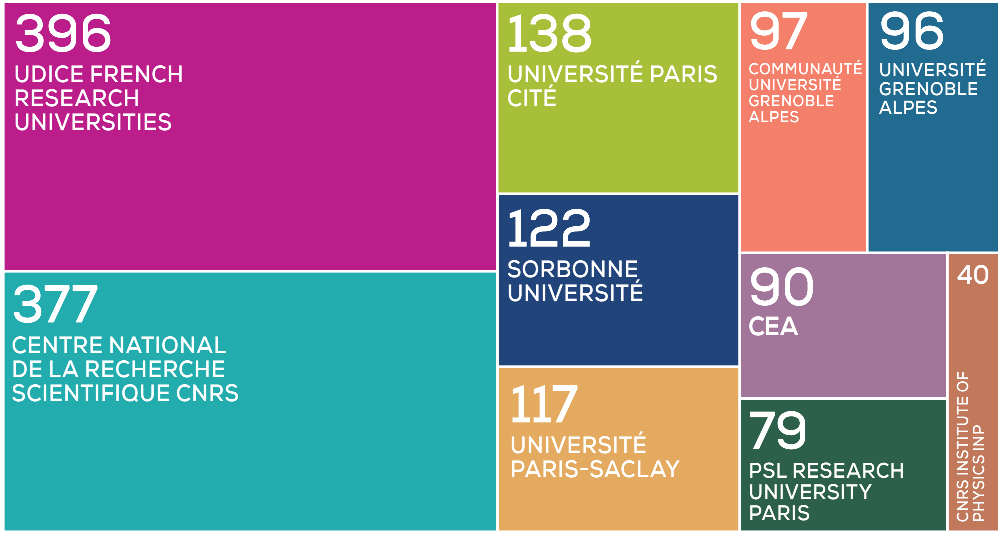
The multinational Thales, which is headquartered in Paris and in which the French State has over a 25% stake [34], is notably active in quantum technologies. In September 2021 Thales signed an MoU with the National University of Singapore (NUS), marking the start of a two-year partnership to jointly develop and test quantum technologies for commercial applications [35]. In December of the same year, Thales, PASQAL, the Paris Regional Authority and GENCI announced a multi-year partnership to develop new methods to address planning and scheduling challenges related to the optimization of critical systems through PASQAL's quantum processor. The project is supported by the PAck Quantique program (PAQ), an initiative launched in 2020 by the Paris Regional Authority, GENCI and Le Lab Quantique to accelerate the development of quantum technologies [36].

An analysis of French involvement in EU projects reveals a similar overall involvement to the UK, at 80 projects total, without the post-2020 drop-off (7 projects in 2021 vs 1 for the UK).



We analysed papers published from 2018 onwards, with some or all of the authors are based in French institutions. A visualisation of the top ten funding bodies for these bodies of work is shown below – as well as domestic and European funding, there is also notable activity from the UK and United States. Similar visualisations categorising the papers and showing the affiliations of the authors are also shown.





560 papers from French authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of papers
PHYSICAL REVIEW A	35
PHYSICAL REVIEW LETTERS	26
PHYSICAL REVIEW B	24
NATURE COMMUNICATIONS	17
PHYSICAL REVIEW RESEARCH	16
PHYSICAL REVIEW X	15
PRX QUANTUM	13
NATURE PHYSICS	12
NPJ QUANTUM INFORMATION	12
SCIENTIFIC REPORTS	12

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited over 570 times between them. These citations can provide an indication of activity, as well crosslinks and collaborations between the countries in question.

Journal	Number of citations
Argentina	6
Australia	12
Austria	17
Belgium	5
Brazil	6
Canada	14
Chile	1
China	19
Denmark	4
France	142
Germany	48
Hungary	1
India	2
Ireland	1
Israel	1
Italy	22

Journal	Number of citations
Japan	6
Netherlands	14
New Zealand	2
Portugal	1
Republic of Korea	1
Romania	6
Singapore	1
Slovenia	1
South Africa	1
Spain	44
Sweden	3
Switzerland	29
UK	11
USA	152
Grand Total	**573**

The lead author's institutional country for these fifty papers is shown in Table 2.

Journal	Number of papers
Austria	1
Belgium	1
Brazil	1
Canada	1
Denmark	1
France	15
Germany	6
Italy	2
Japan	1
Netherlands	2
Spain	4
Switzerland	1
USA	14
Grand Total	**50**

Germany

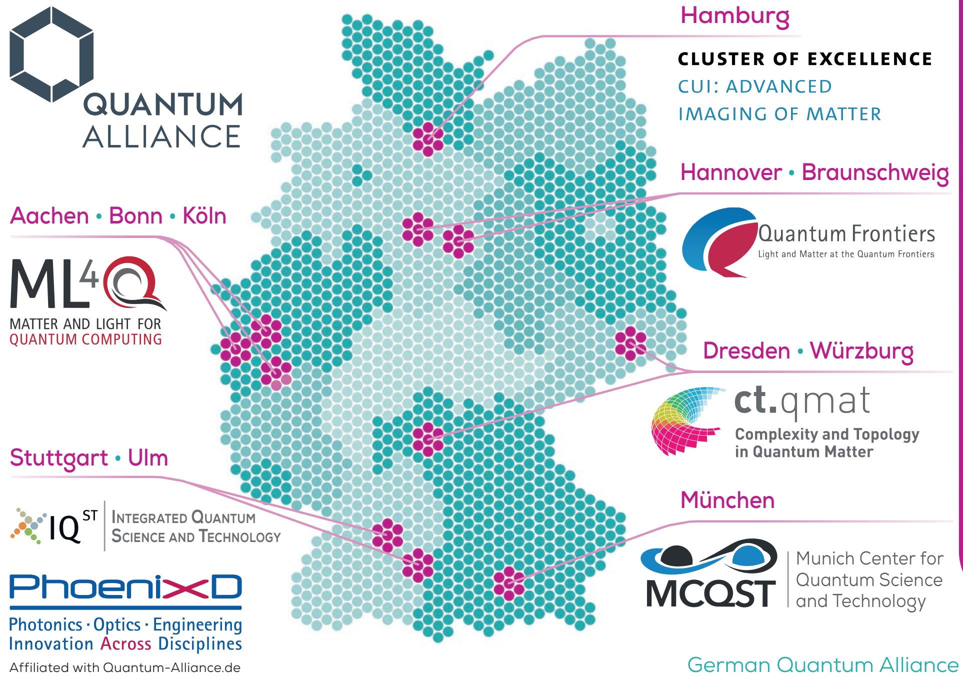
The Federal Republic of Germany is based on the principle of federalism and on constructive cooperation between the Federal Government and the 16 individual states (called the Länder). The Federal Government and the states act independently regarding the funding and organisation of research. In 2018 across Germany more than 104 billion euros were invested in research and development generally, with the public sector providing approximately 30% of funding – in addition to funding higher education, the public sector also finances non-university research organisations that are especially involved in fostering research talent. There are more than 5,000 foundations incorporated under civil law in Germany that aim to promote science. The Stifterverband is an association of foundations, which in 2019 alone provided 17.2 million euros in funding for education, science and cooperation between business and science. Additionally, roughly €15.5 million are used to fund endowed chairs. [37] In 2019, business enterprises invested more than €75.6 billion in R&D, making industry the biggest contributor to R&D funding. The Federation of German Industries (BDI) is the umbrella organisation for more than 40 affiliated industrial associations that represent the interests of over 100,000 companies with more than 8 million employees.

In May 2021, Germany announced a €2bn national programme, divided into two streams. The science ministry committed to spend €1.1bn by 2025 to support research and development in quantum computing. The economy ministry will spend €878m backing practical applications, of which Germany's Aerospace Center (DLR) will receive the bulk of the funding - about €740m to partner with industrial companies. Then Science Minister Anja Karliczek said the government's goal was to meet the target of building a competitive quantum computer in Germany in five years, and to create a network of companies in the field to develop cutting-edge applications [38].

Quantum Centres

Quantum Alliance

The Quantum Alliance is a consortium of "German Clusters of Excellence" and research centres working in quantum science and technology across Germany, which was formed in 2019. The Quantum Alliance is funded by the German Research Foundation [39].



German Quantum Alliance [40]

Quantum computing related centres include:

Name	Description	Institutions
ct.qmat	Complexity and Topology in Quantum Matter	• Julius-Maximilians-Universität Würzburg(JMU) • Technische Universität Dresden
ML^{4}Q	Matter and Light for Quantum Computing	• University of Cologne • RWTH Aachen • University of Bonn • Research Center Jülich
MCQST	Munich Center for Quantum Science and Technology	• Ludwig-Maximilians-Universität Munich (LMU) • Technical University Munich (TUM) • Max Planck Institute of Quantum Optics (MPQ) • Walther-Meißner-Institut (WMI) • Deutsches Museum (DM)
IQST	Integrated Quantum Science and Technology	• University of Stuttgart • Ulm University • Max Planck Institute for Solid State Research, Stuttgart
PhoenixD	Merge optical systems, design and simulation tools with all relevant production technologies into one combined platform	• Leibniz Universität Hannover • TU Braunschweig • Laser Zentrum Hannover e.V. • Max Planck Institute for Gravitational Physics (Albert-Einstein-Institute)

Munich Quantum Valley

At a state level, notable is The Munich Quantum Valley (MQV), an initiative for the promotion of Quantum science and technology supported by the Bavarian state government. As a hub between research, industry, funders and the public it is intended, among other things, to help develop and operate competitive quantum computers in Bavaria, in addition to education and training. It is part of Bavaria's Hightech Agenda+, a fund of €900m to strengthen the state's technology investment in 2021 and 2022.

The MQV was founded in January 2022 by:

- The Bavarian Academy of Sciences and Humanities (BadW),
- The German Aerospace Center (DLR)
- The Fraunhofer Society (FhG)
- The Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)
- The Ludwig-Maximilians-Universität München (LMU)
- The Max Planck Society (MPG)
- The Technical University of Munich (TUM) [41]

The MQV has published a three-point plan, which includes the establishment of a centre for quantum computing and quantum technologies, a quantum technology park, and qualification and training.

The MQV operates across the full stack, with particular strengths in neutral atom, superconducting and trapped ion technologies, and with over 50 research groups involved across the institutions. It is divided into the following work packages, with interlinks between them. [43]

Superconducting Qubit Quantum Computer (SQQC)	• Implement fast (re-)calibration and tune-up schemes including specific firmware for the operation of generalized types of qubits. • Efficient optimization algorithms including real-time pulse sequencing and high-fidelity reset operations for high trigger rates will be developed. • In collaboration with the THEQUCO, Q-DESSI and HAT consortia, the SQQC consortium will then develop and run benchmark algorithms in a high-performance computing environment
Trapped Atom Quantum Computer (TAQC)	• The construction of a gate-based quantum computer based on neutral strontium atoms. • This includes fast and high-quality optical switches (together with partners at Qubig and the University of Heidelberg) and their fast electronic control (together with Fraunhofer IIS). • The TAQC consortium will also leverage the synergies within the MQV to develop a remote access point to our quantum computing demonstrator
Theoretical Quantum Computing (THEQUCO)	• The development of the quantum information theory behind Noisy Intermediate-Scale Quantum (NISQ) and analog devices. • New quantum algorithms both for present and planned scalable generations of devices. • builds new methods and protocols to certify quantum computers and their capability of demonstrating a quantum advantage. Finally, it investigates the improvement of current quantum computers by establishing new control and error mitigation methods, and helps scaling them up by devising and improving error correction techniques.
Quantum Development Environment, System Software & Integration (Q-DESSI)	• The creation of a Munich Quantum Software Stack: a unified software stack, enabling the use of quantum-computing systems for reliable, scalable and multi-user access, and supporting hybrid HPC/QC applications. • The development of a programming environment, including problem-independent programming abstractions and development tools, hybrid abstractions integrating QC into Von-Neumann-based languages, quantum operating and runtime systems, new architectures for control processors as well as the integration into the HPC ecosystem
Scalable Hardware & Systems Engineering (SHARE)	• The development of electronic components and systems for future quantum computers • Semiconductor Technology and Integration for Functional and Scalable QC-Hardware.
Quantum Algorithms for Application, Cloud & Industry (QACI)	• The focus will be on the implementation and evaluation of NISQ-compatible variational or kernel-based algorithms in order to identify a potential quantum advantage already on existing noisy hardware. For the underlying theory, the QACI consortium will work closely together with the THEQUCO consortium.
Hardware Adapted Theory (HAT)	• Make best use of the planned hardware generations within the MQV. • Contribute to the hardware development itself by providing numerical modeling of hardware components • Developing tools to characterize the hardware and its errors. • The consortium will develop hardware-adapted quantum control strategies and quantum error-correction protocols to optimize the fidelity and robustness of experimental quantum operations in the presence of noise and experimental imperfections and constraints.

There have been several notable activities by the MQV since its formation at the start of 2022. In February 2022, a Call for Lighthouse Projects was announced, targeting application-oriented fundamental research projects. In August that year the first five projects to be funded were announced, totalling around €17m. [44] In March MQV launched its "Fit for Quantum" initiative, designed to promote quantum technologies among young scientists, with universities in Augsburg, Bayreuth, Erlangen-Nuremberg, Munich, Regensburg, and Würzburg will each receive around €144k in funding. [45] Finally, in June 2022 MQV made around €20m available for new professorships in Bavaria to strengthen the state's profile in quantum sciences and quantum technologies [46].

Jülich Supercomputing Centre

The Jülich Supercomputing Centre, based in the state of North Rhine-Westphalia, was the first German supercomputing centre, opening in 1987. It opened a new quantum computer building in summer 2021, and now offers JUNIQ (Jülich UNified Infrastructure for Quantum computing) – a "Quantum Computing Platform as a Service," providing European users support and access to quantum computer emulators and quantum computing technologies of different types and maturity. JUNIQ will also integrate quantum computers in the form of quantum-classical hybrid computing systems into the modular HPC environment of the Jülich Supercomputing Centre. [47]

An important part of this is QSolid, a four-year project running from January 2022 to December 2026, which aims to develop a comprehensive ecosystem for a demonstrator based on superconducting qubits, which will be made accessible to external users via JUNIQ. 25 companies and research institutions are involved in the project, which has a budget of €76.3m, the majority of which is funded by the Federal Ministry of Education and Research. The first prototypes of the planned demonstrators in QSolid are being produced at Leibniz IHPT in Jena and are expected to be operational by 2024. [49]

Research institutions involved in QSolid include:

- Seven subinstitutes from Jülich's Peter Grünberg Institute
- Jülich Supercomputing Centre (JSC),
- Central Institute of Engineering, Electronics and Analytics (ZEA-2)
- Qruise (a spin-out from Forschungszentrum Jülich)
- Fraunhofer IPMS
- Fraunhofer IZM-ASSID,
- Karlsruhe Institute of Technology (KIT),
- Leibniz IPHT
- National Metrology Institute (PTB),
- CiS Forschungsinstitut für Mikrosensorik,
- Ulm University,
- University of Stuttgart,
- Freie Universität Berlin,
- University of Konstanz,
- University of Cologne

[49]

Fraunhofer-Gesellschaft

The Fraunhofer-Gesellschaft, based in Germany, is a leading applied research organization which plays a significant role in the innovation process. Founded in 1949, it operates 76 institutes and research units throughout Germany and has over 30,000 employees, with an annual research budget of €2.9 billion, of which €2.5 billion is from contract research [50]. In June 2021 it announced a collaboration with IBM, through the hosting of the first IBM quantum computer outside the United States, within the "Competence Center Quantum Computing Baden-Württemberg". The system is available to industrial companies, SMEs, startups and academic institutions, with all processed project and user data remaining in Germany. "Our goal is to enable Baden-Württemberg, as a leading industrial and innovative region in Europe, to play a major role in creating added value with quantum computing" said Dr. Nicole Hoffmeister-Kraut, the state's Minister of Economic Affairs, Labour and Housing [51], [52].

