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Quantum Technologies
Trends and Implications for Cyberdefence

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Julian Jang-Jaccard, Cyber-Defence Campus, armasuisse
Valentin Mulder, Cyber-Defence Campus, armasuisse

1.1 Introduction

This second semi-annual report examines the quantum ecosystem at both global and national levels. It presents potential adoption strategies and insights from early adopters of quantum technologies.

Brendan Karch from Swissnex first begins by analyzing the global quantum strategies of four countries — Canada, Denmark, the Netherlands, and the UK — widely regarded as leaders in quantum technologies. Despite differences in population size and the scope of their quantum programs, these nations demonstrate considerable diversity in their approaches. Notable examples include Canada's vibrant startup culture, Denmark's collaborative research centers, and the centralized innovation model of the Netherlands, all of which emphasize the intersection of public and private initiatives to drive quantum progress. Switzerland has an opportunity to draw valuable insights from these models, gaining inspiration and a deeper understanding of the competitive landscape. Although the USA and China are global quantum leaders, their vastly different scales and approaches make direct comparisons with Switzerland less relevant for this analysis.

In a second step, Brendan Karch also explores Switzerland's quantum ecosystem. Despite its relatively small size, Switzerland has established a strong foundation rooted in academic excellence, international collaboration, and a growing private sector. Institutions such as ETH Zurich and EPFL, together with pioneering companies such as ID Quantique, showcase Switzerland's strengths in quantum sensing, communications, and photonics. However, he argues that challenges, such as exclusion from major European funding streams, underscore the need for a coordinated national strategy. By leveraging lessons from global peers and building on its decentralized, innovation-driven culture, Switzerland can obtain a competitive edge and shape the future of quantum technologies.

Finally, Yvonna Yun Li highlights how quantum technologies are being adopted by Roche, an early mover in the pharmaceutical sector. Defense, along with finance and pharmaceuticals, is widely recognized as one of the sectors most likely to be significantly impacted by or benefit from quantum technologies as they mature. Adoption strategies and developments in the pharmaceutical industry provide valuable insights for other sectors, including defense, on the effective use of quantum technologies.

This report aims to offer a comprehensive understanding of the quantum ecosystem while providing actionable insights for the strategic adoption of quantum technologies.

1.2 Trend Analysis

To provide quantitative quantum computing related trends, we developed two dashboards that rely on data from Wikipedia [1], OpenAlex [2] and Crunchbase [3]. The two dashboards give a snapshot of how quantum computing and post-quantum cryptography are growing, with one considering the global picture (Figure 1), and the other one focusing only on Switzerland (Figure 2). Both dashboards provide insights into how fast quantum computing volume is growing, how much research is being published, and how much money is being invested. This makes it possible to see how Switzerland compares and fits into the larger global picture.

The global dashboard shows that quantum technology is taking off across all dimensions. Companies such as IBM and Quantinuum are leading the way, increasing their quantum volumes year after year. There has also been a huge surge in research, with thousands of new studies published every year. Investors are also backing the technology to a large extend, with more than USD 7 billion raised for quantum computing relatd organizations since 2004. All signs indicate that quantum technology is gaining momentum around the world.

An upward trend is also visible in Switzerland. The number of studies coming out of Swiss companies and institutions has been increasing significantly over the past years. In total, about USD 98 million has been raised for quantum computing related organizations, with USD 75 million alone in 2022.

In conclusion, the global quantum tech scene is growing rapidly, with industrial players such as IBM and Quantinuum leading the way, thousands of new research papers being published and billions of dollars being invested at the global scale.

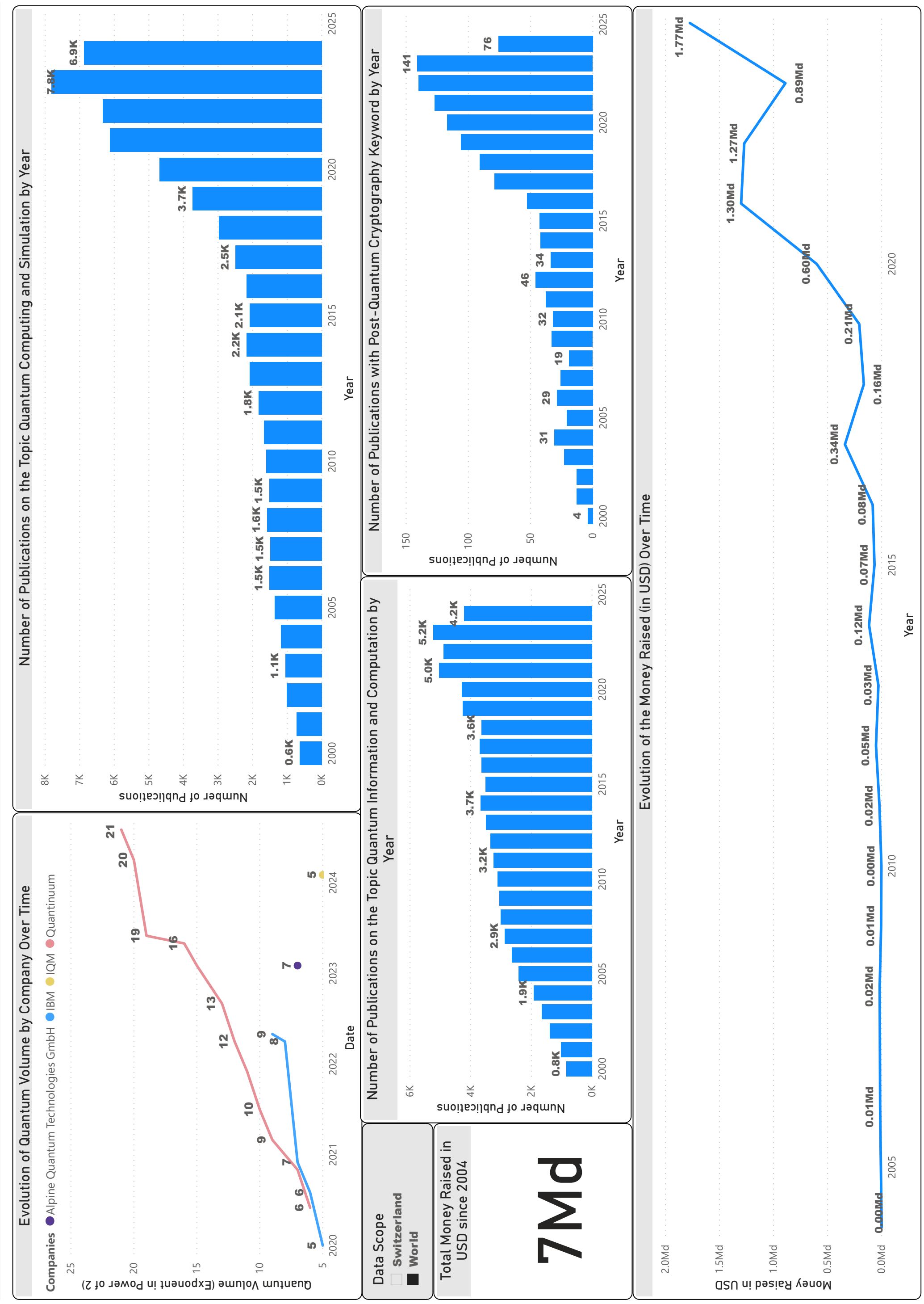

Figure 1: This dashboard shows worldwide trends in quantum computing. The data is from Crunchbase [3], Wikipedia [1] and OpenAlex [2]. "Quantum volume is a metric that measures the capabilities and error rates of a quantum computer. It expresses the maximum size of square quantum circuits that can be implemented successfully by the computer" [1].

