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# Proposal for a bi- or trilateral collaborative R&D-project

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## Title:

**Toward Utility and Fault-Tolerance for Photonic Quantum Computing**

Project duration: 36 months

## Acronym:

TUF-ToPiQC

**Key Words (max. 10):**

photonic quantum computing, ultrafast integrated optics, photonic integrated chips, single photon sources, error correction, quantum algorithms, quantum utility

**Partners of the Consortium:**

Name **Quandela (QUA) – FR – Coordinator**

Institution Quandela

Address 7 Léonard de Vinci, 91 300 Massy, France

Telephone +33 1 88 21 35 35

Scientific contact: Shane Mansfield shane.mansfield@quandela.com

Administrative and financial contact: Yara Hodroj yara.hodroj@quandela.com

Name **Centre de nanosciences et de nanotechnologies (C2N) – FR – Partner**

Institution Centre National de la Recherche Scientifique CNRS

Address 10 Boulevard Thomas Gobert, 91120 Palaiseau, France

Telephone +33 1 70 27 01 00

Scientific contact: Pascale Senellart pascale.senellart-mardon@universite-paris-saclay.fr

Administrative and financial contact: Lucie Martinez Charton lucie.martinez-charton@cnrs.fr

Name **Qubit pharmaceutical (QBIT) – FR – Partner**

Institution Qubit pharmaceutical

Address 29, rue du Faubourg Saint Jacques 75014 Paris, France

Telephone +33 674139014

Scientific contact: Alberto Peruzzo alberto.peruzzo@qubit.pharmaceuticals.com
Administrative and financial contact: Robert Marino robert@qubit-pharmaceuticals.com

Name **Single Quantum (SQ) – NL– Partner**
Institution Single Quantum
Address Rotterdamseweg 394, 2629 HH Delft, Netherlands
Telephone +31 850 400 900
Scientific contact: Mario Castaneda m.castaneda@singlequantum.com
Administrative and financial contact: Sander Dorenbos s.dorenbos@singlequantum.com

Name **MicroAlign BV (µA) – NL – Partner**
Institution Micro Align BV
Address Het Eeuwsel 57; 5612 AZ Eindhoven; Netherlands
Telephone +31 6 4779 0324
Scientific contact: Dario Lo Cascio d.locascio@microalign.nl
Administrative and financial contact: Simone Cardarelli scardarelli@microalign.nl

Name **Paderborn University (UPB) – DE – Partner**
Institution Paderborn University
Address Warburger Straße 100, 33098 Paderborn, Germany
Telephone +49 5251 60-2486
Scientific contact: Klaus Jöns klaus.joens@upb.de
Administrative and financial contact: Katherina König katharina.koenig@zv.uni-paderborn.de

Name **Swabian Instruments GmbH (SWA) – DE – Partner**
Institution Swabian Instruments GmbH
Address Stammheimer Strasse 41, 70435 Stuttgart, Germany
Telephone +49 711 400 479 0
Scientific contact: Jan Bruin jan.bruin@swabianinstruments.com
Administrative and financial contact: Mirco Kolarczik mirco@swabianinstruments.com

# 1. Project Objective and Aims

The consortium combines world-leading expertise from France, Germany and the Netherlands, both at the academic and industrial level, to provide an unprecedented push to move photonic quantum computing towards **utility** (i.e. useful industrial applications in the NISQ regime) and **fault tolerance** (unlocking the path to large-scale quantum computation). We adopt a holistic approach to addressing these two objectives by covering the full photonic quantum computing stack, from hardware components, to integration, to software and algorithms. While targeting critical breakthroughs in quantum computing, the project will also tackle important technological challenges, strengthen each partner's leadership in their respective domain and impact the development of photonic quantum technologies as a whole in the EU.