Six collaborative projects have been announced by the Competence Centre for kick-off in 2021 and 2022. Six Fraunhofer Institutes are collaborating on these projects, along with 16 other university, college and non-university institutes from the state as well as about 40 associated corporate partners from Baden-Württemberg and wider Germany [52], [53]. A call for proposals for a second phase of projects was announced in June 2022, aiming to transfer research into practical applications and further expand the quantum computing ecosystem of universities, research institutes, start-ups and companies in Baden-Württemberg [52].

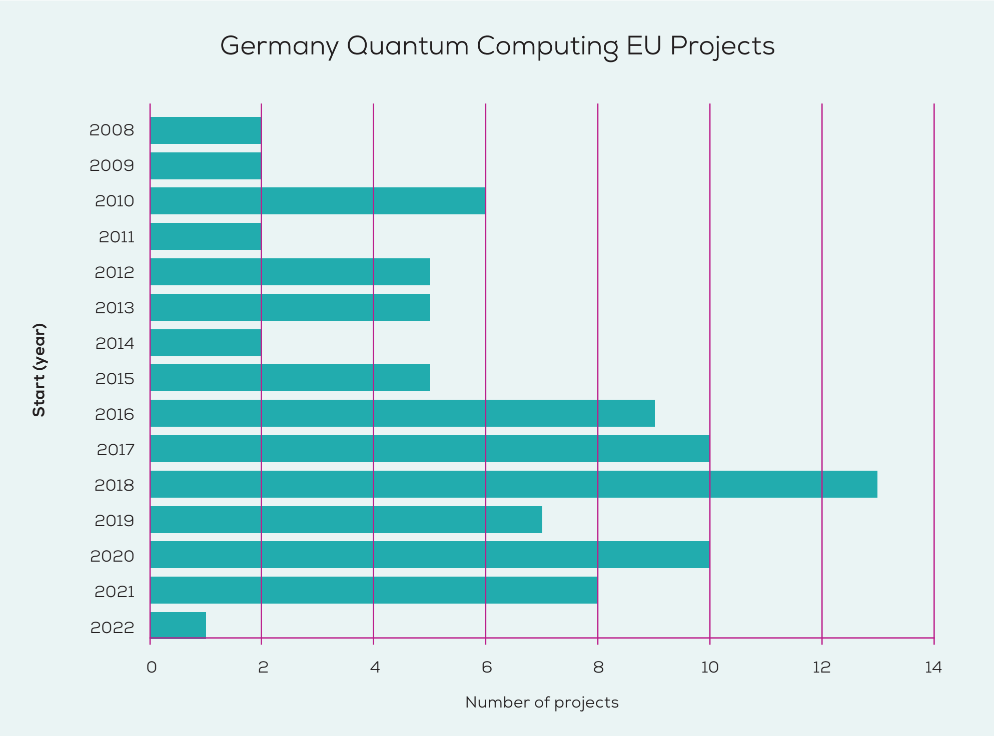
Project	Description
QC-4-BW	Diamond-based spintronic quantum register for a scalable quantum processor
QORA	Quantum optimization using resilient algorithms
SEQUOIA	Software engineering of industrial, hybrid quantum applications and algorithms
SiQuRe	Modeling and simulation of qubit registers from chains of NV centers on dislocations in diamond
QuESt	Material design for electrochemical energy storage and conversion devices using innovative simulation techniques
EFFEKTIF	Stability analysis and error correction protocols for critical infrastructure networks

Collaborations

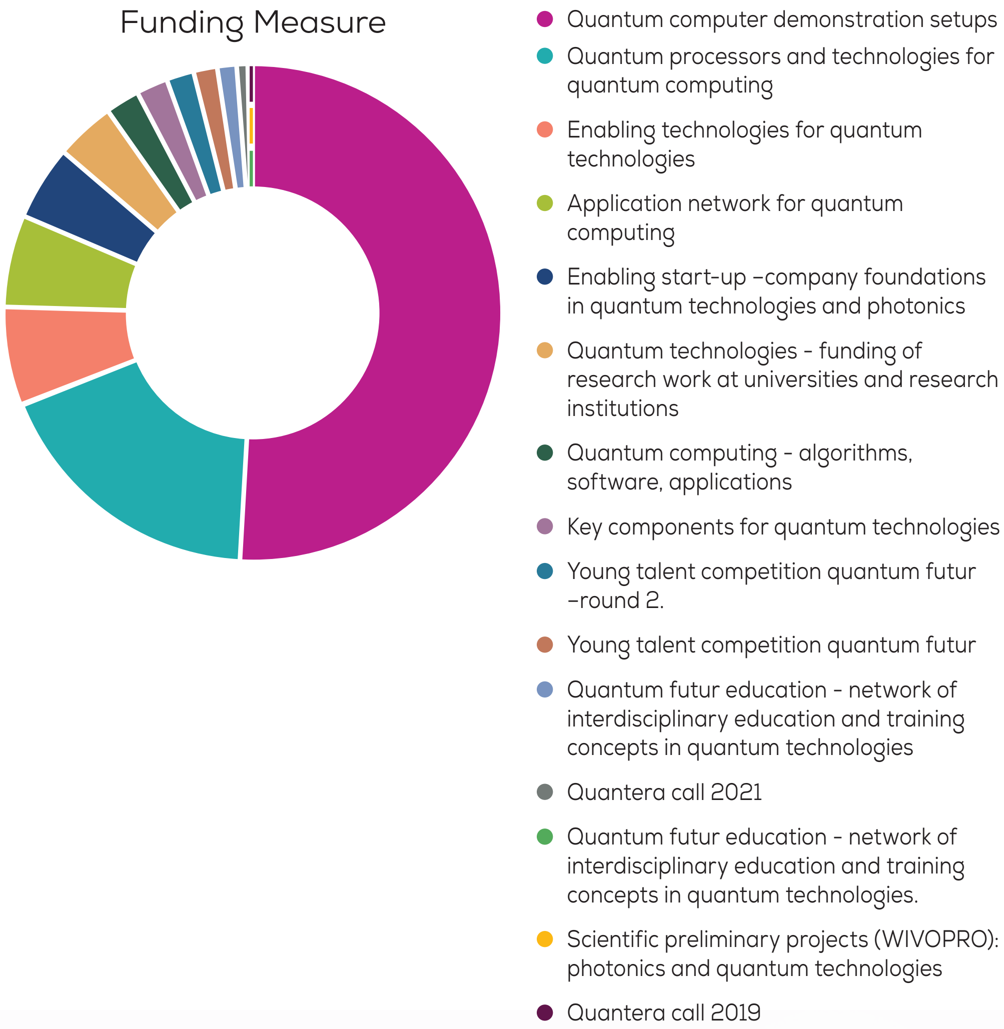
In July 2018 Germany's Forschungszentrum Jülich and the DESY (Deutsches Elektronen-Synchrotron) research centre signed an MoU with the Canadian companies TRIUMF, TRIUMF Innovations, D-Wave Systems and 1Qbit. The MoU sets out to jointly establish Canadian and German quantum computing and machine learning networks and to collaborate on applied quantum computing and machine learning initiatives of mutual interest [54]. This represents a strong, international collaboration between the research and private sectors.

In 2021, a report completed for Canada's National Research Council (NRC) by Global Advantage identified Germany as a priority collaboration partner in research and development of quantum technologies [55].

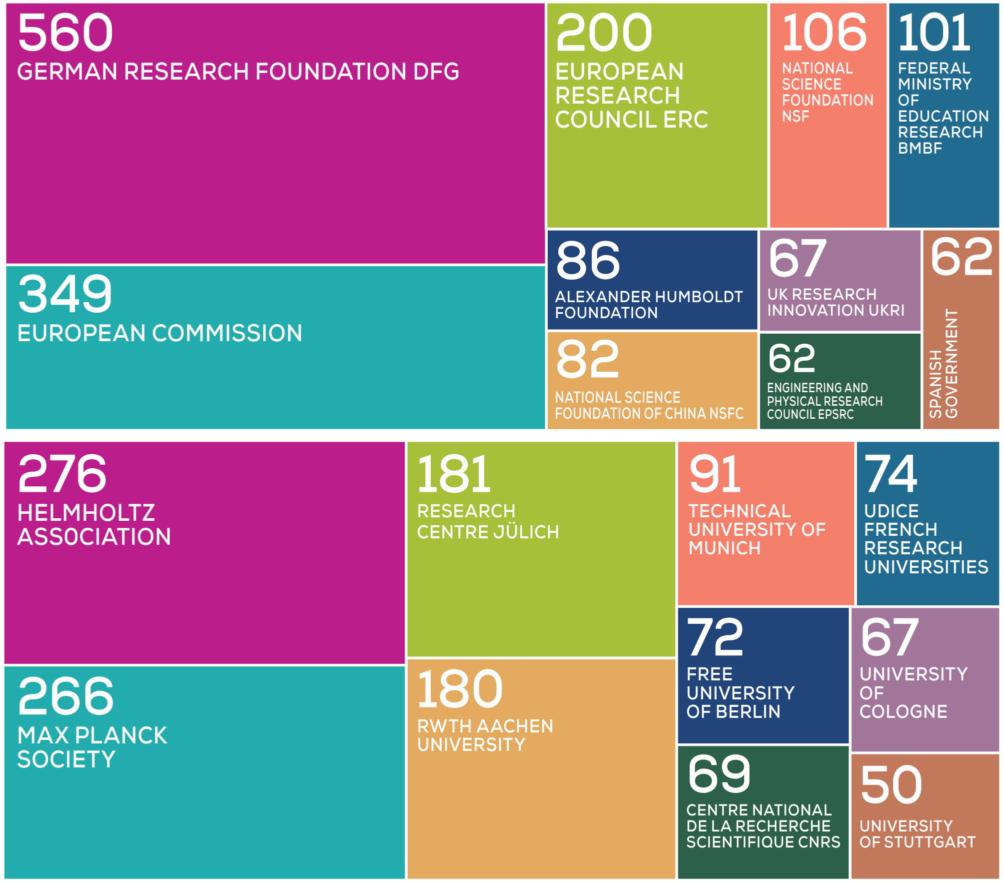
An analysis of German involvement in EU projects reveals more activity than any other country, at 87 projects total, 48 of which began between 2017 and 2021.



An analysis of the funding categories for German active QIT-related projects reveals the majority of activity is contained within "quantum computer demonstration setups."



We analysed papers published from 2018 onwards, with some or all of the authors are based in German institutions. A visualisation of the top ten funding bodies for these bodies of work is shown below – as well as domestic and European funding, there is also notable activity from China, the UK and Spain. Similar visualisations categorising the papers and showing the affiliations of the authors are also shown.



1,326 papers from German authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of publications
PHYSICAL REVIEW B	111
PHYSICAL REVIEW A	102
PHYSICAL REVIEW LETTERS	93
PHYSICAL REVIEW RESEARCH	60
NATURE COMMUNICATIONS	36
NEW JOURNAL OF PHYSICS	36
QUANTUM	33
QUANTUM SCIENCE AND TECHNOLOGY	31
NPJ QUANTUM INFORMATION	28
PHYSICAL REVIEW APPLIED	27

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited over 880 times between them. These citations can provide an indication of activity, as well crosslinks and collaborations between the countries in question, with China third on the list, behind the USA and Germany, and ahead of Spain and the UK.

Journal	Number of citations
Argentina	6
Australia	23
Austria	20
Azerbaijan	5
Belgium	8
Brazil	3
Canada	4
China	55
Czech Republic	1
Denmark	5
Finland	1
France	25
Germany	125
Hungary	1
Iceland	1
Israel	7

Journal	Number of citations
Italy	14
Japan	21
Mexico	2
Netherlands	10
Poland	6
Russia	15
Slovakia	1
South Africa	1
Spain	50
Sweden	1
Switzerland	37
Thailand	1
UK	49
USA	386
Grand Total	**884**

Journal	Number of papers
Australia	1
Austria	1
Belgium	1
China	4
France	2
Germany	15
Israel	1
Japan	1
Poland	1
Russia	1
Spain	2
Switzerland	3
UK	5
USA	12
Grand Total	**50**

Austria

The Quantum Austria Research Initiative launched November 2021 and runs until 2026. At the initiative of the Austrian Federal Ministry of Education, Science and Research (BMBWF), €107m in funding was invested from the NextGenerationEU Development and Resilience Plan to accelerate the development of quantum research and technologies. The aim is to enhance Austria's competitiveness and increase European cooperation in this strategic key technology sector, with funding available for both basic research as well as the development of practical applications. A total of three calls for applications are planned until 2026 [56], [57].

The first Quantum Austria projects were announced in July 2022. The first project to be approved was the proposal "MUSICA" (Multi-Site Computer Austria) with a funding amount of €20 million. This joint project under the consortium leadership of the Vienna Scientific Cluster, a collaboration of several Austrian universities, aims to establish a powerful new research infrastructure in the field of high-performance computing in Austria in the coming years. Coupling this HPC infrastructure with a quantum computer is one of the funding initiative's key goals. [58] €3 million of funding was also made available for ten university-led research projects in Graz, Innsbruck, and Vienna.

Quantum Centres

The Vienna Centre for Quantum Science and Technology (VCQ) is a joint initiative of the University of Vienna, the Vienna University of Technology, the Austrian Academy of Sciences, and the Institute of Science and Technology Austria, which unites quantum physicists of Vienna's research institutions in one collaborative centre. The research institutions are the University of Vienna, the Vienna University of Technology, the Institute of Science and Technology Austria, and the Austrian Academy of Sciences. There are 14 research groups in the Quantum Information / Computing / Communication work package, and it is notable how the VCQ so closely groups the work between computing and communication [59], [60].

Vienna is also home to the Vienna Doctoral Program on Complex Quantum Systems (CoQuS), a training center for around 40 students who are selected from an international pool of applicants, based primarily on their academic excellence. The doctoral program is funded by the Austrian Science Fund, and jointly hosted and co-financed by the University of Vienna and the Vienna University of Technology. Research in CoQuS covers experimental and theoretical quantum physics, including quantum information science and computation, cold atoms and atom chips, and quantum integrated devices.

Research groups include:

- Quantum information science and quantum computation
- Matter-wave interferometry
- Many-body quantum theory
- Theory of quantum foundations
- Quantum micromechanics
- Relativistic quantum information
- Quantum information and foundations of physics and several other areas [61].

In a similar vein, the Austrian Academy of Sciences runs the Erwin Schrödinger Center for Quantum Science & Technology (ESQ). ESQ is described as an Austria-wide postdoc programme, supporting the integration of incoming experienced researchers, and discovery programme allowing the exploration of highly innovative research. It is financed by the BMBWF, with the project also receiving funding from the EU's Horizon 2020 programme, and is operated in partnership with 40 Austrian research groups at the University of Vienna, the Vienna University of Technology and the University of Innsbruck, as well as the Austrian Academy of Sciences [62].

