Institution: Imperial College London		
Unit of Assessment: 9 – Physics		
Title of case study: B9-1 Commercial investment in PsiQuantum – a photonic quantum computing company		
Period when the underpinning research was undertaken: 2005-2015		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Prof Terry Rudolph	**Role(s) (e.g. job title):** Professor of Quantum Physics	**Period(s) employed by submitting HEI:** 11/2003 - present
Period when the claimed impact occurred: 2015 – 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

PsiQuantum is a US incorporated with UK subsidiary, Later Stage Venture Capital funded, company which has received more than US$215M investment to build the world's first large scale quantum computer based on the theoretical photonic architectures which Prof. Rudolph's research group discovered and developed from 2005-2015. The company received seed investment in July 2016 and, as of January 2020, has more than 130 employees, approximately 1/4 of whom are theoretical physicists working under the leadership of Prof. Rudolph, with 2/3 of the remaining total staff being engineers from the silicon-electronic and silicon-photonic industries. Currently PsiQuantum has more than 30 patents and [redacted from public version].

2. Underpinning research (indicative maximum 500 words)

PsiQuantum is building a photonic quantum computer based on developing the architecture published in **[1]**, **[4]**, **[6]**.

In 2005 Rudolph discovered a way **[1]** to undertake photonic quantum computing using so-called "fusion gates". This approach was very many orders of magnitude simpler and more robust to imperfection than prior proposals for using photons as qubits. The work was developed with Dan Browne, now Professor at UCL, and a consultant with PsiQuantum.

In **[2-5]** Rudolph and collaborators published many further simplifications that greatly reduced the amount of switching required and vastly improved the potential tolerance to loss, which is the primary error mechanism when using photons as carriers of quantum information. The PhD student who worked on **[4]**, Konrad Kieling, is now a full time PsiQuantum employee.

The line of research culminated in the paper **[6]** and 2015 PhD thesis of Controlled Quantum Dynamics CDT student Mercedes Gimeno-Segovia. There were two key breakthroughs in that work:

(i) It was shown that all photonic components required could be efficiently laid out on a plane. This is critical because all silicon manufacturing is inherently 2-dimensional, and it opened up using the nascent field of silicon photonics https://en.wikipedia.org/wiki/Silicon_photonics.

(ii) It was shown that every individual photon in the quantum computer need only travel through a small, constant number of components, regardless of how large the final computer. Because photon loss is a primary error mechanism this vastly improved the viability of the architecture.

Of the authors of **[6]**, Dr. Gimeno-Segovia is a PsiQuantum employee leading the Optical Architecture Team, Dr. Shadbolt is a co-founder and Chief Technology Officer of PsiQuantum.

3. References to the research (indicative maximum of six references)

[1] *Resource-Efficient Linear Optical Quantum Computation*, Daniel E. Browne and Terry Rudolph
Phys. Rev. Lett. 95, 010501 – Published 27 June 2005
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.95.010501

[2] *Loss Tolerance in One-Way Quantum Computation via Counterfactual Error Correction*, Michael Varnava, Daniel E. Browne, and Terry Rudolph
Phys. Rev. Lett. 97, 120501 – Published 20 September 2006
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.97.120501

[3] *Loss tolerant linear optical quantum memory by measurement-based quantum computing,* Michael Varnava, Daniel E. Browne, and Terry Rudolph
New Journal of Physics, 9 – Published 1 June 2007
https://iopscience.iop.org/article/10.1088/1367-2630/9/6/203

[4] *Percolation, Renormalization, and Quantum Computing with Nondeterministic Gates*, K. Kieling, T. Rudolph, and J. Eisert
Phys. Rev. Lett. 99, 130501 – Published 25 September 2007
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.99.130501

[5] *How Good Must Single Photon Sources and Detectors Be for Efficient Linear Optical Quantum Computation?* Michael Varnava, Daniel E. Browne, and Terry Rudolph
Phys. Rev. Lett. 100, 060502 – Published 12 February 2008
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.100.060502

[6] *From Three-Photon Greenberger-Horne-Zeilinger States to Ballistic Universal Quantum Computation*, Mercedes Gimeno-Segovia, Pete Shadbolt, Dan E. Browne, and Terry Rudolph
Phys. Rev. Lett. 115, 020502 – Published 8 July 2015
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.115.020502

4. Details of the impact (indicative maximum 750 words)

Commercial investment in PsiQuantum – General purpose silicon photonic quantum computing

Starting with the breakthrough result in 2005 at Imperial College London **[1]**, Prof Rudolph has been the world leader in theoretical photonic quantum computing. Combined with hardware advances by the team at the Centre for Quantum Photonics in Bristol under Professors O'Brien and Thompson this culminated in them co-founding PsiQuantum in 2015 **[A]**.

Rudolph joined with O'Brien and Thompson, who had experimentally pioneered using single photons in silicon photonics at Bristol, to seek resources to scale the small university lab scale technology to the millions of qubits required for building a universal, fault tolerant quantum computer. Since then, there have been two rounds of investment in PsiQuantum (www.psiquantum.com) by Venture Capitalists and by potential future users from the pharmaceutical, aerospace, high-performance computing and automotive industries.