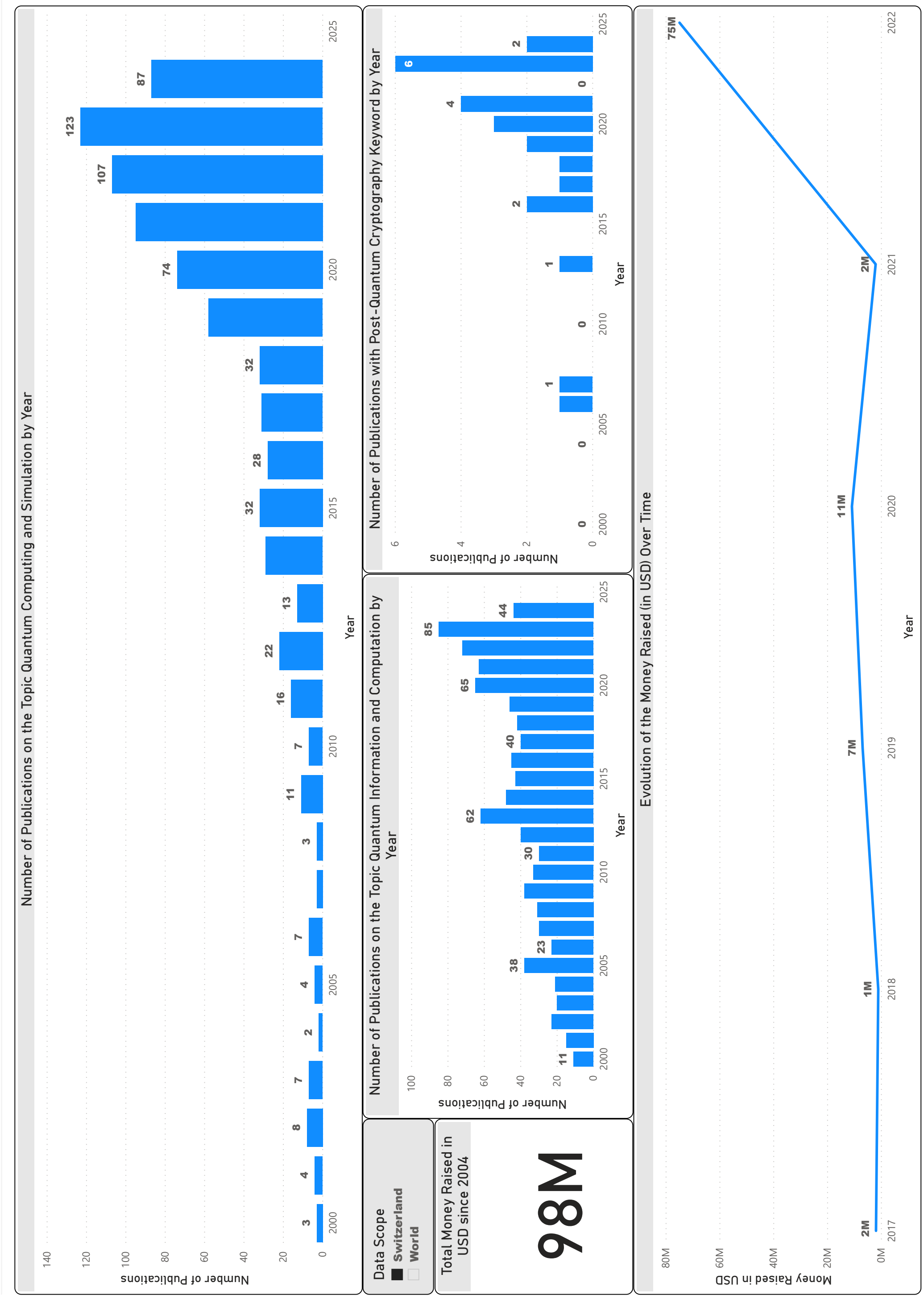

Figure 2: This dashboard shows swiss trends in quantum computing. The data is from Crunchbase [3] and OpenAlex [2]. There is no data available on quantum volume for Switzerland.

2 Global Quantum Strategies

Brendan Karch, Swissnex

2.1 Introduction

Experts debate the precise timing for a commercial "breakthrough" in quantum technologies, yet there is widespread agreement that long-term investments are required, particularly for quantum computers with useful real-world advantages and applications. These investments are being made not just in research and development, but in the wider ecosystems that will support a new quantum economy. For this broad set of tasks, governments have been playing an increasing role through the deployment of national funding schemes, programs, and initiatives. To coordinate these efforts, several countries have gone further by developing national quantum *strategies*.

Quantum strategies are generally more involved than quantum programs or initiatives, in that they are multi-stakeholder, cross-sectoral, and consider the wider social implications. According to the OECD, national science, technology, and innovation strategies generally incorporate the following characteristics:

- They express the government's vision on how the scientific field can contribute to the country's economy and society;
- They create public investment priorities and how to create structures to enable them; and
- They help rally private and/or public actors around a common goal, and facilitate coordination to enable a common vision [4].

Switzerland has yet to create or deploy a national quantum strategy. However, several of its peer countries have. The aim of this chapter is to describe in detail the quantum strategies of four countries – Canada, Denmark, the Netherlands, and the United Kingdom – and then analytically compare their strategies and provide preliminary recommendations for Switzerland.

These countries were selected because they have developed extensive quantum strategies, because they are considered among the leading nations in quantum technologies, because they prioritize international engagement, and because the size of their populations and quantum programs provide considerable diversity as a basis of comparison. As a relative late mover in developing a quantum strategy, Switzerland can benefit from carefully studying the diverse models of national strategies for inspiration and understanding of the competitive landscape. While the two global leaders in quantum technologies, the USA and China, also are important, it is more difficult to draw useful comparisons given their large size and very different models – especially in the case of China, where public information is lacking and national autonomy is a primary aim.

2.2 National Quantum Strategies

2.2.1 Canada

Canada's National Quantum Strategy (short: "Canadian Strategy"), created by the Canadian Ministry of Innovation, Science, and Industry, debuted in January 2023, although spending had begun in 2021. The Canadian Strategy consists of three interlocking missions: to make Canada "a world leader" in quantum technologies, to focus on privacy and cyber-security, and to become early adopters through both government and industry. The three core pillars to achieve these missions are research, talent, and commercialization, with CAD 360 million in targeted public funding planned over seven years starting in 2021 [5, p. 3].

Program implementation through funding streams comes from a wide array of pre-existing organizations and initiatives. Major funders for research and development of quantum technologies include the Canada First Research Excellence Fund (CFREF) and Natural Sciences and Engineering Research Council (NSERC). Through NSERC, a new "Alliance Quantum" funding scheme is devoting around CAD 130 million over seven years to allow for greater research and development collaborations – with CAD 100 million targeted for domestic collaborations and CAD 30 million for international collaborations. The first round of international grants in 2024 provided up to CAD 300,000 per project over 1-3 years [5, p.18] [6].

The focus of the Canadian Strategy leans heavily towards the computing sector, with the goal to amplify Canada's strong position in quantum hardware and software. Focus areas include hybrid computing, quantum simulators, and use cases in fields such as digital security, banking or advanced manufacturing. On the commercialization side, innovation challenge programs are issuing calls for advancements such as quantum computing as a service, smaller dilution fridges, or computing prototypes [5, pp.11-12]. There is also support promised for the quantum sensing sector, which follows an analogous strategy of investing in research, backing prototypes, supporting common standards, and using the government as an early adopter for technologies [5, p. 16].

Canada benefited from significant early private and research investment, which helped to create pioneering and robust startup ecosystem in quantum technologies. The country ranks second globally in number of quantum startups (after the USA), with 28 total. D-Wave launched the first commercial quantum-based computer, a quantum annealer, in 2011. Overall, estimated private funding in the last two decades into Canadian quantum technologies has totaled CAD 1.3 billion, close to the CAD 1.4 billion in public investment, according to McKinsey. In fact, total investment in quantum startups in Canada from 2001-2023 has exceeded all investments in EU startups in the same time frame [7, pp. 19, 45, 68] Incubators have played a large role, especially the Creative Destruction Lab from the University of Toronto, which has helped launch more than 50 quantum-related companies. The government has pursued commercialization through large grants and investments directly in companies, as well as challenge programs and regional innovation clusters such as Quantum City in Calgary or DistriQ in Sherbrooke [5, pp. 22-25] [8]. The Canadian Strategy is thus able to build its funding for commercialization on the shoulders of a very robust quantum private industry.