The University of Innsbruck is a major centre for the development of trapped ion technologies, and was the first research group to successfully demonstrate controlled teleportation of quantum information [ref Deterministic quantum teleportation with atoms, Nature 429 734 (2004)]. They have research programmes in:

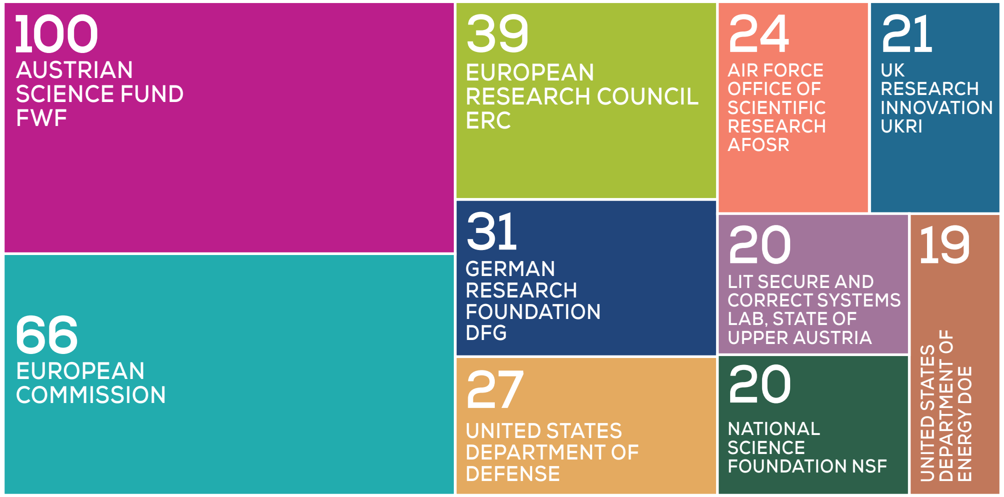
- 2D ion crystals for quantum simulation
- Single ion-single photon interactions
- Surface ion traps
- Photon frequency conversion for ions
- Precision measurements
- QCosmo (Quantum Control of Molecules)
- Quantum information
- Quantum Simulation
- Ultrafast two-qubit phase gates

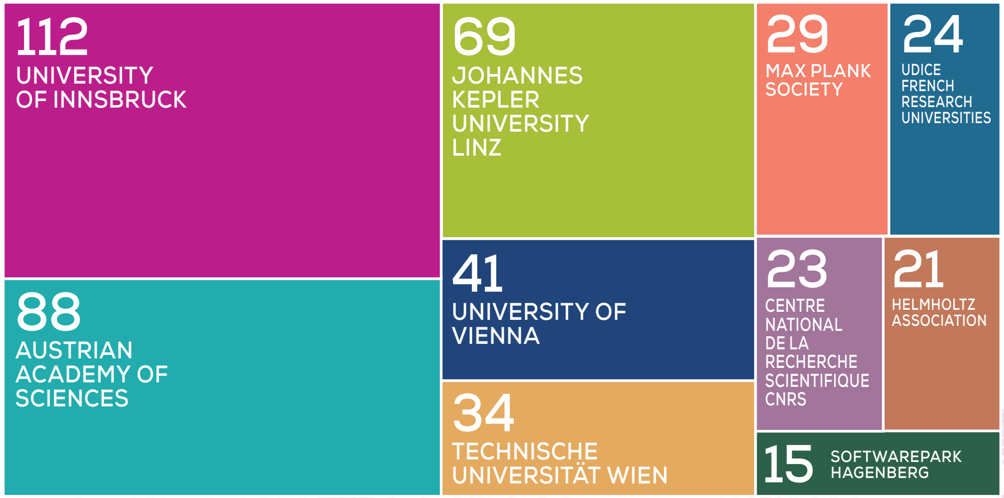
Collaborations

Austrian research is also highly collaborative, with the BMBWF stating "international collaboration and international exchange in education, science and research are essential prerequisites for assuring Austria's quality location for activities in these fields," [63]. The EU is particularly important in this context. Since 2014 Austria has received around €1.5 billion from Horizon 2020 across all fields, with 3,656 participations (of which approximately 37% can be attributed to businesses and 29% to universities), ranking third in Europe. [64]. In the context of Quantum Austria, the Austrian Research Promotion Agency (FFG) described how "The funding instruments of FFG and FWF (Austrian Science Fund) provide tailor-made support here for local stakeholders along the entire innovation axis. In addition, through its European network, FFG is contributing to strengthening transnational cooperation on this important key technology," [56].

An example of Austria's collaboration with European neighbours is a project around spin qubits, as published in Nature Materials under *A singlet-triplet hole spin qubit in planar Ge*. The authors are affiliated with institutions in Austria, Italy, Germany and Spain, with the research supported by funding from multiple sources, [65] [66].

An analysis of papers published from 2018 onwards, with some or all of the authors are based in Austrian institutions, was undertaken. A visualisation of the top ten funding bodies for these bodies of work is shown below – as well as domestic and European funding, there is also notable activity from Germany and the United States. Similar visualisations showing the affiliations of the authors are also shown.





291 papers from Austrian authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of publications
PHYSICAL REVIEW LETTERS	26
PHYSICAL REVIEW A	19
NATURE	13
NPJ QUANTUM INFORMATION	12
NEW JOURNAL OF PHYSICS	10
PRX QUANTUM	10
QUANTUM	8
IEEE TRANSACTIONS ON COMPUTER-AIDED DESIGN OF INTEGRATED CIRCUITS AND SYSTEMS	7
NATURE PHYSICS	7
PHYSICAL REVIEW RESEARCH	7

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 630 times between them. These citations can provide an indication of activity, as well crosslinks and collaborations between the countries in question, with the USA, Germany, Spain and China leading after Austria.

Journal	Number of citations
Australia	11
Austria	147
Azerbaijan	5
Belgium	2
Brazil	3
Canada	3
Chile	1
China	35
Czech Republic	2
Denmark	5
France	26
Germany	68
India	1
Israel	3

Journal	Number of citations
Italy	14
Japan	4
Korea	1
Netherlands	18
Poland	1
Republic of Korea	1
Russia	13
Spain	51
Sweden	2
Switzerland	26
Thailand	1
UK	19
USA	161
Grand Total	**630**

Journal	Number of papers
Austria	21
China	2
France	2
Germany	7
Italy	1
Netherlands	2

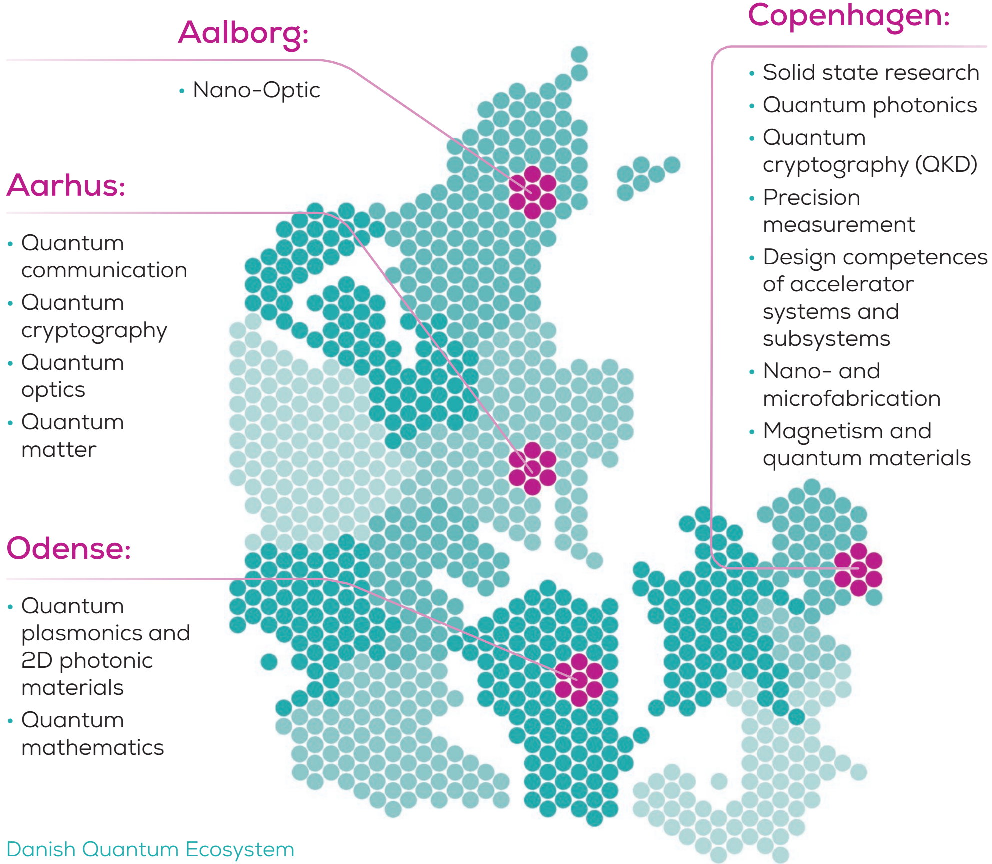
Journal	Number of papers
Russia	1
Spain	1
Switzerland	1
UK	3
USA	9
Grand Total	**50**

Denmark

Denmark

Denmark has a proud history in quantum, from Niels Bohr formulating his theory on the hydrogen atom in 1913. Its quantum research activity is strong. The University of Copenhagen ranks 7th in the world on quantum scientific impact measured by the number of unique first-author publications, and Danish quantum researchers receive a higher proportion of EU research funds than researchers in other fields. Denmark has the highest concentration of enrolled graduates attending quantum-related scientific studies globally, with 635 graduates attending quantum-related studies per million inhabitants. France has the second most graduates with 438 per million inhabitants [67], [20].

The Ministry of Foreign Affairs of Denmark highlights the competencies shown within the Danish quantum ecosystem. Despite this, Denmark does not have a formal national programme in place. Certain stakeholders consider the government's official stance on quantum technology and support for funding applied research and innovation to be weaker than in neighbouring countries, though the stakeholders do recognise that some government actors show dedication to the quantum agenda, notably Innovation Fund Denmark and the Ministry of Foreign Affairs, [20].



Danish Quantum Ecosystem

A noteworthy project recently funded by the Innovation Fund is PhotoQ, a four-year, circa €3m initiative. The project has the overarching ambition to build a scalable photonic-based quantum computer. The consortium behind this works across the entire value chain, with expertise in logistics optimization provided by AMCS Group, quantum chemistry via Molecular Quantum Solutions, quantum algorithmic expertise at Aarhus University and Kvantify, laser technology from NKT Photonics, and in the development of photonic quantum computer hardware at the Technical University of Denmark, [68].

Following an earlier national programme (Qubiz), the Danish Quantum Community was initiated in January 2020, on the initiative of the Department of Physics and Astronomy at Aarhus University, Department of Physics at the Technical University of Denmark (DTU), and the Niels Bohr Institute at Copenhagen University. The purpose of the Danish Quantum Community is to unite all national stakeholders and to create a room for synergies across research institutions, industries, and funding bodies with the aim of advancing the development of quantum technologies in Denmark [70].

In June 2022 the University of Copenhagen, in collaboration with DTU, announced Denmark's first programme of study in quantum information science, aimed at ensuring the development of a qualified quantum sciences workforce. The programme is a two-year MSc that is interdisciplinary, combining the fields of physics, mathematics, chemistry and computer science, and begins with a general introduction to quantum information theory before specialisations [71].

A notable trait in Denmark is the significant role of foundations in the funding of quantum research and development. This can be shown with the activity of two foundations, The Villum Foundation and The Novo Nordisk Foundation. The Villum Foundation, founded in 1971, primarily supports research activities in science and technology, and makes large grants to "research centres without walls" – the VKR Centres of Excellence. [72] In 2016 it granted 30m DKK (~€4m) for a new research centre at the University of Copenhagen - The Villum Centre of Excellence for the Mathematics of Quantum – with the aim to contribute to the mathematical understanding of quantum physics, with a special emphasis on the interaction between quantum matter and quantum information.

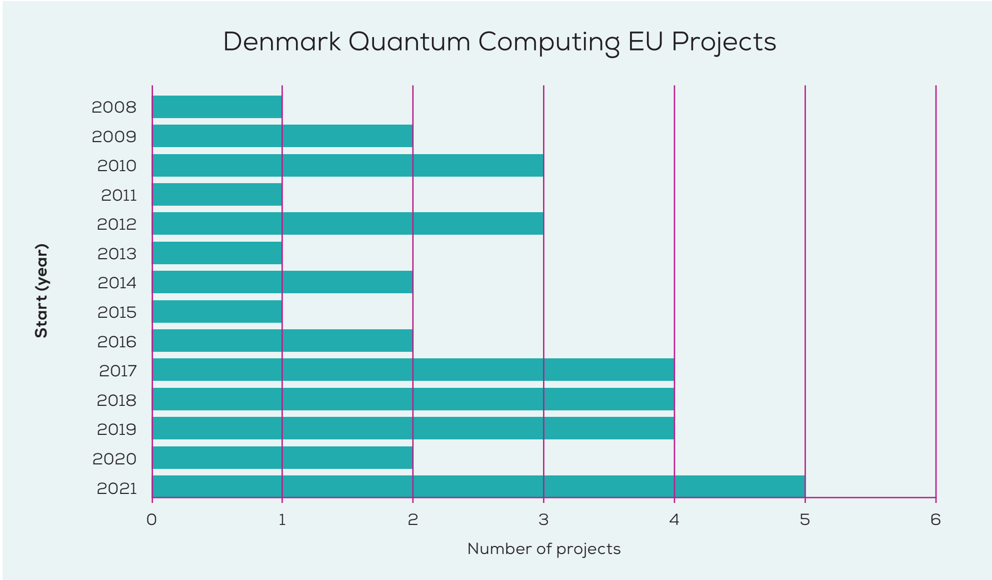
The Novo Nordisk Foundation is an independent Danish foundation with corporate interests, which awarded nearly 9bn DKK in grants for new projects and initiatives in 2021 alone. [73] In September 2020, it awarded 108.6m DKK (~€14.6m) to the University of Copenhagen for two new centres, focussed on quantum simulation in the field of biochemistry. The Solid-State Quantum Simulators for Biochemistry (Solid-Q) centre will work on applying and integrating two types of quantum simulation hardware, whilst the Quantum for Life centre aims to develop mathematical algorithms that can be used for the quantum simulation of biomolecules. [74] More recently, in July 2022 the foundation provided 13.7m DKK for the research project Fundamentals of Neutral Atom Quantum Simulators, as part of its NERD programme. [75]. In September 2022, the Novo Nordisk Foundation announced a twelve year programme to develop Denmark's first fully functional generally applicable quantum computer, with funding of DKK 1.5 billion [76].

Collaborations

Denmark is a small nation and traditionally relies on collaboration and partnerships to overcome key barriers [20]. In April 2022, it was announced that NATO had selected a Danish site to host a quantum technology centre, as part of the Defence Innovation Accelerator for the North Atlantic (DIANA). The centre will be based at the Niels Bohr Institute with contributions from the Technical University of Denmark (DTU), the Aarhus University, and the Danish National Metrology Institute. The project will consist of an accelerator to provide training and mentoring for companies to develop commercial solutions, and a centre for development and testing of physical components for quantum technologies.
A test centre and manufacturing unit composed of physical laboratories and testing facilities that could be involved in the development and testing of physical components for quantum sensors, quantum encryption units, or quantum computers [76].

On June 8th 2022, Denmark and the United States signed a Joint Statement on Cooperation in Quantum Information Science and Technology, described as a means of leveraging both countries' strengths in quantum information science and technology (QIST) and QIST-enabling fields to pursue innovative research, grow the future marketplace, build a strong supply chain, and nurture future skills. Anne Hougaard Jensen, Director of Invest in Denmark, noted that with the Joint Statement "I am sure that our increased cooperation with American companies and research institutions will grow our world-class ecosystem further," [77].

An analysis of Denmark's involvement in EU projects reveals 35 projects funded in total, with over half that number starting since 2017.



An analysis of papers published from 2018 onwards, with some or all of the authors based in Danish institutions, was undertaken. A visualisation of the top ten funding bodies for these bodies of work is shown below – there is heavy European funding, along with notable funding from foundations. Microsoft, which in 2018 opened a Quantum Materials Lab in Copenhagen tasked with fabricating the materials for a scalable quantum computer [78] – in collaboration with the University of Copenhagen and DTU – also features on the list.

Similar visualisations showing the affiliations of the authors are also shown.

174 papers from Danish authors were published in this period. The most common journals these papers were published in are shown right.

Journal	Number of papers
PHYSICAL REVIEW B	13
PHYSICAL REVIEW LETTERS	13
PHYSICAL REVIEW A	12
NATURE PHYSICS	8
NPJ QUANTUM INFORMATION	5
PHYSICAL REVIEW RESEARCH	5
PRX QUANTUM	5
QUANTUM	5
NANO LETTERS	4
NATURE COMMUNICATIONS	4

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited just under 500 times between them. These citations can provide an indication of activity, as well crosslinks and collaborations between the countries in question. After Denmark, the USA tops the list, followed jointly by the UK and the Netherlands.