The core of PsiQuantum's architecture, known internally as "Fusion based quantum computing" (FBQC) is based Prof. Rudolph's research on the fusion gates and protocols introduced in **[1]** and **[6]**. PsiQuantum is the only company with a fully simulated architecture (from hardware through to logical gates) capable of creating a million physical qubit machine capable of fault tolerant operation. This simulation took a team of more than 25 physicists at PsiQuantum over 2 years to implement. PsiQuantum are the only company with a technology that can be fully built within a Tier 1 semiconductor foundry, the same facilities which create the semiconductors found in all modern electrical devices such as laptops and mobile phones. This is in contrast to other quantum computing ventures which require far more custom manufacturing processes. PsiQuantum has partnered with one of these leading foundries, Global Foundries, who are committed to achieving the engineering specifications required **[B]**. Production of the early versions of these chips has begun **[B]**.

IP impact: Imperial College London and Bristol University received a patent in 2015 on one feature of the silicon photonic architecture **[C]**. This patent was subsequently purchased by PsiQuantum. PsiQuantum now has more than 30 other patents **[D]**.

The strengths of the photonic approach to quantum computing are briefly summarized in Sec 5.4 p.124 of this report by the US National Academy of Sciences **[E]**. They state the following:

"*Photons have a number of properties that make them an attractive technology for quantum computers: they are quantum particles that interact weakly with their environment and with each other. This natural isolation from the environment makes them an obvious approach to quantum communication.*"

Investment: PsiQuantum is still a stealth mode start-up, however, some investment information is public. In November 2019, the company completed a Later Stage Venture captial, Series C, funding raising and PsiQuantum has raised approximately $215 million building general purpose silicon photonic quantum computers **[A, B]**. This is one of the biggest investments to date in quantum computing. It included investment from former Google executive Andy Rubin's Playground Global venture fund, Ballie Gifford, BlackRock, Founders Fund, Atomico and Microsoft's M12 Ventures **[A, B]**.

Employment and training: PsiQuantum has 130 employees (as of January 2020), including 13 Imperial College alumni (from Physics and Computer Science) and many other UK citizens have been employed by the company. Four UK physics students have done internships with the company **[A]**.

[Redacted from public version]

Wider economic and political importance of Quantum Computing:

The growth of companies such as PsiQuantum fits into a wider economic and political landscape of investing and developing the technologies of the future. Accenture consulting estimated that in 2016 $1 Billion was invested in quantum computing from public and private investment **[G]**. They also identified over 150 use cases for quantum computing with industries ranging from healthcare and manufacturing to financial services and resources **[G]**.

Boston Consulting Group report "The Coming Quantum leap in computing" from 2018 states that: *"the use of quantum computers to model physical systems has immediate applications in industries such as pharmaceuticals, chemicals, and energy. Algorithms using quantum math can unlock value by vastly speeding up data-intensive applications in such fields as search, cryptography, and machine learning."* […] "*Several such algorithms, in fields such as cryptography and machine learning, already exist. The processors are under active development, and announcements of increasingly capable processors come at an accelerating pace*" **[H]**

Given the importance and wide-reaching implications of developing and producing quantum computers and technologies, national levels of investment and governmental policy are required to help create the conditions for this sector to flourish. To this end national governments are developing Quantum future strategies, for example, the US government report 'National strategic Overview for Quantum Information Sciences' states that: "*Through developments in QIS*

[Quantum information science], the United States can improve its industrial base, create jobs, and provide economic and national security benefits." **[I]**

The UK government states that: "*The UK already has a lead in some forms of quantum computing, and with the right environment we can benefit from developing the devices, exploiting their power and running the new quantum IT services that will follow.*" (page 48) **[J]**. The Quantum Age: technological opportunities report **[J]** (page 47) also highlights the important of photonic quantum computing in the UK Government's priorities in developing Quantum technologies.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Letter from PsiQuantum CEO – details the investments, number of employees and the direct connection of Prof. Terry Rudolph's research to the formation of PsiQuantum in 2015.

[B] Business Bloomberg story on PsiQuantum https://www.bloomberg.com/news/articles/2020-04-06/quantum-computing-startup-raises-215-million-for-faster-device (Archived here)

[C] https://patents.google.com/patent/US9952482B2/ - this is the key patent held by PsiQuantum for the photonic based quantum computer (Archived here)

[D] patents.google.com/?assignee=PsiQuantum – lists the patents held by PsiQuantum, currently approximately 35. (Archived here)

[E] 5. Essential Hardware Components of a Quantum Computer. National Academies of Sciences, Engineering, and Medicine. 2019. *Quantum Computing: Progress and Prospects*. Washington, DC: The National Academies Press. doi: 10.17226/25196. https://www.nap.edu/catalog/25196/quantum-computing-progress-and-prospects (Archived here)

[F] Redacted from public version

[G] Accenture Report on Quantum Computing https://www.accenture.com/t20170628T011725Z__w__/us-en/_acnmedia/PDF-54/Accenture-807510-Quantum-Computing-RGB-V02.pdf (Archived here)

[H] Boston Consulting Group report on Quantum Computing https://www.bcg.com/publications/2018/coming-quantum-leap-computing.aspx (Archived here)

[I] White House report on Quantum Information Science https://www.whitehouse.gov/wp-content/uploads/2018/09/National-Strategic-Overview-for-Quantum-Information-Science.pdf Page 2 from the opening paragraph of the introduction (Archived here)

[J] UK government review of Quantum Technologies and Computing https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/564946/gs-16-18-quantum-technologies-report.pdf (Archived here)