Given these strengths, Canada is highly optimistic about the scale of quantum technologies in its long-term future economy. The Canadian National Research Council estimated that by 2045 the national quantum industry would be valued at CAD 139 billion and constitute 3% of the country's GDP [5, p.4] [8]. If the quantum economy achieves this scale, then significant investments in talent and workforce development are needed – an area of action for the Canadian Strategy. Much of the national initiative for talent development comes from individual university programs, such as a new Bachelors in Quantum Science at Université de Sherbrooke or a new Masters at University of Waterloo. The Canadian Strategy is also providing CAD 40 million to Mitacs for internship and professional development training in quantum [9]. The government is likewise involved in broader science outreach programs to increase diversity in quantum [5, pp. 20-21].

Quantum security is a major pillar of the Canadian Strategy. Canada hopes to identify vulnerable communications and assets, work with researchers on post-quantum cryptography solutions, and also potentially build a quantum secure network [10]. In these activities, the government sees itself as enabling research and development, being an early adopter of critical technologies, and also promoting international collaboration and innovation exchange [5, pp.13-14].

On the international front, Canada's association into Horizon Europe in 2024 will bring new international funding and collaboration possibilities, although the impacts will take time to assess [11]. Bilateral agreements with UK and US funding agencies also cover scientific exchange more broadly. The "Alliance Quantum" grants will specifically target international collaboration in quantum with funding at CAD 30 million over seven years.

2.2.2 Denmark

Denmark's National Strategy for Quantum Technology (short: "Danish Strategy") was published in two parts by the Ministry of Higher Education and Science in June and September 2023. On a four year timeline through 2027, the government intends to commit DKK 1 billion (CHF 126 million) for quantum research and innovation, and an additional DKK 200 million (CHF 25 million) for commercialization, security, and international collaboration [12, p.4].

The Danish Strategy funding programs are mainly administered via Innovation Fund Denmark. The fund is expected to shift its focus over time towards demonstration and scale-up technologies as the ecosystem matures. In order to advise the direction of programs and allocation of funds, a National Forum for Quantum Technology has been established [13, pp. 13-16]. The strongest academic research clusters to support this ecosystem are located at University of Copenhagen, Technical University of Denmark, and Aarhus University.

Danish government expenditure is supplemented by significant private-sector funding. Most notably, the Novo Nordisk Foundation has established a Quantum Computing Program at the University of Copenhagen, pledging DKK 1.5 billion (CHF 189 million) in 2022 for a 12-year program to build fault tolerant quantum hardware and algorithms to solve life-science problems [13, pp.6]. To leverage private-sector computing expertise, part of the Novo Nordisk funding has been used to establish an IBM Quantum Hub established at the University of Copenhagen [12, p.9]. Moreover, KPMG established its Global Quantum Hub in Denmark, collaborating with leading universities [14]. More recently, in February 2024, Novo Nordisk Foundation also pledged DKK 150 million (CHF 18.9 million) to establish a Copenhagen Center for Biomedical Quantum Sensing [15].

In commercialization of quantum technologies, two concrete measures stand out in the Danish Strategy. Denmark pledges to establish a Quantum House Denmark with approximately DKK 16 million (CHF 2 million) yearly funding. This physical hub will provide lab and office space, business development guidance, and networks spanning universities, startups, funders, and corporations. Closely connected will be a national test center, funded through Novo Nordisk. These are still under construction as of mid-2024. The second concrete measure is a new Quantum Fund administered by Denmark's Export and Investment Fund – although exact funding will be dependent on private co-investment and leftover funds from other initiatives [12, p. 15].

In contrast to some other countries, Denmark only has a very modest startup ecosystem in quantum technologies. Sparrow Quantum, producer of single-photon chips, and Kvantify, a hybrid software builder, are among the most notable Danish players. Two other Danish quantum companies were recently acquired by international players: QDevil by Quantum Machines, and NKT Photonics by Hamamatsu.

As part of the EU, Denmark benefits significantly from EU funding instruments such as Horizon Europe and the EU Quantum Flagship. From 2014-2020 Denmark received around DKK 500 million (CHF 63 million) from the EU framework programs for quantum projects [13, p.6]. Denmark is establishing strong security guardrails in navigating the international environment, particularly with non-EU actors, and prioritizes collaboration with NATO and other strong allies [12, pp. 18-19]. In 2023 Denmark was selected as the site of a new NATO Center for Quantum Technologies, hosted at the Niels Bohr Institute in Copenhagen [16].

Denmark's key internationalization initiative will be a new International Quantum Hub funded with DKK 10 million (CHF 1.25 million) yearly through 2027. It is intended as the primary entrypoint for international quantum collaborators to reach Danish authorities and the quantum ecosystem. The hub will likewise represent a coherent tone and Danish viewpoint on international and security policy questions related to quantum technologies [12, p.23]. As of mid-2024, this was still in development.

2.2.3 The Netherlands

The Netherlands' National Agenda for Quantum Technology (short: "Dutch Strategy") was published in September 2019. Uniquely among the countries covered, the Dutch Strategy created a single prominent institution, Quantum Delta Netherlands (QDNL), to execute the Dutch quantum strategy. QDNL was proposed as a "world-leading centre and hub for quantum technology" analogous to Silicon Valley [17, p.9]. QDNL describes itself as an ecosystem, developing its own initiatives while also consolidating the naming of pre-existing quantum centers under the umbrella of "Delta hubs" [18].

QDNL is uniquely positioned as a distinct nonprofit agency that is mandated to execute the government's strategy. To this end, the Dutch government in 2020 invested an initial EUR 23 million, followed in 2021 by an additional EUR 615 million over seven years, in QDNL to coordinate the Dutch quantum ecosystem. This model has created a uniquely powerful and centralized institution that is nonetheless able to operate distinct from government ministries [19].

QDNL has developed three specific technology catalyst programmes in quantum computing and simulation, quantum networking, and quantum sensing. Additionally, they have four main action lines devoted to building quantum research, talent, societal impact, and the wider ecosystem. Much of the presence of QDNL in the ecosystem comes through initiatives, events, and programs; however, they also have built a physical site directly through the House of Quantum in Delft. This center was designed to support research, startup space, and facilities and programs that inspire interaction and collaboration among quantum players [20]. Other House of Quantum locations are planned, with the goal of creating an interconnected "national campus" for quantum technology development [21]. The development of a Dutch quantum national strategy has benefitted from the geographic density of quantum expertise. The three main pre-existing quantum research centers (QuTech in Delft, QuSoft in Amsterdam, and QT/e in Eindhoven) are within roughly two hours travel distance [17, p. 56].

Public investment in quantum technologies, research, and infrastructures far exceeds private investment in the Netherlands. As of 2024, the Netherlands has pledged a total of around USD 1 billion in public investments. This dwarfs the roughly USD 40.5 million in private investments made in Dutch quantum technologies, with around a dozen quantum companies active in the Netherlands [7, p. 59].

Dutch international activities in quantum have largely focused on EU cooperation. In addition to being a core participant in Horizon Europe and EU Quantum Flagship programs, QDNL has set up a trilateral research program with Germany and France. The Dutch contribution to the trilateral program of EUR 62 million will fund joint centers of excellence, as well as strategic research and development projects through a trilateral call [22].

2.2.4 United Kingdom

The UK published its National Quantum Strategy (short: "UK Strategy") in March 2023. They had already committed GBP 1 billion in public funding since 2014 through the National Quantum Technologies Programme, but starting in 2023 have pledged another GBP 2.5 billion in the following 10 years [23, p.12]. The UK Strategy programs from 2024-34 will be split into two five-year phases. The first phase includes new research hubs and centers, outcome-focused innovation programs, industry-led innovation, accelerator programs, training and talent development, international collaboration, and infrastructure investments [23, pp.24-25].