Journal	Number of citations
Australia	22
Austria	10
Belgium	2
Brazil	2
Canada	5
Chile	1
China	13
Czech Republic	2
Denmark	188
France	13
Germany	20
Greece	1
Hungary	1
India	2
Iran	1
Israel	2
Italy	14
Japan	8
Malaysia	1
Netherlands	38
Norway	1
Poland	1
Portugal	1
Republic of Korea	1
Singapore	1
Slovenia	1
Spain	29
Sweden	2
Switzerland	13
UK	38
USA	65
Grand Total	**499**

The lead author's institutional country for these fifty papers is shown.

Lead Country	Total
Australia	1
Austria	1
China	1
Denmark	25
Germany	3
Iran	1
Italy	2
Netherlands	3
Spain	4
Switzerland	1
UK	5
USA	3
Grand Total	**50**

Finland

Finland established a national Centre of Excellence – Quantum Technology Finland (QTF) – in 2018. The programme, initially running until 2025, brings together researchers from Aalto University, the University of Helsinki and VTT Technical Research Centre of Finland. The research combines experimental, theoretical and applied, with a strong focus on superconducting and silicon-based devices, superconducting-metal interfaces. QTF is described as a global leader in thermodynamics and control of heat in quantum circuits, thermal microwave detection on hybrid devices made out of 1D and 2D materials cooled down into deep-mK regime, as well as on industrial-level production of superconducting sensors, building on Finnish expertise in developing electronics, superconducting circuits and sensors [79] [80] [81]. With an annual budget of around €12M, the programme is split into 5 work packages:

1. Control of quantum coherence and dissipation
2. Quantum machines and simulators
3. Hybrid architectures
4. Enabling technologies
5. Future quantum technologies

The 11 research teams include Superconducting Qubits and Circuit QED, Quantum Computing and Devices, and Photonics. QTF also partners with OtaNano, founded and developed by AALTO and VTT, and described as Finland's national research infrastructure for micro-, nano-, and quantum technologies. OtaNano provides nanofabrication, nanomicroscopy, and ultra-low temperature measurement facilities for quantum technologies, with around 500 users of the facilities annually and with over 30 collaborating companies [82].

Quantum Centres

As well as QTF, In July 2021 Aalto University, the University of Helsinki and VTT – the same institutions collaborating in QTF – announced InstituteQ. The partners described how the need to the need to team up resources and expertise across a wide spectrum in a collaborative center to pursue goals was well-demonstrated by similar initiatives across the EU. [83] The overall goals of InstituteQ are: to enable the partners to develop, coordinate and carry out the highest-level research in QSIT; to provide the best possible education for future workforce in this field, both in graduate and industrial programs; to drive innovation and leverage the national ecosystem building in quantum technology and to foster the development of relevant national infrastructures.

There is a strong regional push for QIT in Helsinki. All three aforementioned institutions are based within the Greater Helsinki region. The City of Helsinki owns Helsinki Partners, a city marketing, investment and talent attraction company. It has begun promoting quantum computing, advertising a complete supply chain with activity from R&D to production. As well as the three institutions, Helsinki partners showcase IQM – a hardware provider for quantum computers, focusing on superconducting technology – and Bluefors, a manufacturer of dilution refrigerator systems [84] [85].

Focus areas for the Helsinki region include:

- Dilution refrigeration
- Superconducting chip design and simulation
- Delivery and installation of quantum computing systems
- Superconducting electric circuits
- Quantum software and algorithms
- Fabrication of superconducting circuits
- Characterization of electronic circuits in cryogenic temperatures
- New quantum computing, control, initialization and readout schemes
- Cryogenic measurement systems
- Control electronics and QPUs

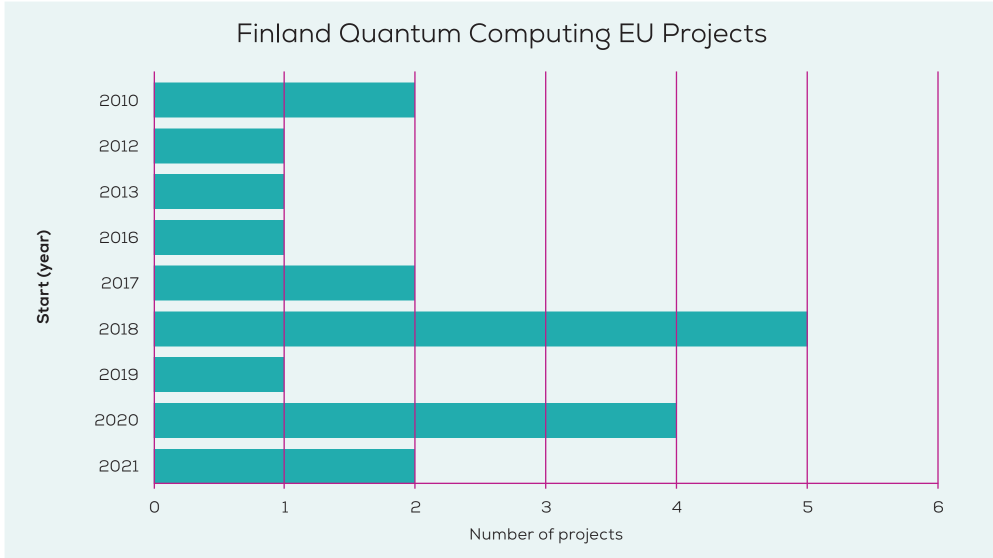
Outside of this, VTT and IQM are co-developing Finland's first quantum computer (superconducting) as part of a €20.7m public procurement project funded by the Ministry of Economic Affairs and Employment. This begins with an initial five-qubit computer, Helmi, with an overall goal to build a larger, 50-qubit device by around 2024. [79]. Helmi, hosted at VTT, will be connected with the Finnish LUMI exa-scale supercomputer. LUMI is co-funded by the European High-Performance Computing Joint Undertaking (through the EU's Connecting.

Europe Facility and Horizon 2020) and the LUMI Consortium, composed of the following countries: Finland, Belgium, Czech Republic, Denmark, Estonia, Iceland, Norway, Poland, Sweden, and Switzerland [86] [87].

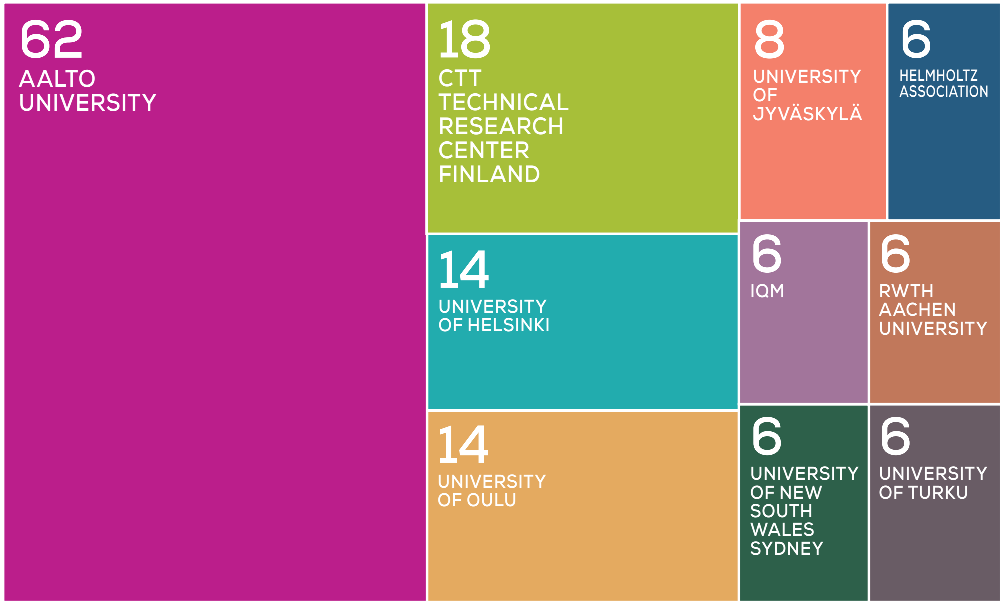
Collaborations

In April 2022 a Joint Statement of the United States and Finland around cooperation in QSIT was issued. This described collaboration and joint promotion in quantum computing and networking, as well as other quantum technologies, as underpinning the development of society and industry. It also included a statement "committing to create inclusive scientific research communities and tackle cross-cutting issues of common interest such as equity, diversity, inclusion, and accessibility, so that every person is able to fully participate and have an equal opportunity to succeed [88]. In the same month, it was announced that India and Finland will establish an Indo-Finnish Virtual Network Centre on Quantum Computing. The bilateral collaboration between the two countries attempts to stimulate innovative research and development projects that address a specific need or challenge, demonstrate high industrial relevance and commercial potential, and deliver benefit to both nations [89].

An analysis of Finland's involvement in EU projects reveals 19 projects funded in total, with over half starting in the last four years.



We analysed papers published from 2018 onwards, where some or all of the authors are based in Finnish institutions. A visualisation of the top ten funding bodies for these bodies of work is shown below, together with the affiliations of the authors. Finnish and European funding dominates, there is also activity from Japan, the UK and Germany. Unsurprisingly, Aalto University, VTT and the University of Helsinki top the affiliation list, with the University of Oulu also featured.



98 papers from Finnish authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of papers
PHYSICAL REVIEW B	6
NATURE COMMUNICATIONS	5
APPLIED PHYSICS LETTERS	4
NATURE	4
PRX QUANTUM	4
ANNALEN DER PHYSIK	3
PHYSICAL REVIEW RESEARCH	3
SCIENTIFIC REPORTS	3
ADVANCED QUANTUM TECHNOLOGIES	2
COMMUNICATIONS PHYSICS	2

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 621 times between them. These citations can provide an indication of activity, as well crosslinks and collaborations between the countries in question. After Finland, there is plenty of activity in the USA, followed by Australia, ahead of Germany.

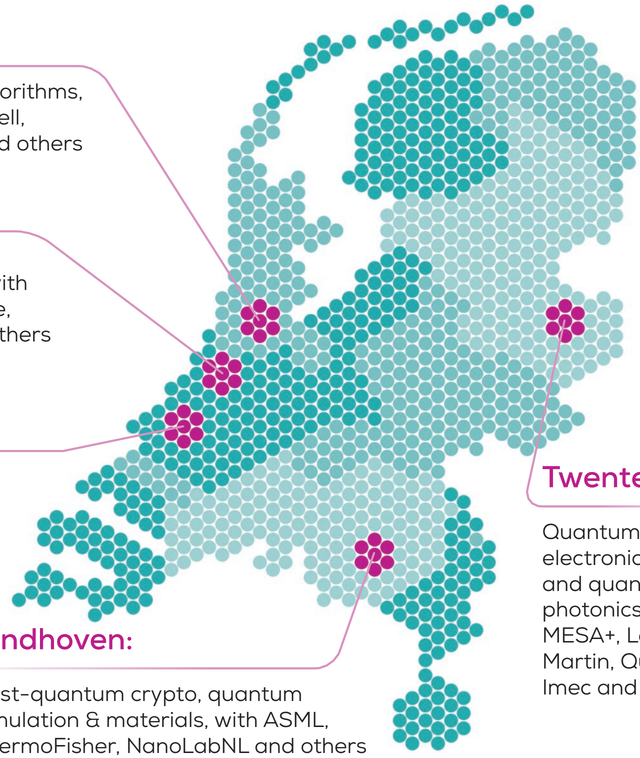
Journal	Number of citations
Australia	56
Austria	9
Belgium	4
Brazil	2
Canada	16
Chile	1
China	12
Colombia	1
Czech Republic	2
Denmark	4
Finland	179
France	12
Germany	46
Hungary	3
Iceland	1
India	3
Italy	9
Japan	19
Mexico	2
Netherlands	9
Poland	12
Portugal	2
Russia	11
Singapore	12
South Africa	1
Spain	12
Sweden	4
Switzerland	13
Thailand	1
UK	19
Ukraine	3
USA	140
Vietnam	1
Grand Total	**621**

The lead author's institutional country for these fifty papers is shown.

Journal	Number of papers
Australia	1
Austria	1
China	1
Denmark	25
Germany	3
Iran	1
Italy	2
Netherlands	3
Spain	4
Switzerland	1
UK	5
USA	3
Grand Total	**50**

Netherlands

September 2019 saw the release of National Agenda for Quantum Technology (NAQT), with the intent of positioning the Netherlands as a world-leading centre and hub for quantum technology. The Netherlands has invested approximately €615 million in quantum technology research and development, with funding from the Dutch Ministry of Economic Affairs and Climate Policy. In 2021, €54m was allocated from the National Growth Fund for the programme's first phase, with a further € 228m conditionally allocated for a second phase. In 2022, this conditional grant was converted into a definitive grant, and a further €333m reserved from the National Growth Fund for a 3rd phase. There is emphasis on creating a strong ecosystem connecting research, industry, startups, and national facilities [90] [91]. Core areas for the programme include Quantum Computation, Quantum Communication, Quantum Simulation and Quantum Sensing. For each area, the programme is building a network of suppliers, equipment manufacturers, application developers and end users [92].



Leiden:

Applied quantum algorithms, with aQa, Google, Shell, Volkswagen, Total and others

Delft:

Quantum computing, internet & network, with QuTech, Kavli Institute, Microsoft, Intel and others

Amsterdam:

Applied quantum algorithms, quantum sensing & simulation, with QuSoft, CWI, UvA, VU, SURFsara and others

Eindhoven:

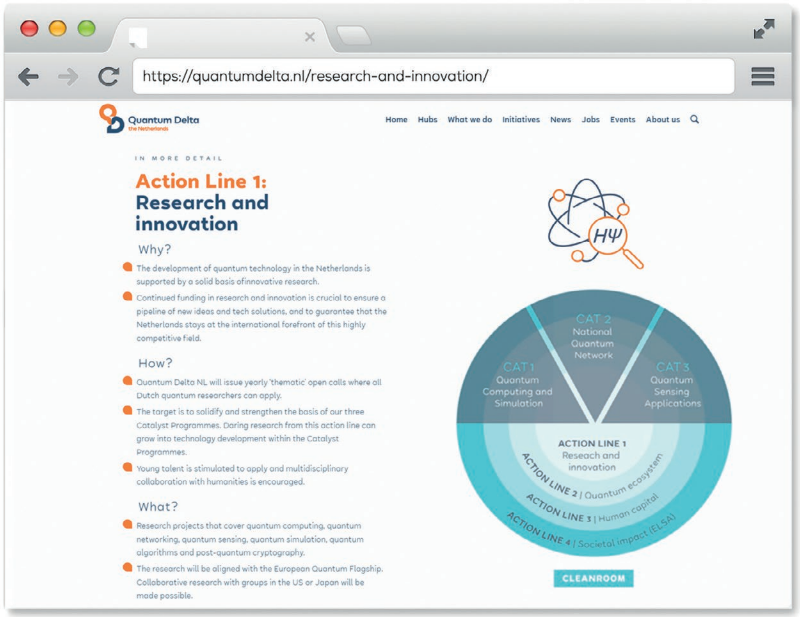
Post-quantum crypto, quantum simulation & materials, with ASML, ThermoFisher, NanoLabNL and others

Twente:

Quantum electronics and quantum photonics, with MESA+, Lockheed Martin, QuiX, Imec and others

Quantum Delta Netherlands (QDNL) is a public-private partnership of global technology companies, government agencies and all major quantum research centers in the Netherlands, launched in 2020 with the mandate to coordinate and execute the Netherland's national agenda for NAQT. QDNL is described as a comprehensive program to "turn the NL into a Silicon Valley for Quantum Technologies," aiming to position the Netherlands as a leading ecosystem in quantum technologies, with actions targeting all aspects of the ecosystem [93].

There are five hubs within QDNL, as shown, headquartered at Delft, Amsterdam, Leiden, Eindhoven, and Twente. Each hub consists of research institutes, universities, companies, and startups. QDNL's funding will be used to train 2,000 researchers and engineers, to scale 100 startups and to host three corporate R&D labs in the Netherlands by 2027.



Quantum Computing and Simulation is one of the QDNL's three key technology demonstrators, with research and innovation and quantum ecosystem forming the first two action lines [94] [93]. Furthermore, as part of the QDNL network, researchers at Eindhoven University of Technology are building a hybrid quantum computer, with an aim to deliver by 2024 [95].