Like many other countries, the UK is motivated by international competition. "We are in a global race," the UK Strategy states. "The UK was an early mover, but other countries are accelerating their own efforts" [23, p.8]. The UK Strategy's mission outlines several core performance metrics to achieve by 2034: for example, to maintain its top 3 national position in quality and impact of quantum publications; to fund 1,000 new postgraduate students; and to develop five new bilateral funding arrangements. On the innovation front, they aim to attract 15% of total global private equity investment to the UK, have a 15% share of the global quantum technology market, and motivate 75% of UK companies to prepare for quantum computing. Most of these figures represent meaningful leaps over current figures [23, p.11].

The UK has been an early mover in quantum research and innovation. Since 2014 the UK has funded a network of four Quantum Research Hubs at universities, and institutions such as the Quantum Metrology Lab at the National Physical Laboratory, and National Quantum Computing Centre focused on building a scalable device. This pre-existing Quantum Program touts the distributed network of research hubs across the country, which also includes the Fraunhofer Centre for Applied Photonics in Glasgow, Scotland. In 2024 the UK government announced five new hubs for quantum technology development with an additional investment of GBP 160 million [24].

The UK's early strength in quantum innovation is evidenced by around 50 quantum startups that have emerged (with government assistance) since 2014 – the most in Europe. These companies have attracted a combined GBP 425 million in private investment [23, pp. 18-19]. At least 160 companies are active in the UK quantum sector, which ranks second globally in private equity investment after the USA [23, p. 32] [25]. The UK Strategy aims to leverage its GBP 2.5 billion in public investment to attract an additional GBP 1 billion in private funding by 2033 [23, p. 10]. The UK Strategy also hopes to attract further quantum businesses to the UK, such as with the return of PsiQuantum, or the IBM collaboration on a National Centre for Digital Innovation [23, p.40] [26].

Aside from challenges general to quantum technology deployment, specific UK challenges include demand for quantum skilled labor, higher salaries especially in the USA, and competition from larger countries and multinational corporations – all of which can erode the UK's strong early position in the "quantum race" [23, p.20]. To compete on talent, the UK has special workforce development provisions. They aim to double the number of PhDs in quantum or supporting technologies in 2024-2034 period to over 1,000, with an initial 2-year investment of GBP 25 million. They also will expand a STEM outreach program in schools and push for enhanced visa pathways for foreign talent [23, p.29] [27].

The UK Strategy emphasizes the application of quantum technologies in a few key sectors to strengthen their overall economy and society, in particular sustainability, security/defense, life science, and data analytics/AI. The SparQ program run through the National Quantum Computing Centre will explore these and other early applications. Defense in particular is seen as a useful early adopter and purchaser of quantum technologies, providing government support for emerging technologies [23, pp.42-44]. More broadly, the National Quantum Computing Centre, in addition to serving as a research and development hub, will also explore critical applications, standards, and regulations, and act as a first purchaser for prototype platforms [23, p.59].

The UK has made notable advances in international partnerships. The government signed its first major joint statement for bilateral cooperation with the USA in 2021. The UK Strategy's goal is to develop this into a "comprehensive programme of bilateral arrangements". Since 2021 additional quantum MoUs or partnerships have been announced with several countries, including Australia, Canada, Denmark, South Korea, and Germany [23, p.31].

2.3 Comparative Analysis

Given the different timescales, goals, and country population sizes, it is very difficult to do a strict quantitative comparison between the quantum strategies of Canada, Denmark, the Netherlands, and the UK. One can however roughly compare the pledged public investment on a per person, per annum (pp/pa) basis. On this metric, Canada's public quantum investment in its national strategy is modest, at less than CHF 1 pp/pa. The UK and Netherlands each have pledged slightly over CHF 4 pp/pa in their strategies, while Denmark has pledged around CHF 6.4 pp/pa. Thus, while the headline spending numbers for the various quantum strategies are designed to impress, the amount of taxpayer funds going towards supporting the emergence of this specialized technology are relatively modest.

Qualitative comparisons between the different countries' strategies reveal both fundamental differences in philosophy, but also similar strategies to shepherd quantum technologies to commercial viability. Canada and the UK are both notable for their very strong, early private sector investments in quantum research and innovation. The impressive array of quantum startups and established quantum companies in the two countries has been backed by an ecosystem of research translation, accelerators, supply chains, and investors, which combine to give Canada and the UK a strategic advantage. Their quantum strategies thus seek to build on these existing strengths. Denmark and the Netherlands, in contrast, are confronted with the task of building up a quantum commercial ecosystem from a less robust prior basis.

These different backgrounds inform the direction of investments and the level of centralization. Canada arguably has the "lightest touch" in terms of overall government coordination, as its effort can be seen mainly as a funding boost for regional hubs and bottom-up research and development clusters. On the opposite end of the spectrum is the Netherlands, which has created a new centralized organization, Quantum Delta NL, that provides a single platform for all strategic quantum funding and activities. The UK sits in between these poles, investing heavily in regional clusters but also working to elevate the National Quantum Computing Centre into a robust institution for promoting its strategic priorities across sectors.

The level of government involvement can be seen in the relative balance of public vs. private investments. While all quantum strategies hope to create a robust commercial quantum sector, the UK and Canada aim to use their investments explicitly to attract sizable private sector funds. According to McKinsey, the UK has spent or pledged USD 4.3 billion in public investment, compared to USD 1.5 billion in private monies. In Canada, it is 1.4 billion USD public investment for USD 1.3 billion in private money [7, pp.44-45]. In contrast, the level of prior private investment into quantum companies is comparatively small in the Netherlands and Denmark. In Denmark specifically, government investment is exceeded by a single huge corporate foundation – Novo Nordisk – which exerts major influence to steer quantum technologies towards use cases in biopharma and the life sciences. The question remains if the government or foundation investment can eventually yield a self-sustaining commercial industry, or if it instead leads to continued large-scale public subsidies. The German case may be the starkest example of this imbalance, with USD 5.2 billion in public investments spent or pledged, compared to just USD 104 million in private investment [7, pp.55-56].

Given these very large public investments, many countries feel themselves to be in a competitive landscape against other governments. The Dutch and UK strategies explicitly mention this; the Dutch Strategy argues that "urgent action [is] required" since "other countries are not standing still" [17, p. 16]. Because of the government-driven nature of national quantum strategies, there is often significant weight placed on defense applications and government procurement of quantum technologies as an early boost for quantum commercialization. This was prominent in most quantum strategy documents.

The international strategies in the national quantum strategies are often among the least concrete sections. Overall it is challenging politically and bureaucratically to direct significant funds to foreign research and development. Nonetheless, different strategies emerge. The UK, Canada, and the Netherlands have all engaged in bilateral (or trilateral) calls to build up specific relationships with other countries, based on perceived mutual strengths and geographic proximity. This is especially valuable for countries outside EU programs. The Netherlands and Denmark also benefit from being core EU member states, and are well integrated into the EU Quantum Flagship. Canada and the UK are also set to benefit from EU framework funding. Canada has also pledged significant funds for international research collaborations through open calls, offering CAD 30 million for "Alliance Quantum" grants. In a different vein, Denmark has pledged to establish an International Hub that serves as a single "open door" for international collaborators.

2.4 Recommendations for Switzerland

It is not feasible to make any specific policy recommendations for Switzerland based on this survey of several other countries' national quantum strategies. The relatively later development of the Swiss National Quantum Initiative may, however, provide an advantage in the ability to learn from other countries' programs and investments. There is no single strategy for success, as each country has sought to identify and capitalize on its particular strengths. In the Swiss case, the role of the National Quantum Initiative will likely entail strengthening the core values and priorities of the Swiss quantum ecosystem, as identified by the Swiss Quantum Commission to include:

- Support for bottom-up, curiosity-driven research and innovation, rather than top-down directives
- Development of shared infrastructure and platforms
- Avoidance of direct subsidies, in favor of market processes and private competition
- Support education, workforce, and quantum literacy efforts
- International engagement
- Long-term, continued support necessary to reach quantum technology breakthroughs and commercial viability [28].

These priorities suggest that an overarching Swiss Quantum Strategy, if developed, may entail a "lighter touch" system of supports for ongoing research and innovation, similar to the Canadian model, rather than a more centralized program as in the Dutch case. Nonetheless, given the perceived competition among national governments for resources and talent, and Switzerland's modest size, the country may also benefit from a more coordinated "public face" – especially for the public and international collaborators – that can help give visibility to Swiss excellence and build support for collaborations and public investments. As in Denmark and the Netherlands, the geographic density of Switzerland also lends itself to greater coordination of clusters, as opposed to dispersed regional hubs in countries like in Canada.

The Swiss reliance on bottom-up excellence in research, education, and innovation means that a national strategy will likely play a coordinating rather than generative role in the development of a quantum ecosystem. Pre-existing initiatives such as new Masters programs in quantum engineering and Bachelors programs at multiple universities of applied sciences are already creating a growing workforce, and Switzerland can build on its strength as a world-leading talent factory. One main area where a Swiss Strategy might play a more "generative" role is in stimulating common infrastructure, perhaps even reaching an ambitious scale such as the UK's National Quantum Computing Centre.

The UK provides a similar model of a European country with a strong foundation of research that nonetheless has previously been excluded from core EU funding schemes, and thus pushed to collaborate on a more bilateral basis internationally. The UK strategy of developing several bilateral agreements has been mirrored in early Swiss efforts, for example through the Joint Statement of Cooperation in Quantum Technologies with the United States. The Swiss government has also signed agreements to promote broader advanced technologies, sometimes including quantum, with several other countries. As Swiss research and innovation thrive on international collaboration, it is essential to create programs and platforms that invite the outside world to work with Switzerland on quantum. This might include new funding schemes, an international hub, or programs and initiatives using pre-existing international platforms such as Swissnex.

2.5 Conclusion

As of early 2024, governments worldwide have announced a combined USD 42 billion in public investments in quantum technologies, which includes USD 10 billion in new funding announced in 2023 [7, pp. 4, 23]. Many of these countries are explicitly steering this money to create a broader quantum ecosystems, backed by national strategies.

Time will tell if these public investments can sustain themselves, or whether government impatience or shifting priorities lead to a "quantum winter" in terms of public commitment. The Swiss ecosystem has sustained itself thus far largely on bottom-up energy, an excellent education and innovation pipeline, and long-standing infrastructures. This suggests that the current Swiss quantum ecosystem is more resilient, since it is less dependent on a single national program or initiative.

Nonetheless, given the competitive landscape as countries struggle to make large quantum breakthroughs, Switzerland will want to consider carefully whether a national quantum strategy can secure its future continued leading position and relevance in the emerging global quantum economy. The four peer countries studied here – all of whom are also strong international collaboration partners for Swiss quantum actors – provide lessons in how to structure such a potential strategy.

3 Quantum Ecosystem of Switzerland

Brendan Karch, Swissnex

3.1 Introduction

Switzerland, despite being a small country with fewer than nine million inhabitants, maintains a robust ecosystem of quantum research, education, private-sector innovation, and governmental or international initiatives. As an early research pioneer in nanoscience and quantum physics, it maintains an integrated pipeline for bringing new ideas to market while also addressing the societal dimensions of new quantum technologies. In a competitive global ecosystem where other countries are investing heavily into quantum technologies, Switzerland can continue to innovate and prioritize international engagement.

3.2 Analysis

Curiosity-driven research at universities and research institutes constitutes the backbone of Swiss contributions to global efforts at achieving a second quantum revolution. Switzerland has been supporting basic scientific research into quantum technologies for decades. From 2001-2013, two National Centers for Competence in Research (NCCRs) – on nanoscale science and quantum photonics – coordinated large bodies of quantum-related research across Switzerland. From 2010-2022 NCCR QSIT (Quantum Science and Information Technology) played a leading role in organizing Swiss quantum researchers, while a newer research center NCCR SPIN (ongoing since 2021) focuses on the development of spin qubits. The cumulative investment in these NCCRs will total about CHF 200 million, not including the research grants for individual researchers projects [29].

This investment in research has created a broad base of expertise across quantum technologies (computing, sensing, communications, algorithms, simulation, and theory). NCCRs have helped attract over 30 new professors to universities like the Swiss Federal Institutes of Technology in Zurich and Lausanne (ETH Zurich and EPFL), as well as the University of Basel, and the University of Geneva [30]. The investments are reflected in the importance of Swiss-affiliated quantum publications, which had the highest impact factor of any country in the world, relative to the global average, from 2016-20 [31].

Four research universities are notable for their extensive contributions in the fields of quantum information science and theory: ETH Zurich, University of Basel, EPFL, and the University of Geneva. Launched in 2020, the Quantum Center at ETH Zurich encompasses 38 research groups from six departments. It interconnects quantum research and teaching across ETH departments, and serves as a contact point for larger projects, including collaborations with industrial partners. The Center also helps to support ETH Zurich's interdisciplinary Master's Degree in Quantum Engineering. The Center for Quantum Science and Engineering (QSE Center) at EPFL serves as the school's research and teaching hub for all quantum efforts. The Center promotes research through collaborative grants, multidisciplinary education, and innovation. Its key focus areas are applied quantum algorithms and data science, along with quantum hardware materials and systems. The Center also helps to support EPFL's Master's Degree in Quantum Science and Engineering [30].

The Basel Quantum Center comprises 15 research groups at the University of Basel working on condensed matter, atomic, molecular and optical systems, covering a broad range of applications in quantum computing, quantum sensing and metrology, quantum networking, and quantum simulation. The Quantum Center

Table 1: **Key Swiss startups and companies active in quantum technologies** [30]

Company	Region	Founded	Quantum specialization
ID Quantique	Geneva	2001	Cryptography, RNG, single photon detectors
Zurich Instruments	Zurich	2008	Qubit controllers, amplifiers, software
Ligentec	Lausanne	2016	Photonic integrated circuits
Qnami	Basel	2017	NV diamond sensing systems
Enlightra (formerly MicroR Systems)	Lausanne	2018	Multi-frequency lasers
Basel Precision Instruments	Basel	2018	Ultra-low noise electronics
QZabre	Zurich	2018	NV diamond scanning microscopes
Terra Quantum	St. Gallen	2019	Quantum services and algorithms
Miraex	Lausanne	2019	Quantum interconnects

supports a PhD program and a cross-border postdoc cluster in collaboration with the University of Freiburg, Germany. A subset of the research groups are also involved in the affiliated Center for Quantum Computing and Quantum Coherence (QC2). The Geneva Quantum Centre at the University of Geneva brings together around 20 research groups building on a tradition of pioneering research in quantum sciences, most notably in quantum communications, quantum sensing, quantum materials, and in the theoretical foundations of these domains. It targets broad education programs for the general public, schools, and the training of engineers, and has launched new Bachelor and Masters programs [30].

In addition to the four largest quantum research univesities, the Paul Scherrer Institute (PSI) maintains a quantum computing hub in partnership with ETH Zurich in May 2021. It brings together the resources of ETH Zurich with PSI, the largest research institute for natural and engineering sciences in Switzerland. The Hub's central aim is to target the technical and scientific challenges on the way to realizing large- scale quantum computers based on both superconducting circuits and trapped ions. The University of Lugano (USI), meanwhile, features a group dedicated to cryptography and quantum information. The higher education landscape also includes Switzerland's Universities of Applied Sciences, where several institutions in regions such as Zurich, Lucerne, and Basel are training students in quantum algorithms, engineering, or applications [30].