In August 2021, an MoU was signed between the Netherlands and France, with responsibility for implementation lying with QDNL and the French national quantum programme. The MoU is designed to strengthen cooperation in areas of mutual interest, including scalable quantum computers, cross-border quantum communication networks, private investment in start-ups and industry involvement in quantum. The first action from the MoU was a joint Dutch/French job board, an initiative of QDNL which offers a free overview the majority of jobs available in the quantum-ecosystem of the Netherlands and France, which are collected daily from the sites of startups, knowledge institutes and businesses [96].

In March 2022, the Quantum Application Lab (QAL) opened to explore the advantages and business opportunities for quantum computing

- QAL is a public-private R&D partnership that offers a unique team of scientists, researchers, engineers, application developers, software and hardware specialists in a leading platform to explore and bring to market the benefits of quantum computing. QAL will support companies to navigate this complex and changeable environment. It will focus initially on optimization, simulation and machine learning applications. The founding consortium partners of QAL are: **the University of Amsterdam (UvA) and Centrum Wiskunde & Informatica (CWI, the national research institute for mathematics and computer science),**
- The Netherlands Organization for applied scientific research (TNO)
- the Dutch collaborative ICT Organization for Dutch higher education and research (SURF)
- Technical University TU Delft (on behalf Quantum Inspire)
- The Netherlands eScience Centre.

IBM Quantum will serve as a technology provider [97].

Quantum Centres

In June 2015, TU Delft and TNO, along with the Dutch Research Council, the Ministry of Economic Affairs and the Ministry of Education announced their intention to support QuTech for a period of 10 years, with the Knowledge and Innovation programme Holland High Tech also partnering on the endeavour. Holland High Tech is one of the nine key economic focus areas established and supported by the Dutch government to further strengthen the Dutch international position through the "golden triangle" formed by companies, research institutes and government. [98] QuTech is a mission-driven research institute for quantum computing, covering the full stack from and with particular strengths in solid-state qubits, as well as the quantum internet [87] [88]. Since 2015 QuTech has collaborated with Intel on spin qubits in quantum dots, superconducting qubits, cryogenic control electronics, and quantum computer architecture. [99] QuTech's goals for quantum computing are:

1. To build a modular spin-qubit processor
2. To release a scalable error-protected logical qubit with a 17-qubit superconducting circuit
3. To develop a scalable quantum computing control system stack
4. To implement cryogenic integrated control and readout electronics operating in close proximity to the qubits
5. To provide analyses and ideas towards implementing and assessing the performance of quantum error correction for superconducting spin qubits [99], [100].

QuTech also has the Qubit Research (QuRe) division, working to develop novel qubits that are protected from noise by design, on the belief that protected qubits will enable them to build a scalable quantum computer.

In 2019 QuTech announced a partnership with Microsoft, who opened a new lab at Delft called the *Microsoft Quantum Lab Delft* in 2019. Ernst-Jan Stigter, General Manager of Microsoft Netherlands, asserted that "Joint public-private investments in resources and infrastructure, as we see here today, are critical to a quantum future," [101].

In May 2020, QuTech announced Quantum Inspire, a prototype full-stack quantum computer, serving as a training and education platform, a test-bed for application development and as an invitation for co-development and collaborative R&D of quantum computers. Quantum Inspire is described as a platform with a high degree of modularity, containing a processor made of semiconductor spin qubits whilst also providing access to a processor made of superconducting (transmon) qubits. [102] QuTech is also a founder of Quantum Delft, a research and business community working within the growing quantum ecosystem at Delft [103].

As well as QuTech, QuSoft – collaboration between the University of Amsterdam (UvA) and Centrum Wiskunde & Informatica (CWI) – was also founded in 2015. QuSoft's mission is to develop new protocols, algorithms and applications that can be run on small to full-scale prototypes of a quantum computer [104]. The research at QuSoft can be divided into five research lines: Quantum Simulations & Few-Qubit Applications, Quantum Information Science, Cryptography in a Quantum World, Quantum Algorithms & Complexity and Quantum for Society and Business.
One notable project QuSoft is working on is Project DisQover, a collaboration with ABN AMRO that explores potential applications of quantum computing in the financial industry. It aims to identify the complex computing problems ABN AMRO is currently tackling or would like to tackle in the near future, and research if and how these problems can be solved more efficiently on a quantum computer. QuSoft is also working with the Bosch Group in a two-year collaboration, investigating potential quantum computing use cases at Bosch, in topics ranging from optimization to machine learning. The collaboration involves an exploratory study of the use cases, as well as in-depth analysis and proof-of-concept simulations of the most promising applications [105].

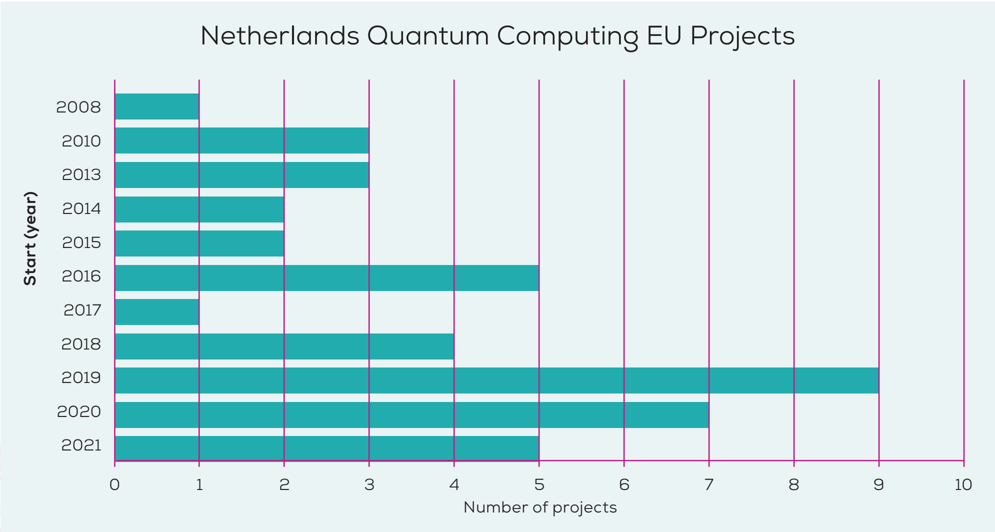
QuSoft has also started an exchange program with Quantum Leap Africa (QLA), a research institute in Rwanda closely linked to AIMS, the African Institute for Mathematical Sciences. For this exchange program QuSoft hosts QLA Master students – during their time in the Netherlands, they work on an MSc research project under the guidance of QuSoft researchers to prepare them for a future in quantum research [106].

At a regional level, QuSoft founded Quantum.Amsterdam, along with partners Centrum Wiskunde & Informatica and The University of Amsterdam. It is an innovation hub with a mission to connect academia, industry and society in a quantum ecosystem in the Amsterdam region by facilitating knowledge exchanges and innovation [107].

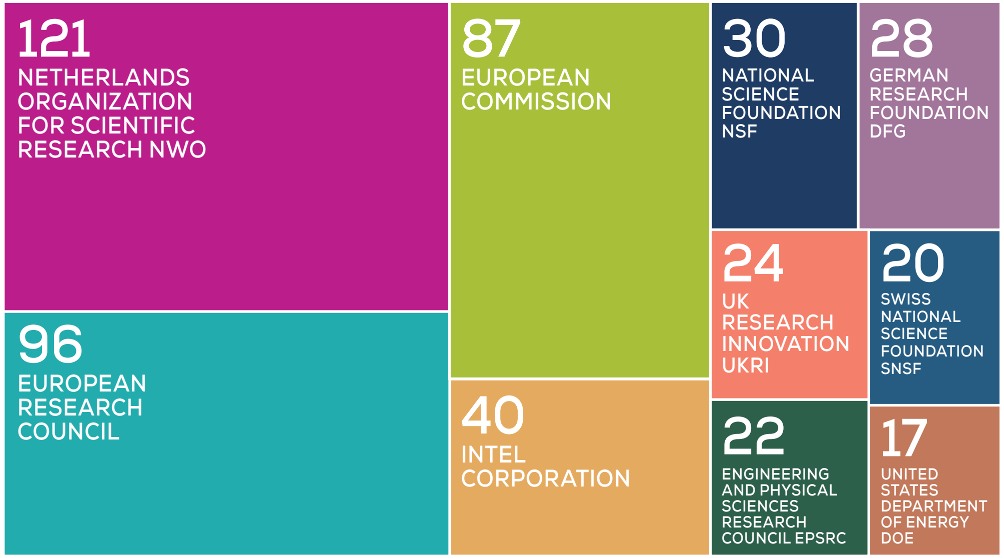
Both QuTech and QuSoft are collaborating as part of the Quantum Software Consortium (QSC). QSC is a project of University of Amsterdam, Leiden University, Delft University of Technology, Center for Mathematics and Computer Science (CWI) and Vrije Universiteit Amsterdam, partnered with QuTech and QuSoft, which is funded through the Gravitation programme of NWO (Netherlands Organization for Scientific Research) and awarded a 10-year grant for fundamental research in 2017. The QSC leverages the nearby clusters of expertise in quantum software (QuSoft, QuTech & Leiden) and quantum hardware (QuTech, Amsterdam & Leiden), and acts across four research lines, (i) software for quantum computers, (ii) software for quantum networks, (iii) cryptography in a quantum work and (iv) demonstrators [108] [109].

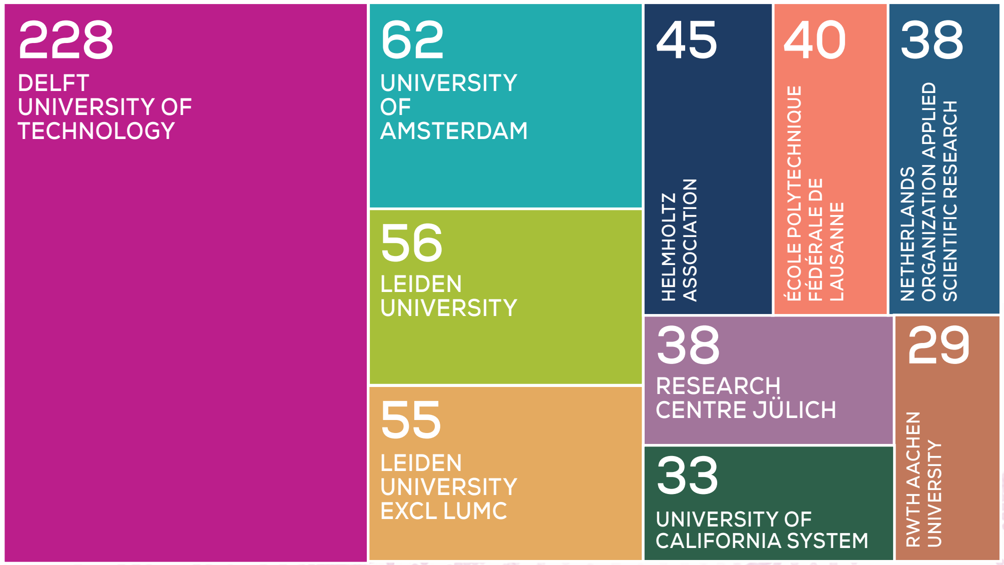
Women in Quantum Development, or in short WIQD (pronounced "wicked"), is a professional network for quantum technology enthusiasts from industry, academia, and policy. Its mission is to bring together women in quantum in the Netherlands, and beyond, for support, networking, and community growth [110].

An analysis of the Netherlands's involvement in EU projects reveals 42 projects funded in total, and a clear ramp-up in activity – half of the projects have started within the last three years alone.



We analysed papers published from 2018 onwards, where some or all of authors are based in Dutch institutions. A visualisation of the top ten funding bodies for these bodies of work is shown below, along with visualisations showing the affiliations of the authors are also shown. After funding from the Netherlands and Europe, Intel tops the list. Unsurprisingly, Aalto University, VTT and the University of Helsinki top the affiliation list, with the University of Oulu also featured.





457 papers from Dutch authors were published in this period. The most common journals these papers were published in are shown below.

Journal	No. of papers
PHYSICAL REVIEW A	32
QUANTUM	19
PHYSICAL REVIEW LETTERS	18
NATURE	15
PHYSICAL REVIEW B	14
QUANTUM SCIENCE AND TECHNOLOGY	14
NATURE COMMUNICATIONS	13
NEW JOURNAL OF PHYSICS	13
NPJ QUANTUM INFORMATION	13
PHYSICAL REVIEW X	11

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 619 times between them. These citations can provide an indication of activity, as well crosslinks and collaborations between the countries in question. Again, the USA dominates the list after the Netherlands itself, followed at some distance by several EU countries, along with China and the UK.

Journal	Number of citations
Australia	13
Austria	4
Belgium	2
Brazil	2
Canada	6
Chile	1
China	21
Denmark	10
Finland	1
France	11
Germany	28
Hungary	1
India	2
Ireland	1
Israel	1
Italy	7
Japan	4
Netherlands	218
Poland	4
Republic of Korea	2
Singapore	1
Spain	22
Sweden	2
Switzerland	25
UK	20
USA	210
Grand Total	**619**

Journal	Number of papers
Australia	1
Belgium	1
China	3
Italy	1
Netherlands	32
Poland	1
Spain	4
Switzerland	1
USA	6
Grand Total	**50**

Poland

Quantum computing is contained within Poland's Cyber Poland 2025 program, under "High Performance Computing & Quantum Computing." The program aims to bring quantum computing to Poland's strategic resources [111]. In February 2022 it was announced the Polish Poznań Supercomputing and Networking Center (PSNC) would join the IBM Quantum Network, becoming the first such hub in central and eastern Europe. Janusz Cieszyński, Secretary of State, Government Plenipotentiary for Cybersecurity noted: "In order to keep a strong position in the European economy, Poland needs to actively participate in research and development work focusing on quantum computing. Also, to meet the ambitious objectives in the area of digital innovation benefiting science and the information society, we need to ensure that Poland has access to innovative e-infrastructure. Such access is vital for ensuring that all interested Polish parties are capable of taking advantage of highly advanced engineering and big data computing technologies. The incorporation of quantum computers into Poland's strategic resources is one of the tasks we have ventured to achieve under the Cyber Poland 2025 program," [112].

Whilst Poland lacks a coordinated national quantum programme, there is a strong research activity in quantum, and cooperation between leading institutions helps drive the quantum agenda.

In 2007, The Quantum Information Centre in Gdańsk (KCIK) was established at the University of Gdańsk as a joint research unit with eight Polish universities and research institutions: Gdańsk University of Technology, Adam Mickiewicz University, University of Gdańsk, Jagiellonian University, Nicolaus Copernicus University, University of Łódź, University of Wrocław, and the Polish Academy of Sciences (PAN). In June 2011, membership of KCIK was expanded to include the Centre for Theoretical Physics PAN.

The mission of the Centre is to create an integrated basis for interdisciplinary research in fields of quantum information processing and foundations of physics. Its research areas include Quantum Cryptography, Quantum Error Correction and Fault-Tolerant Quantum Computation [113].