The private-sector innovation ecosystem in quantum technologies draws its strength from university research discoveries. Switzerland is the sixth leading country worldwide in number of quantum technology patents granted since the year 2000. Pioneering Swiss startups such as ID Quantique and Zurich Instruments, spin-outs of University of Geneva and ETH Zurich respectively, have grown into important suppliers in the global quantum value chain. Zurich Instruments was founded in 2008 and has since developed into a leading global manufacturer of quantum computing control systems. ID Quantique is a global company with offices and engineering labs across the world. They are a leading company for mature technologies in quantum key distribution (quantum-safe cryptography), random number generation, and photonic sensing. In 2007, Switzerland deployed the world's first commercial quantum cryptography system, developed by ID Quantique, which is used to secure elections in the State of Geneva [32].

Many younger Swiss companies, many of them university spin-offs, are emerging with particular strengths in quantum microscopy and measurement, as well as enabling technologies such as photonics and precision nanomanufacturing. It is impossible to list all these companies, however some notable examples include QZabre and Qnami, who work on ultra-sensitive sensing technologies using manufactured diamonds with nanoscale nitrogen-vacancy centers. In the devices field, Basel Precision Instruments provides ultra-low noise electronics, cyrogenic microwave filters, and thermalizers. Miraex creates quantum interconnects between microwave and optical frequencies. Ligentec delivered low-loss photonic integrated circuits. And Enlightra (formerly MicroR Systems) focuses on low-noise microwave generation, satellite up- and downlinks as well as quantum laser sources. In the services field, Terra Quantum provides access to quantum algorithms, simulated quantum processing units, and quantum security solutions. These companies represent just a small cross-sample of the growing commercial quantum ecosystem in Switzerland [30].

Other important players at the private, national, and multinational levels are also working in Switzerland to build quantum ecosystems. The Swiss Center for Electronics and Microtechnology (CSEM), a public-private nonprofit innovation center, has developed key technologies in quantum sensing. The industry association Swissphotonics has significantly grown its portfolio and activities in the quantum space.

Most conspicuously, the new privately funded uptownBasel campus features the QuantumBasel Competence Center for Quantum & AI, as well as the investment accelerator QAI Ventures, which have attracted top-level quantum companies and startups to the Basel area. The uptownBasel ecosystem of companies is

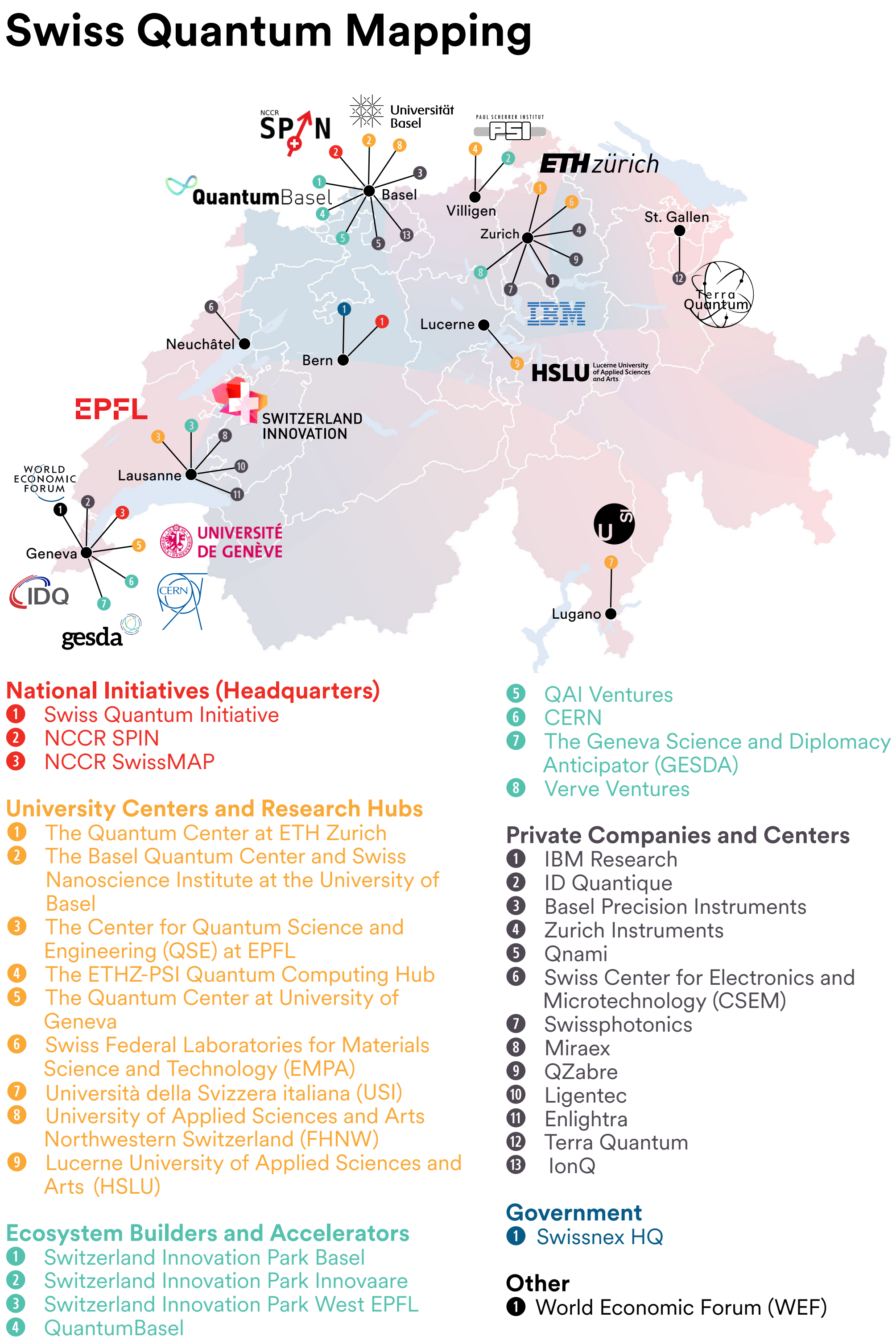

Figure 3: A mapping of selected Swiss institutions in quantum research and technology. This represents a partial overview and is not comprehensive [30].

investing over CHF 500 million in quantum technology development. For example, IonQ, a leading producer of trapped ion quantum computers based in the USA, announced in 2023 that they are establishing their quantum innovation center for the European, Middle East, and Africa (EMEA) region at QuantumBasel, which will include physical installation of two quantum systems [33].

At the international level the Open Quantum Institute, hosted at CERN and incubated by the Geneva Science Diplomacy Anticipator (GESDA), is working to ensure that quantum technologies have broad benefits for the global scientific community and societies at large. Switzerland relies heavily on international collaborations to extend both its research and commercial impact. From 2016 to 2020, 89 percent of quantum publications from Switzerland featured international collaborators, among the highest rates in the world [31]. Finally, a new Swiss National Quantum Initiative, which began operating in January 2023, is tasked with defining frameworks for research calls, supporting infrastructure developments, promoting curricula, and strengthening international partnerships [34].

3.2.1 Maturity

The maturity of the quantum ecosystem in Switzerland varies by sector and technology. Thanks to long-term support for academic research in nanoscience and quantum physics, Switzerland maintains a strong research profile across most quantum subdisciplines. The fields of quantum sensing and communication are particularly strong. For example, CSEM has led international research on vapor cell based atomic clocks, including the fabrication of MEMS cells and PICs for chip-scale atomic clocks. University spin-offs in NV diamond sensing technology scuh as Qnami and Q-Zabre are also among global piooners in the field. Additionally, pioneering quantum communications research from University of Geneva results in ID Quantique, one of the oldest "pure quantum" companies in the world. The innovation sector in Switzerland has focused on producing technically advanced solutions that serve important scientific applications.

In terms of government involvement and multilateral engagement, the initiatives are relatively new. Switzerland's education and innovation sectors have long relied on bottom-up energy and associations. The Swiss Quantum Initiative – led by a Commission and hosted at the Swiss Academy of Sciences – began operation in January 2023 with a mission to coordinate quantum activities at a national level. They are expecting to secure about CHF 80 million in funding from 2024-28, which will enable a growing profile in supporting quantum research calls, infrastructure, and innovation. Internationally, the Swissnex network – an initiative of the Swiss State Secretariat for Education, Research, and Innovation (SERI) – has actively promoted increased visibility and connections for the Swiss quantum ecosystem since 2022 through its Project Quantum [35].

3.2.2 Swiss Trends in International Perspective

The steady pace of academic research and basic funding has resulted in a relatively stable and robust Swiss ecosystem, but there are concerns about remaining competitive in an increasingly hot global market for quantum science and technology. Significant recent headwinds in the Swiss quantum ecosystem included the 2021 exclusion from Horizon funding measures such as the EU Quantum Flagship. Another, more abstract threat, comes from the potential for larger countries to focus on national programs over international collaborations, which remain essential for smaller countries like Switzerland. From 2016-202, some 89% of Swiss quantum publications featured international partnerships [31].

Some Swiss actors express concern that, as other countries invest hundreds of millions to billions of dollars in public funding into quantum research and innovation, (see chapter on Global Quantum Strategies), that Switzerland's efforts may be too modest. At the same time, huge investments abroad may be raising expectations and hype for quick results in a field still working on fundamental discoveries. Switzerland is well positioned to persist through any hype cycles and remain a leading ecosystem. Its strengths reside in bottom-up collaboration, long-term commitment to research, strong international engagement, quality engineering, and a broad base of expertise across quantum subfields and enabling technologies.

3.3 Conclusion

The long-standing tradition of high-quality academic research in quantum technologies will likely continue to form the backbone of Swiss contributions to the second quantum revolution. At the same time, the Swiss quantum ecosystem has adapted in recent years to meet the growing commercial, government, and societal interest in applied quantum technologies. Since 2016 many new Swiss startups are actively deploying quantum technologies, with relative strengths in photonics and sensing.

The rise of private-sector actors has been accompanied by new ecosystem builders. The QuantumBasel initiative, for example, has grown into an internationally recognized "brand." Swiss government interest in coordinating the ecosystem can be seen with the creation of the Swiss Quantum Initiative, although the organization has operated with a light touch emphasizing the centrality of bottom-up energy rather than top-down mandates. Finally, initiatives such as the Open Quantum Institute at CERN, and Swissnex's Project Quantum, have emphasized the importance of a global cooperative approach, especially if quantum technologies are to be harnessed for socially beneficial purposes if and when they achieve decisive advantage.

4 Quantum Computing in the Pharmaceutical Industry: a Perspective from Roche pRED

Yvonna Yun Li, Roche

Abstract

Hoffmann La-Roche is a world-leading biotech company. Any technology with the potential to significantly impact the pharmaceutical industry in one or more key processes warrants close inspection for relevance and timeline to impact. Quantum Computing (QC) is one topic that has promised to revolutionize the field of chemistry simulation since its inception. Since then, many more quantum algorithms with applications beyond chemistry simulation have been proposed, including machine learning and optimization. At the same time, quantum hardware has seen steady progress yearly with growing system size and gate accuracy. This chapter aims to give an overview of how the team in Roche has tackled the mission of gauging the potential impact of QC on the pharma industry, given the constant progress made in quantum hardware and software. The work starts with a general introduction to the drug discovery process, a summary of how the QC team works to deliver on its mission, and moves to outline the high-level findings from the team, including three concrete use cases with a focus on the quantum machine learning effort before closing with comments on the future directions.

4.1 Introduction

Roche is one of the leading biotech companies in the world, with two divisions: pharmaceuticals and diagnostics. Three independent research and early development departments exist within the pharma division, each focusing on therapeutic areas and expertise. Their mandate is to develop first-in-class and best-of-care medicines for patients by being at the cutting edge of science and technology.

4.1.1 Overview of the Drug Discovery Process

Drug discovery is a long process with the lofty goal of delivering life-changing treatments, which comes with the associated risks. From the start of the process, i.e., identification of a therapeutic target, to successful approval by the health authorities, it can take over ten years to bring one medicine to market. Many molecules are screened and tested repeatedly for efficacy and safety during this process.

At the highest level, the drug discovery process begins with pre-clinical research and then moves to be tested in humans in clinical trials before ending in approval for commercialization. The pre-clinical phase begins with target selection, which aims to establish a therapeutic hypothesis consisting of two nodes and a vertex. The two nodes include a disease state and a target, which is usually a protein in the human body, and a causal link between the two needs to be established. Given a specific disease state, such as a headache,

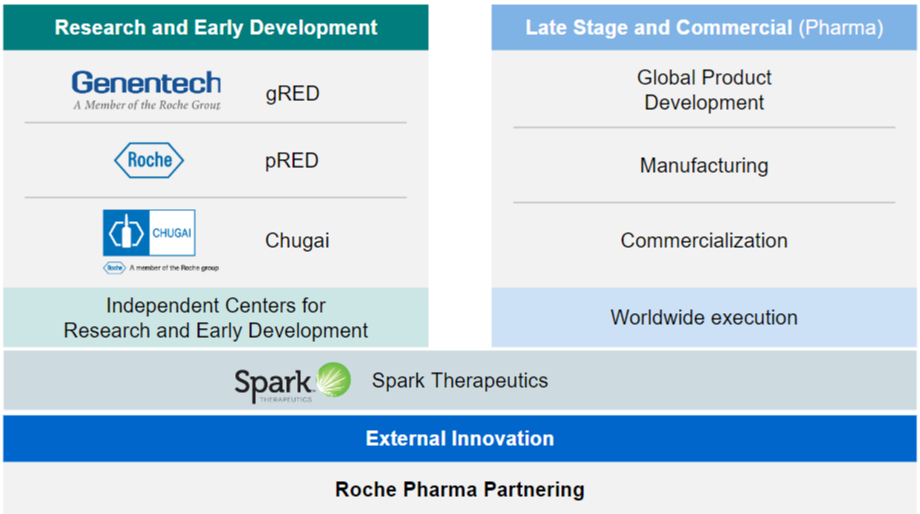

Figure 4: Roche pharma structure with 3 independent R&D engines and shared global late stage and commercial process.

Figure 5: High level overview of the pharma pipeline: from target identification to clinical trials.

target selection aims to find a protein that can modulate the headache effectively. Having identified the target protein, the next step is to look for the right molecule that can modulate the behavior of the said protein, i.e., effectively inhibit or amplify its function. This step is called lead identification.

Once there is enough evidence that a molecule, or in many cases a few molecules, can modulate our target with reasonable effectiveness and specificity, we can start testing for efficacy and safety in humans, which leads to the next stage in the pipeline, clinical development. The molecule must fulfill a specific criteria set within each clinical development phase. Phase 1 tests mainly for the safety of different doses of the molecule. Phase 2 establishes efficacy in a small group of people. Phase 3 then compares the molecule to the standard of care. Once a molecule passes phase 3 and successfully reaches its endpoint, which is usually statistically significant superiority over the standard of care, approval by the respective local health authority for the commercialization of this molecule is applied. Phase 0 is an optional, exploratory step where specific biomarkers or pharmacokinetic characteristics are tested.

4.2 Mission of the Quantum Computing Team

The drug discovery process is highly time-consuming and risky, where the industry average time to market and success rate are in constant decline. It is widely acknowledged that the industry's overall productivity has declined over the last decades, where more and more time and resources are required to successfully bring new medicines to patients [36]. This decline in productivity is ultimately a burden on society and the patients in need. Therefore, any progress to make parts of the pipeline more efficient can translate into big gains in terms of cost and time saved.

The QC team is tasked with investigating the potential impact that QC could have on the drug discovery process. In order to investigate whether this technology will be able to meet the needs of the pharma industry, business analysis is conducted to generate an overview of the various algorithms used in drug discovery that could benefit from QC, together with a survey of the QC field for available solutions. The two aspects of business analysis and industry landscape together provide a comprehensive perspective to inform internal decision-making.