In 2018, the Centre for Quantum Optical Technologies was founded at the University of Warsaw. It has research programmes in

- Quantum Technologies
- Quantum Memories
- Quantum Information and Inference
- Quantum Resources and Information
- Quantum Optical Devices

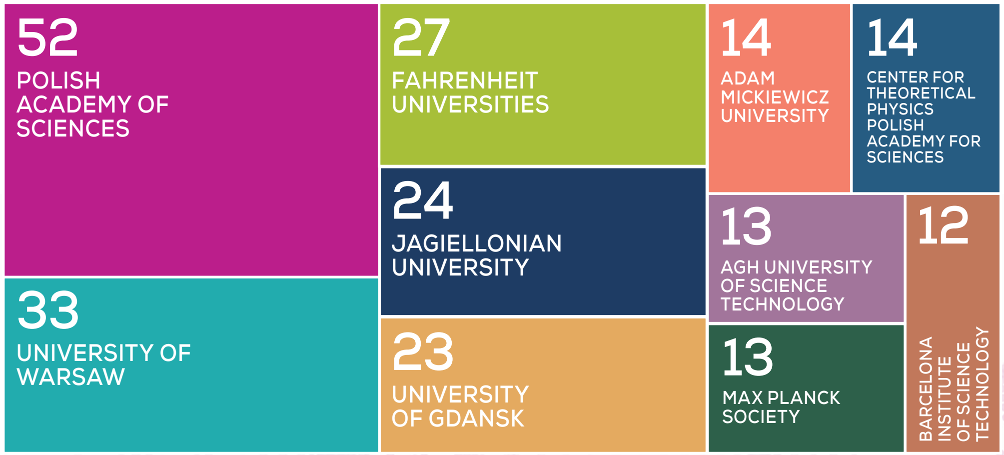
The Centre was established with involvement from the University of Oxford under the International Research Agenda Programme, operated by the Foundation for Polish Science, and is hosted in the Centre of New Technologies.

More recently, in February 2021 six Polish universities and two institutes of the Polish Academy of Science, signed a letter of intent on cooperation and the development of research. The cooperation between scientific centres will aim to establish an organisational structure for research and development of quantum technologies in Poland. The signatories of the letter also recognise the need for systemic and financial support from state bodies for world-class research in this field conducted in Poland. The signatories were as follows: Warsaw University, University of Gdańsk, Centre for Theoretical Physics PAN, Jagiellonian University, Nicolaus Copernicus University in Toruń, Adam Mickiewicz University, Wrocław University of Technology and the Institute of Physics of PAN [114].

There are some notable large-scale projects in Poland. One such example is the TEAM-NET project "Quantum computers in the near future: challenges, optimal implementations and practical applications". TEAM-NET is a programme of the Foundation for Polish Science which allows the funding of interdisciplinary scientific research carried out by a network of cooperating research teams. This project received PLN 17.77m (~€3.75m), and has four research groups investigating: quantum computing, quantum machine learning, control of complex quantum systems, quantum error correction and the issue of identifying resources responsible for the so-called quantum acceleration. The consortium of institutions include: the Centre for Theoretical Physics, the Faculty of Physics, Astronomy and Applied Computer Science at the Jagiellonian University, the Institute of Theoretical and Applied Informatics of the Polish Academy of Sciences [115]. Another TEAM-NET funded project is "Near-term Quantum Computers," which aims at characterizing the computational power and investigating possible practical applications of quantum computing devices consisting of a limited number of imperfect qubits [116].

In terms of European activity, fifteen research teams from Poland were among the winners of the QuantERA Co-funded Call 2021 for international research projects in the field of quantum technologies. Ten basic research projects will be co-funded by the National Science Centre and five applied research projects will be co-funded by the National Centre for Research and Development. The National Science Centre has awarded funding for that purpose of over PLN 7.7m [117]. Poland has had seven quantum-computing-related projects funded through FP7 and Horizon 2020.

We analysed papers published from 2018 onwards, where some or all of the authors are based in Polish institutions. A visualisation of the top ten funding bodies for these bodies of work is shown below, along with visualisations showing the affiliations of the authors are also shown. Germany, the UK and Spain all feature prominently.



200 papers from Polish authors were published in this period. The most common journals these papers were published in are shown below.

Journal	No. of papers
PHYSICAL REVIEW A	18
PHYSICAL REVIEW LETTERS	11
PHYSICAL REVIEW	7
QUANTUM	7
QUANTUM INFORMATION PROCESSING	7
NEW JOURNAL OF PHYSICS	6
NPJ QUANTUM INFORMATION	5
PHYSICAL REVIEW RESEARCH	5
ENTROPY	4
IEEE TRANSACTIONS ON INFORMATION THEORY	4

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 440 times between them. These citations can provide an indication of activity, as well crosslinks and collaborations between the countries in question. Other than the USA (which tops the list) and Poland itself, Germany, China, the UK, Spain and the Netherlands feature highly.

Journal	Number of citations
Australia	5
Austria	15
Belgium	3
Brazil	4
Canada	5
China	28
Croatia	1
Czech Republic	2
Denmark	5
Egypt	3
Finland	9
France	3
Germany	43
Greece	1
Iceland	1
Ireland	10
Israel	3
Italy	9

Journal	Number of citations
Japan	8
Korea	2
Lithuania	1
Mexico	3
Netherlands	23
Norway	1
Poland	78
Russia	2
Singapore	3
Spain	26
Sweden	1
Switzerland	2
Thailand	1
UK	27
USA	110
Portugal	2
Grand Total	**440**

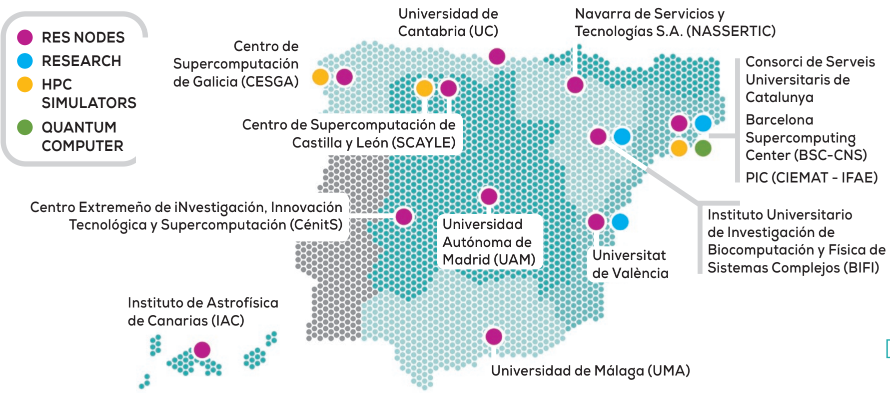
Journal	Number of papers
Austria	1
Canada	1
China	5
Egypt	1
Finland	1
France	1
Germany	7

Journal	Number of papers
Netherlands	3
Poland	19
Singapore	1
Spain	1
UK	2
USA	7
Grand Total	**50**

Spain

Spain's national initiative, Quantum Spain, is framed within the National Strategy for Artificial Intelligence. Its aim is to establish a solid quantum computing ecosystem in Spain, taking advantage of and promoting the talent of local researchers who are experts in this technology. This objective leverages the existing Spanish Supercomputing Network [118]. €22m was initially made available for the endeavour, with funding provided by Spain's Ministry of Economic Affairs and Digital Transformation and the EU's NextGenerationEU.

Quantum Spain involves 25 universities and infrastructure and supercomputing centres, from 14 autonomous communities. The Barcelona Supercomputing Center (BSC, the main node of the Spanish Supercomputing Network) began coordination work on the project in 2021. [118]



[118]

The project foresees the construction of a quantum computer that will be installed at BSC headquarters and that will progressively be equipped with chips of different generations and numbers of qubits, initially based on superconducting circuit technology. The construction of the hardware will be carried out in collaboration with companies [119]. In June 2022, an open call for tender for a quantum computer was announced. This is an €8.2m call for the "acquisition of a computer based on superconducting qubit technology and its quantum processors… for use by the BSC-CNS and the users of the Spanish Supercomputing Network,"

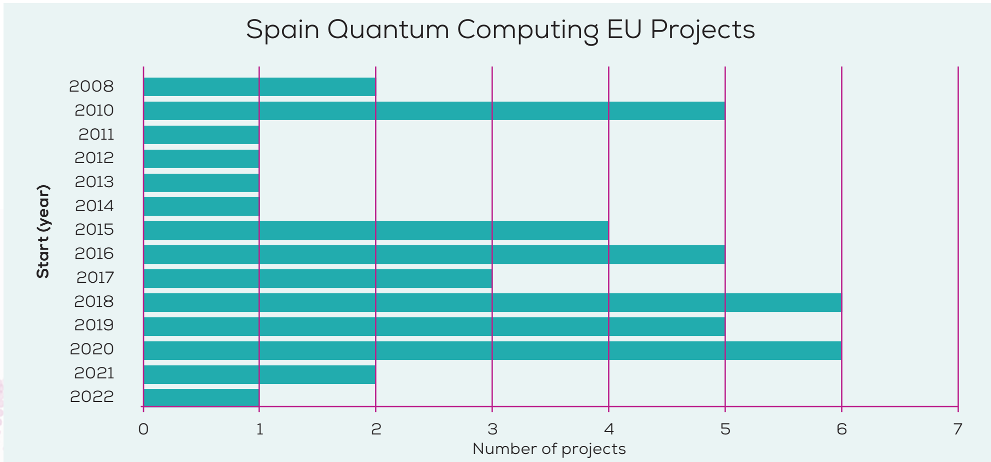
BSC also has a Quantic Group, focussed on quantum simulation architectures in HPC systems, allowing the behaviour of quantum algorithms to be reproduced using the parallelised architecture of supercomputers. These simulators will make it easier for developers to design circuits and algorithms, reproducing the operation of ideal quantum computers (without noise), offering traceability of the steps to be executed, as well as a reference for experimental developments [121].

There are various other groups within Quantum Spain, such as The QUANTIA (Quantum AI for scientific and industrial applications) group of Universidad de Zaragoza is exploring applications of quantum optimization for commercial and scientific interests. These include comparative studies of quantum algorithms of optimization (variational algorithms NISQ, quantum annealers, and qudit type molecular processors), and analysis of non-supervised quantum machine learning algorithms [122]. Another team is the Quantum Computers and Quantum Simulations Group of the University of Valencia, which studies and characterizes noise in quantum computers using AI techniques. [123]

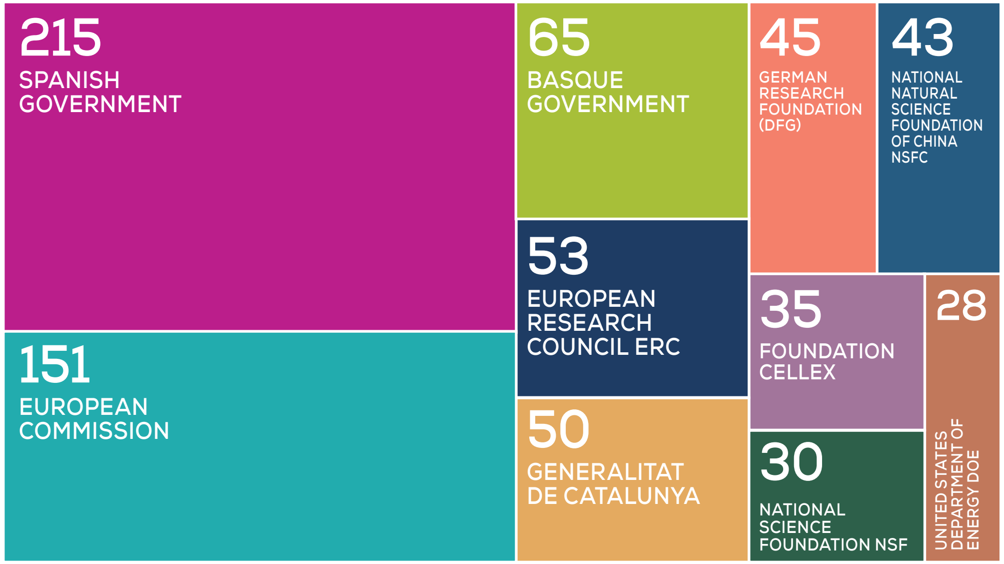
Quantum Spain also has a TalentQ programme, designed to train the next generation of quantum experts. The TalentQ program will promote the search and training of Spanish quantum talent through the organisation of online and face-to-face courses, quantum hackathons, promotion of local initiatives and groups in quantum computing, among other activities [124].

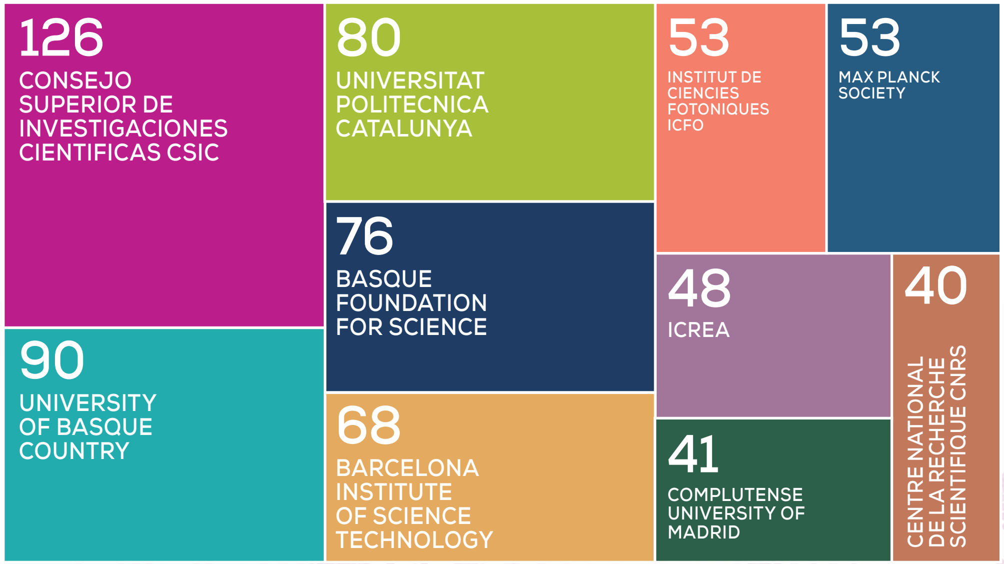
Outside of Quantum Spain, in January 2022, the CUCO (CUantica COmputacion) project to research potential quantum computing applications, led by firm GMV was announced, running for 2 years with €5.8m of funding. The project focuses on quantum computing applications and algorithms in the strategic industries of the Spanish economy such as Energy, Financial, Space, Defence and Logistics. It includes 7 companies (Amatech, BBVA, DAS Photonics, GMV, Multiverse Computing, Qilimanjaro Quantum Tech and Repsol), 5 research centres (BSC, CSIC, DIPC, ICFO y Tecnalia) and the public university UPV (Universitat Politècnica de València). [125] It is financed by the Centre for the Development of Industrial Technology, with support from the Ministry of Science and Innovation [126].

An analysis of the Spain's involvement in EU projects reveals 43 projects funded in total, with a large portion of activity taking place between 2018-2020.



We analysed papers published from 2018 onwards, where some or all of the authors are based in Spanish institutions. A visualisation of the top ten funding bodies for these bodies of work is shown below, along with visualisations showing the affiliations of the authors are also shown. After funding from the Spanish government and Europe, there is clear regional activity shown (Basque, Catalunya), as well as funding from Germany, China and the USA.





512 papers from Spanish authors were published in this period. The most common journals these papers were published in are shown below.

Journal	No. of papers
PHYSICAL REVIEW A	48
PHYSICAL REVIEW B	24
NEW JOURNAL OF PHYSICS	17
PHYSICAL REVIEW LETTERS	16
PHYSICAL REVIEW RESEARCH	14
QUANTUM	13
QUANTUM INFORMATION PROCESSING	12
PRX QUANTUM	10
NATURE COMMUNICATIONS	9
QUANTUM SCIENCE AND TECHNOLOGY	9

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 619 times between them. These citations can provide an indication of activity, as well crosslinks and collaborations between the countries in question. Again, the USA dominates the list after the Netherlands itself, followed at some distance by several EU countries, along with China and the UK.