4.2.1 Strategic Approach

Given the clear mandate to assess time to impact, many options are available to help answer the question. Driven by curiosity and diligence, the team decided to tackle the challenge within the team instead of relying on consulting services to perform business analysis and landscape the industry. The team took on the challenge by looking beyond the hype that shrouds the technology and drawing conclusions based on scientific evidence.

Given that quantum computing is a discipline that currently still lies largely outside the expertise of the biotech industry, The team has approached the problem from the following aspects: education on the basics of quantum computing, collaboration with academia and with partners in the industry, and eventually moving towards general engagement in the community. Given the intellectually challenging nature of the topic, the team first had to educate themselves on the basic principles and mechanisms of QC, which enable quantum algorithms to scale differently compared to classical computing. Coming from diverse backgrounds, including computer science, bioinformatics, and physics, each team member was encouraged to pursue their own learning path. The group held regular forums to share what they had learned and updates.

At the same time, the team started to leverage external expertise to complement their capacity and skillset. Two master students from the University of Oxford worked with the team on quantum chemistry simulation and machine learning, which led to two publications [37] [38]. In addition to academic collaborations, the team attended various industry conferences that brought academics, industry representatives, and different commercial entities together. While academic labs spearhead scientific breakthroughs in algorithmic and hardware development, commercial entities, both start-ups and big tech companies, lead the race to scale up quantum solutions.

After a period of analysis and exploration, the team's efforts consolidated around developing use cases where a concrete impact of QC is expected. Benchmark datasets and classical solutions were also developed with each use case to measure current developments against state-of-the-art (SOTA) classical solutions and generate quantum resource estimates required to achieve quantum advantage. In order to bridge the gap between what is theoretically possible and the practical application of QC, the team collaborated with academic and industry partners to push the envelope in algorithmic development and simulation of quantum circuits and execution on quantum hardware.

4.3 Pharma Relevant Use Cases

Since the inception of QC as a discipline, there has been a wealth of algorithms, including the famous Shor's algorithm for prime factorization and Grover's algorithm for unstructured search, which has a solid mathematical proof for exponential and polynomial scalability advantage compared to classical solutions. However, many of these algorithms with guaranteed scalability require fault-tolerant quantum hardware, which calls for error correction and millions of physical qubits. While quantum hardware has moved from purely academic apparatus into the realm of noisy intermediate scale quantum (NISQ) with a moderate number of qubits and level of gate accuracy, fault-tolerant algorithms could be out of reach for a while.

Between now and the advent of fault-tolerant machines, many efforts have been made to design algorithms suitable for NISQ machines, which often do not come with proof of scalability [39]. These are coined heuristic algorithms, and famous examples include variational quantum eigensolver and quantum approximate optimization algorithms. While considering which algorithm would be relevant for the pharma industry, at least two dimensions are considered: potential for impact and technical feasibility.

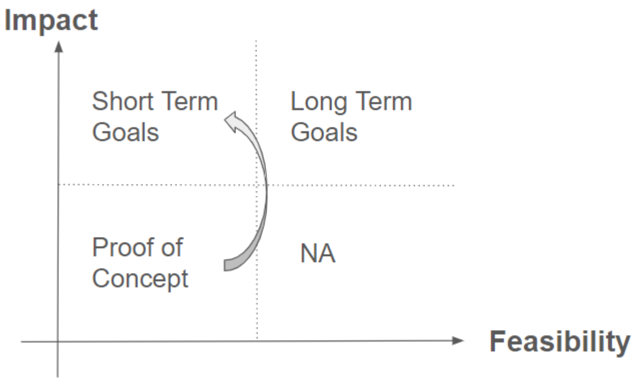

Figure 6: Impact versus feasibility assessment matrix. Fault-tolerant algorithms map well into the long-term goals, while current NISQ applications have the potential to move from proof of concept into short-term goals.

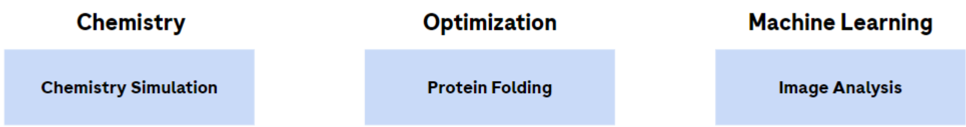

Figure 7: Three pharma relevant areas of application and corresponding use case.

After surveying the field for available solutions, the team has identified three areas of application where quantum algorithms hold promise to deliver an advantage: chemistry simulation, optimization, and machine learning. Each area of application not only offers promising algorithms for both fault tolerant and NISQ machines, but these three topics are also highly relevant for the pharma industry. At a very high level, accurate and efficient chemistry simulation plays an important role in pre-clinical research, especially in lead identification, where the goal is to find the right molecule that binds the target protein with high specificity. One effort in this direction can be found in [40], one of the first works to be published where real quantum hardware was used to rank the binding energy of molecules to a pharma-relevant target.

In the optimization space, the potential for impact is quite broad since optimization algorithms are deployed throughout the drug discovery process, as well as other global functions such as finance, supply chain, and logistics. A particularly impactful use case can be found in the pre-clinical space, namely target identification, where the goal is to predict the 3D structure of a protein given its sequence of amino acids. One formulation of this problem aims to optimize the potential function of the protein based on the geometry of each atom about each other in the sequence. Two works have been published on this topic with different approaches, one working with fault-tolerant algorithm [41] and the other with NISQ-friendly algorithm [42].

4.3.1 Quantum Machine Learning

The third area of application that is particularly relevant for the pharma industry is Machine Learning (ML). With the rise of Deep Learning (DL), many tasks, including image classification and task comprehension, can be performed with near-human, if not superhuman, levels of performance. In contrast to the ubiquity of ML and DL and their impact across different industries is cautious realism of the exact type of advantage QC can deliver for ML [43], especially in competition to GPU technology where the bar is set ever higher. However, the need remains to find more efficient solutions as both model size and the demand for DL continues to grow.

To find out whether QC can make a difference in ML, medical image classification was chosen to benchmark progress. This use case has a broad scope of impact, especially in clinical development, where medical imaging is an indispensable tool for patient evaluation. Image analysis is also a field where classical DL has proven to excel, with plenty of publicly available datasets and SOTA results. Furthermore, advances made in medical imaging could transfer to other data modalities, such as text, where the predominant architecture, such as transformers, is shared.

To address this challenge, different approaches are available, including works that leverage fault-tolerant linear algebraic algorithms to speed up feedforward networks [44]. In another work, components of the convolutional neural network, such as the convolutional kernel and pooling operation, are analyzed and shown to scale favorably under certain constraints such as translation invariance [45]. However, another work looks into the attention mechanism used in the transformer architecture and finds efficient ways to implement it on NISQ machines [46].

4.4 Trends and Future Directions

Given the continuous investment and developments made in the field of quantum hardware, where different technological platforms compete for the next breakthrough in compute capacity and the high level of uncertainty in the time of delivery of these technological roadmaps, the space requires careful monitoring to stay abreast of the latest developments and adjust the timeline of expected impact according to calculated quantum resource estimates.

As the hardware industry progresses, new and adapted versions of quantum algorithms are published daily. For heuristic algorithms developed for NISQ machines, there is potential to move proof of concept use cases into the upper left quadrant of the impact-feasibility map and show more value with higher impact use cases. At the same time, the hardware industry strives toward fault-tolerant solutions. The team has gained insights into the current system scale and obtained realistic estimates of the quantum resources required to achieve impact for specific use cases from previous efforts in designing and testing different quantum algorithms in the three application areas. These are ready benchmarks for assessing new developments in hardware and software.

One final aspect of consideration for the pharma industry is to continue to engage in the general discussion and guide the community in developing industry-relevant solutions. By building close ties to the QC ecosystem, the team is able to scale up and engage with the most suitable partners when the opportunity arises.

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