Journal	Number of citations
Australia	13
Austria	4
Belgium	2
Brazil	2
Canada	6
Chile	1
China	21
Denmark	10
Finland	1
France	11
Germany	28
Hungary	1
India	2
Ireland	1
Israel	1
Italy	7
Japan	4
Netherlands	218
Poland	4
Republic of Korea	2
Singapore	1
Spain	22
Sweden	2
Switzerland	25
UK	20
USA	210
Grand Total	**619**

Journal	Number of papers
Austria	1
Canada	1
China	2
Denmark	2
Finland	1
France	1
Germany	7
India	1
Italy	1
Netherlands	1
Russia	1
Spain	16
Switzerland	2
UK	5
USA	8
Grand Total	**50**

Sweden

Sweden lacks a national programme in quantum, however that is not to say the country lacks large-scale, coordinated activity. A prime example of this is the Wallenberg Centre for Quantum Technology (WACQT), established in 2018 to create long-term expertise in quantum computing, simulation, communication, and sensing. This SEK 1.2bn (circa €110m) centre spans multiple universities and is funded through the Knut and Alice Wallenberg Foundation, with an additional SEK 200m from universities and industry taking total funding to SEK 1.4bn. The research programme is managed and mainly located at Chalmers University of Technology, with KTH Royal Institute of Technology and Lund University, as well as several industrial partners, including Saab, Hitachi ABB, AstraZeneca, Ericsson, Jeppesen and Volvo [127]. The collaboration between academia and industry is seen as key for taking Sweden forward, in this case provide WACQT scientists with real-life applications to investigate whilst companies gain forefront knowledge and competence which allow them to identify business opportunities [127] [128].

Quantum Computing is considered core for WACQT [128]. There is a strong expertise in superconducting qubits, on which the project's principal investigators have worked for many years. The strong cooperation between experimentalists and theoreticians is considered a cornerstone for success at WACQT. The first milestone for the quantum computer project is to build two interlinked blocks each containing ten qubits within four years, which will make it possible to demonstrate basic quantum simulations of small systems. The final goal is to develop a 100-qubit quantum computer within ten years.

WACQT has a vision to is to build an open and interactive Swedish quantum technology community, considering that rich flow of ideas in an open environment increases both the scientific quality and relevance as well as shortens the time to utilisation of results. The following instruments help achieve this: a graduate school, the Swedish Graduate School in Quantum Technology; a postdoc program; a guest researcher program; industrial partnerships [127] [128].

Collaborations

In April 2022, the United States and Sweden signed a Quantum Cooperation Statement, detailing the shared agendas of both countries to engage in good-faith cooperation in QIST, such as to build a global market and supply chain, and to create respectful and inclusive scientific research communities. Anna Ekström, the Swedish Minister for Education, Ministry of Education and Research, said, "By making a joint statement that we want to collaborate in the quantum field, Swedish and American researchers get the opportunity to collaborate with the best researchers in this field in our two countries. It contributes to strengthening our position as leading research nations," [129].

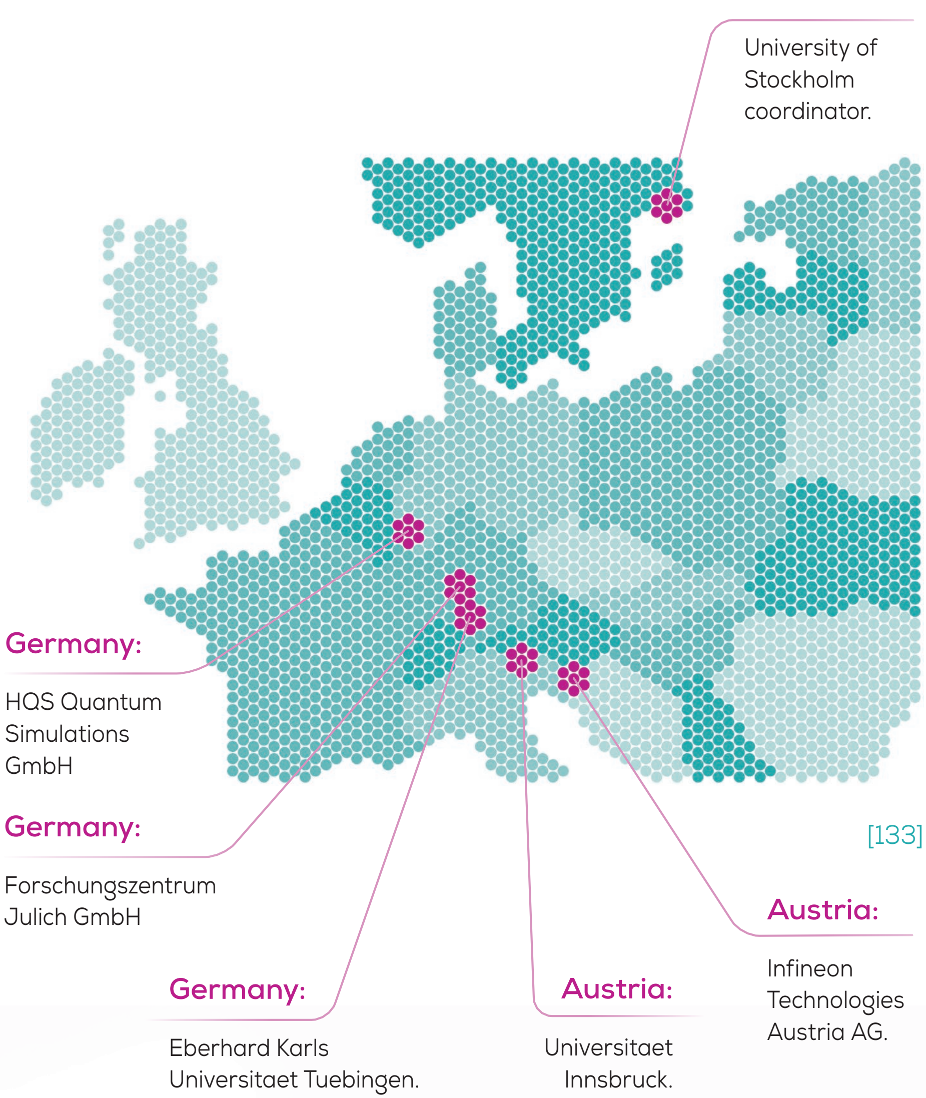
Sweden is involved in several large-scale EU-funded projects, collaborating with European partners. A notable example is at the aforementioned Chalmers University of Technology, Andreev qubits for scalable quantum computation (AndQC). The goal of this project is to establish the foundations of a new solid state platform for scalable quantum computation, based on Andreev qubits. This platform is implemented by utilizing the discrete superconducting quasiparticle levels (Andreev levels) that appear in weak links between superconductors. The €3.6m project runs from September 2019 to March 2023 and consists of the below partners organisations:

- Delft University of Technology (Academic, Netherlands)
- National Research Council of Italy (CNR) (Public, Italy)
- Universidad Autónoma de Madrid (UAM) (Academic, Spain)
- The French Alternative Energies and Atomic Energy Commission (CEA) (Research Institute, France)
- University of Basel (Academic, Switzerland)
- University of Copenhagen (Academic, Denmark)
- Budapest University of Technology and Economics (Academic, Hungary)

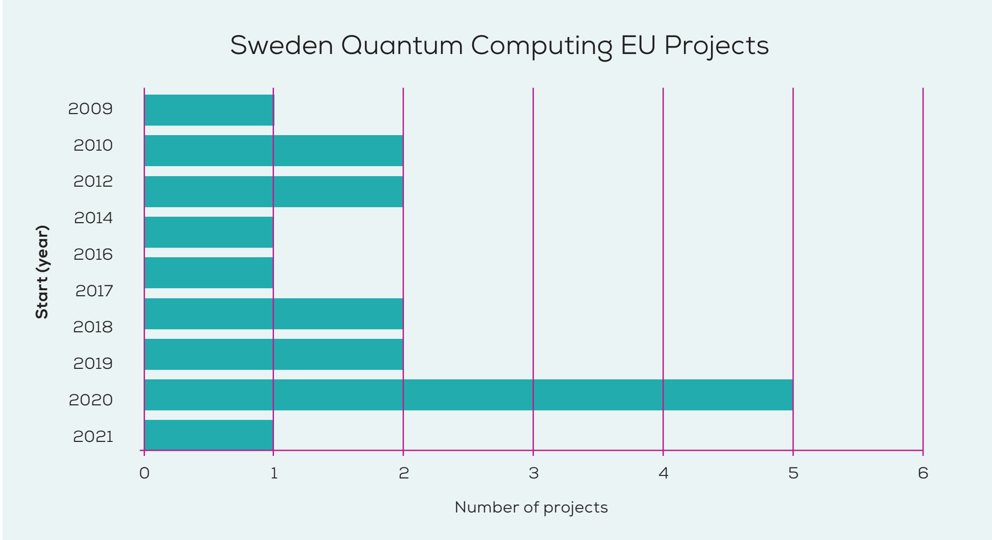
[130]

Aside from the strengths in superconducting in Sweden, there is a notable expertise in trapped Rydberg ions in Stockholm. In 2017, researchers at Stockholm University reported on the excitation of a single trapped strontium ion into the Rydberg state, and that same year carried out the first coherent Rydberg excitation of an ion and performed a single-qubit Rydberg gate, thus demonstrating the basic elements of a trapped Rydberg ion quantum computer [131] [132]. A new 3 year, €3m project in this field begins in October 2022. Brisk Rydberg Ions for Scalable Quantum Processors (BRISQ), led from Stockholm University, aims to realize a prototype of a fully scalable quantum computer which has the capability to run quantum algorithms with a circuit depth exceeding one million.

The collaborators for this project are :



An analysis of Sweden's involvement in EU projects reveals 18 projects funded in total, with a third of these beginning in the last two years (excluding 2022).



We analysed papers published from 2018 onwards, where some or all of the authors are based in Swedish institutions. A visualisation of the top ten funding bodies for these bodies of work is shown below, along with visualisations showing the affiliations of the authors are also shown. After funding from the Swedish government and the EU, the Knut and Alice Wallenberg Foundation is notable, as is funding from Germany, China and the UK.

134 papers from Swedish authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of papers
PHYSICAL REVIEW B	17
PHYSICAL REVIEW A	15
PHYSICAL REVIEW LETTERS	7
NEW JOURNAL OF PHYSICS	5
APPLIED PHYSICS LETTERS	4
PHYSICAL REVIEW APPLIED	4
PHYSICAL REVIEW RESEARCH	4
PRX QUANTUM	4
NATURE COMMUNICATIONS	3
PHYSICAL REVIEW X	3

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 589 times between them. These citations can provide an indication of activity, as well crosslinks and collaborations between the countries in question. Other than Sweden, there are high citation figures from the USA, France, Germany, China and Spain.

Journal	Number of citations
Argentina	6
Australia	17
Austria	19
Belgium	3
Brazil	1
Canada	7
China	42
Croatia	1
Czech Republic	3
Denmark	22
Finland	4
France	60
Germany	59
Greece	1
Hungary	1

Journal	Number of citations
India	1
Italy	13
Japan	11
Netherlands	8
Norway	3
Poland	1
Russia	2
Singapore	1
Spain	41
Sweden	114
Switzerland	28
UK	30
USA	90
Grand Total	**589**

The lead author's institutional country for these fifty papers is shown.

Journal	Number of papers
Austria	2
Belgium	1
Canada	1
China	5
Denmark	4
Finland	1
France	1
Germany	3
Italy	1
Japan	2
Netherlands	1
Norway	1
Spain	1
Sweden	17
Switzerland	2
UK	2
USA	5
Grand Total	**50**

Switzerland

Switzerland was one of the first countries to bring together quantum research in a coordinated programme – through their National Centre of Competence in Research (NCCR) vehicle.

Switzerland has established national centres across different themes, including QSIT – Quantum Science & Technology. Created in 2010 with the goal to advance the fundamental understanding of quantum systems and to establish practical platforms for exploring applications in quantum computing, communication, sensing and simulation, the QSIT initiative brings over 30 research groups together from organisations across Switzerland. A notable research activity is in engineered quantum states, in particular engineered topological states and entangled 'dressed' states between a cavity and a qubit [134]. The participating organisations include ETH Zürich, University of Basel, Université de Genève, EPFL, IBM and Università della Svizzera Italiana.

On the 16th of December 2019, the Federal Government and the Swiss National Science Foundation (SNSF) announced that "SPIN: Spin Qubits in Silicon" was one of six new NCCRs. For its first phase from August 2020 to July 2024, the NCCR SPIN will receive federal funding of CHF 17m (€17.7m). The goal of SPIN is to develop small, fast and scalable quantum bits and quantum interconnects such that wafer-scale quantum circuits can be fabricated by the semiconductor industry [135] It is carrying out research in electron spin qubits, quantum architectures, and hole spin qubits [135].

Quantum Centres

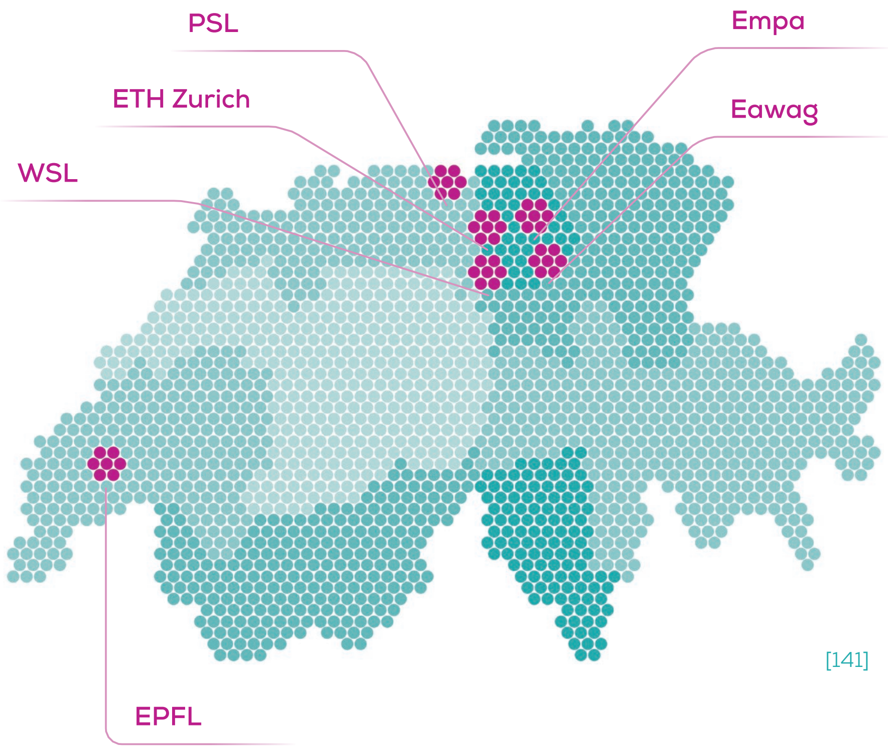
As well as participating in national programmes, various universities have dedicated quantum centres. The Basel Quantum Centre at the University Basel is one such example, with research areas including quantum computing, spin qubits and quantum optics. The centre comprises 15 research groups in theoretical and experimental quantum physics, and is thematically closely connected to the Swiss Nanoscience Institute (SNI), the NCCR Quantum Science and Technology, and the NCCR SPIN. It draws its major funding from the Swiss National Science Foundation and from many European programs including the Quantum Technologies Flagship [136].

The Basel Centre is part of the Georg H. Endress Postdoc cluster, a cross-border collaboration between the University of Basel and the Albert-Ludwigs University in Freiburg (Germany). This is a dedicated ten-year initiative to foster and educate outstanding young scientists to provide the academic talent and technology skills for the rapidly developing fields of quantum science and quantum computing, through engaging young scientists in projects involving existing research groups at Basel and Freiburg [137].

There is also notable activity in Zurich. ETH Zürich's Quantum Center coordinates the institutions various scientific and structural activities in quantum science and technology, in particular interconnecting research and teaching across ETH departments. The Center also serves as an ETH Zürich-wide contact point for larger projects, including collaborations with industrial partners and funding through Swiss and international grant agencies [138] There is also an Engineering Unit, which engages in collaborations with Swiss and international industries. It promotes the creation of spin-off companies based on its own developments and those of its partner labs at ETH. It fosters the creation of intellectual property and supports developments pursued by individual research groups at ETH in the context of quantum engineering [139]. The Engineering Unit is supported by ETH Zürich through an ETH+ Project, the NCCR QSIT, ETH Zürich Foundation, and its member groups.

Related to this is the ETHZ-PSI Quantum Computing Hub, a research facility jointly operated by ETH Zürich and the Paul Scherrer Institut (PSI). PSI is the largest research institute for natural and engineering sciences in Switzerland, employing 2100 people and with an annual budget of approximately CHF 400 million. The hub builds on the extensive experience at the Quantum Devices Laboratory and the Trapped Ion Quantum Information group at ETH Zürich and combines it with the broad expertise and resources available at PSI. The aims of the Hub are to scale up to larger scale systems of tens of qubits, advance materials and control, and to exploit synergies across technologies and the software stack [140].

Both ETH Zürich and PSI are part of the ETH Domain. The ETH Domain comprises Switzerland's two federal institutes of technology (FIT) – ETH Zurich and the EPFL in Lausanne – and four research institutes: the Paul Scherrer Institute (PSI), the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), the Swiss Federal Laboratories for Materials Science and Technology (Empa) and the Swiss Federal Institute of Aquatic Science and Technology (Eawag).

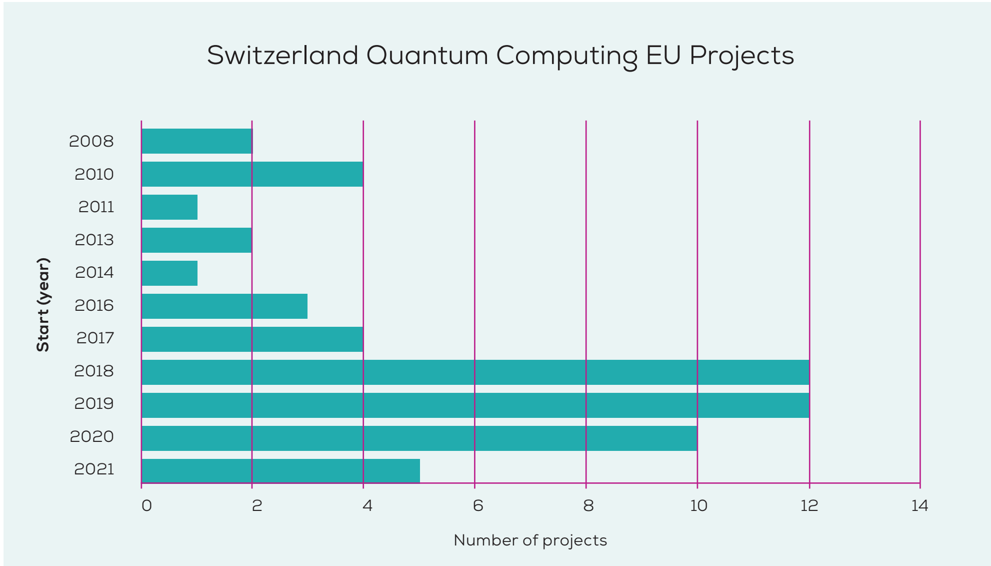


[141]

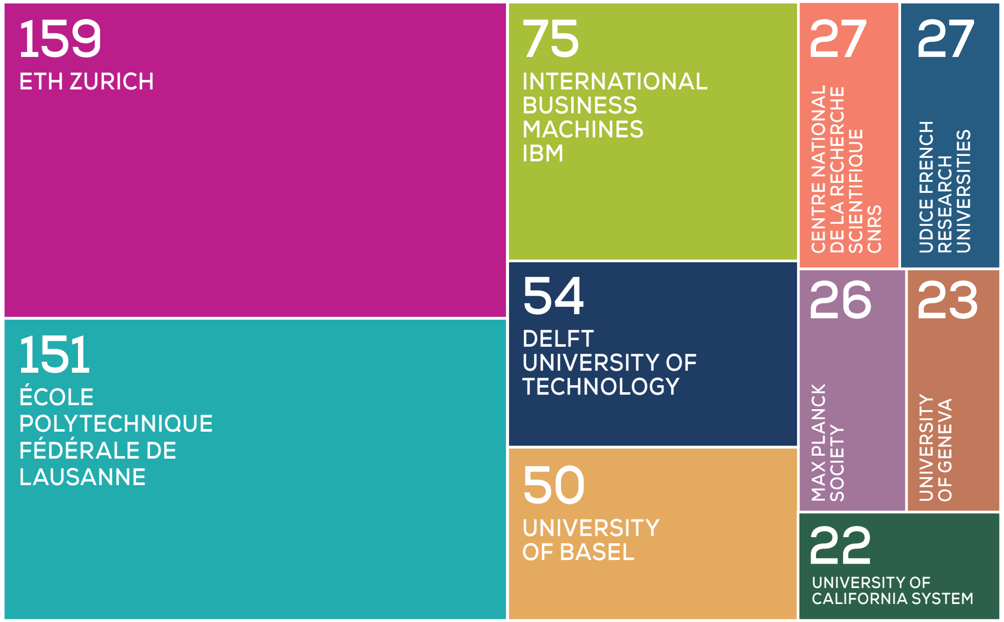
EPFL has its own Center for Quantum Science and Engineering (QSE). The Center promotes and supports collaborative research through the creation of collaborative QSE grants, multidisciplinary education, and innovation, focusing on two pillars: Applied quantum algorithms and data science, and quantum hardware materials and systems. The former looks at fundamental research for the development and improvement of quantum algorithms and the related software infrastructure, to their large-scale implementation. The latter explores new physical implementations of quantum hardware, leveraging the nanofabrication facilities present on campus. In conjunction with EPFL's Startup Launchpad, QSE has launched its Grants for Entrepreneurial Projects in Quantum, aimed at accelerating the journey from lab to market through an investment up to CHF 180k over a period of two years [142] [143].

Finally, there is the Swiss Quantum Hub (SQH) non-profit organization based in Geneva that describes itself as a Think Tank, Startup accelerator and Business Services for the Swiss QC community. SQH provides, among other things, publications, training, a startup accelerator programme and provides links to quantum researchers, businesses and investors [144].

An analysis of Switzerland's involvement in EU projects reveals 56 projects funded in total, one of the highest in Europe, with 39 of these starting in the last four years.



We analysed papers published from 2018 onwards, where some or all of the authors are based in Swiss institutions. A visualisation of the top ten funding bodies for these bodies of work is shown below, along with visualisations showing the affiliations of the authors are also shown.



483 papers from Swiss authors were published in this period. The most common journals these papers were published in are shown below.

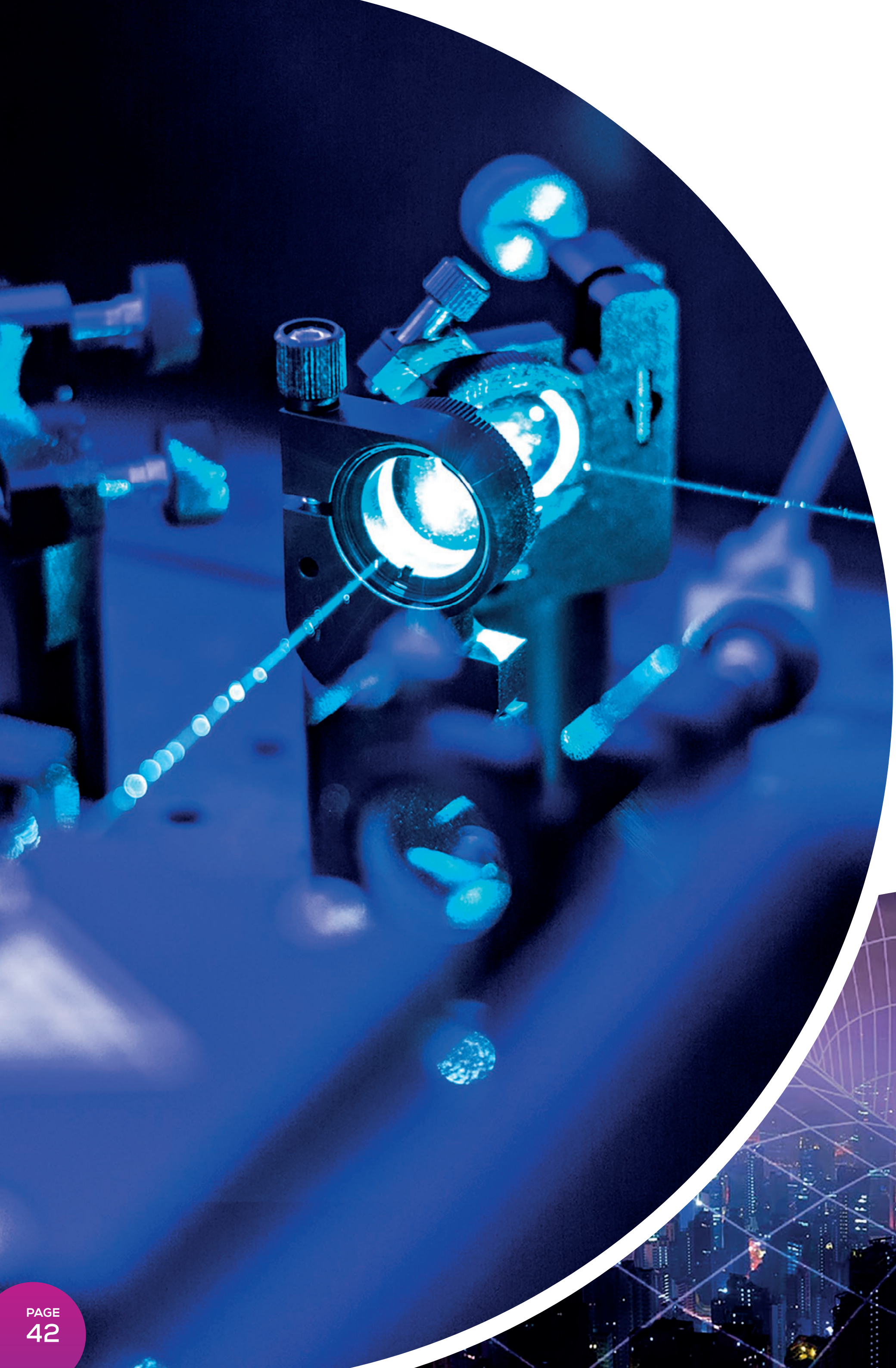
Journal	Number of papers
PHYSICAL REVIEW RESEARCH	26
PHYSICAL REVIEW LETTERS	22
NATURE	17
PHYSICAL REVIEW A	17
NATURE COMMUNICATIONS	16
NPJ QUANTUM INFORMATION	13
PHYSICAL REVIEW B	12
QUANTUM SCIENCE AND TECHNOLOGY	12
NATURE PHYSICS	11
PHYSICAL REVIEW APPLIED	9

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 629 times between them. These citations can provide an indication of activity, as well crosslinks and collaborations between the countries in question. The USA tops the list after Switzerland, followed by Spain, China and Germany.

Journal	Number of citations
Argentina	6
Australia	15
Austria	13
Belgium	6
Brazil	3
Canada	9
Chile	1
China	43
Denmark	18
France	23
Germany	37
Hungary	1
India	2
Ireland	2
Israel	2
Italy	26
Japan	6
Netherlands	20
Poland	1
Portugal	1
Republic of Korea	1
Russia	1
Singapore	2
Slovenia	1
Spain	49
Sweden	3
Switzerland	184
UK	25
USA	128
Grand Total	**629**

The lead author's institutional country for these fifty papers is shown.

Journal	Number of papers
Australia	1
Belgium	1
Canada	1
China	2
Denmark	2
Germany	3
Italy	2
Japan	1
Netherlands	2
Spain	3
Switzerland	23
UK	2
USA	7
Grand Total	**50**



Closing remarks

There is clearly a lot of activity relating to QIT across the European countries investigated in this report. Many countries, following the UK's early example, now have national programmes and strategies in place, with large amounts of funding being committed to enact this. European cooperation is strong, and countries are leveraging the EU's mechanisms as part of this; the UK has historically been a strong partner in EU projects, and its participation in Horizon Europe and its subsequent effects are uncertain. There is much talk on ecosystem development, both at a national and more localised level, with strong regional clusters forming in many countries. Collaboration between research groups is seen as key, even more so when these are linked to industry and part of an overarching national initiative. The USA, with its strong activity and funding in quantum technologies, has a strong presence throughout the report; China is also notably featured throughout, suggesting that there is some collaboration with European countries, at least at an academic level.

This report is the first in a series of two – North America and Asia will be covered in detail in the next publication. If you would like to be kept informed of future QCS Hub reports, please subscribe. The raw data behind the figures displayed in this report are available upon request.

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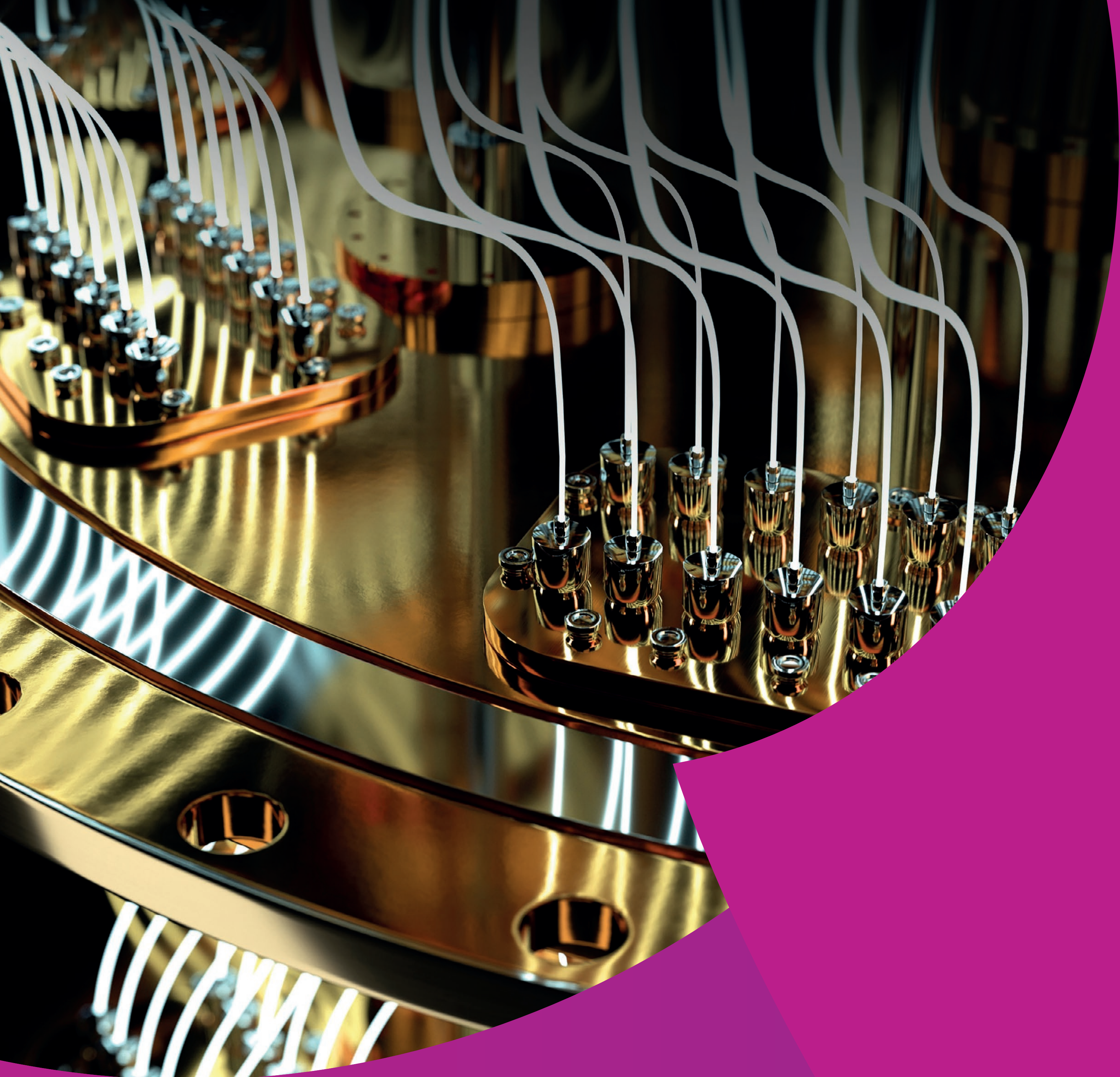

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