## 1.1 *Motivation*

**State of the art.** Photonic technologies are among the most actively developed platforms for quantum computing worldwide, and are one of only two technologies to have demonstrated a quantum-computational advantage to date. Europe boasts the largest and most active photonic quantum-computing community worldwide which has resulted in the emergence of key European industrial actors jointly contributing to the development of photon-based quantum computers. As such, the photonic quantum computing platform developed by Quandela builds on the integration of key technologies developed in the Netherlands, Germany and France, from single-photon and entangled photon sources (C2N, QUA), single photon detectors (SQ), high-precision fibre packaging (µA), dedicated electronic (SWA), ultrafast optical control (PDB). This unique photonic ecosystem has allowed for the first EU-based commercial quantum computing platform made available for end-users on the cloud to be the photon-based (Ascella by Quandela, early 2023). Photonic quantum computer were also the very first ones installed and operated in industrial data centres in Europe, and have recently also been installed in North America. These first photonic quantum processors operate in the NISQ regime and allow for the progressive community-based exploration of relevant real-world use cases. In addition, they enable the identification and testing of the building blocks for fault tolerance, in line with recent detailed roadmaps for fault-tolerance and scaling in photonic quantum computing (FBQC, SPOQC) [1,2].

The key modules of photon-based quantum computers are efficient sources of single or entangled photons, highly transmissive and reconfigurable photonic chips and near-unity-efficiency single-photon detectors. These are assembled and integrated with state-of-the art techniques that minimise photon loss and their operation, synchronisation and readout is performed by specifically tailored high-speed, low-noise electronics. Special algorithms and advanced software ensure a smooth operation of the quantum computer. At the heart of these discrete variable photonic quantum computers lies a unique approach for generating high-quality single photons from semiconductor quantum dots. However, scaling of such platforms will require pushing the boundaries of each of the above-mentioned modules and the integration technologies to their limits and incorporating new features. The present project therefore gathers key expertise for all these various ingredients allowing a true acceleration to reach useful industrial applications within the project lifetime, while driving the performance towards the thresholds required for fault-tolerance, including the exploration and development of error-correction and algorithmic tools to make those thresholds more favourable.

**Towards Utility.** Our notion of Utility is performing a useful quantum computation, for which the time/energy cost of emulating it on a classical device is greater than that of the quantum computation itself. This shifts the focus to a more practical metric compared to the notion of provable quantum advantages that have been the focus of the academic community.

- On the hardware side, we first address key milestones for continuously increasing the number of manipulated qubits. In the case of a photonic quantum computing platform, this implies pushing the performance of single- and entangled-photon sources towards near-unity-efficiency and highest quantum purity, and at the same time increasing the transmissivity and reconfigurability of the processing units, that is the photonic chips. On the detector side, our key objective in this proposal is to reach near-unity-efficiency and in addition to make steady progress towards photon-number resolving detection. Together these efforts will enable us to assemble ever more powerful computing platforms with unparalleled processing power throughout the course of this project.

- On the algorithmic side, the key challenge for the community is the demonstration of true quantum utility before reaching the threshold for fault tolerance in the more distant future. Some of the participants in this consortium have deep theoretical expertise and solid experience in exploring industrial use cases and strongly believe that by combining advances in hardware performance and tailored algorithmic development, the team can help bring utility within reach over the lifetime of this project.

**Toward fault tolerance**

The most straightforward path to fault tolerance for photonic quantum computers relies on the measurement-based quantum computing paradigm which in turn utilises large resources states, i.e. large photonic cluster states with many entangled photons, that are successively individually manipulated and measured. This approach is ideally suited to a photonic platform and results in the same universal computational capabilities as the typical gated-based approaches for matter qubits, but also provides a natural stepping-stone to error-correction techniques with photons.

In the present project, we have gathered critical expertise to accelerate the path towards fault tolerance.

- On the theory side, the teams share strongly complementary expertise for the identification of the most efficient roadmap to fault tolerance, adapted and tailored to our hardware. Resource estimation tools will be co-developed to pinpoint precisely the hardware performances needed for implementing landmark algorithms requiring fault-tolerance, such as Phase Estimation and Shor's algorithm.
- On the hardware side, the team will develop entangled photon states of unprecedented size and trim the processing platform for fast reconfigurability and feed-forwarding that are required for realising measurement-based protocols.

## 1.2 *Concrete Goals*

**Two objectives – supported by multiple technological and theoretical objectives pushing further international state of the art:**

### I. We will push the NISQ photonic platform towards utility grade:

So far, NISQ photonic platforms permit proof-of-concept demonstrations of a number of algorithms which have important industrial applications and use-cases, including in particular variational quantum algorithms, and the variational quantum eigensolver. Nevertheless, all currently accessible QC demonstrations can still be emulated by classical processors. We believe that quantum utility (the regime where time/energy cost of the quantum computation is more efficient than the classically emulated counterpart) is reachable on a NISQ platform running tailored algorithms and processing with a few dozens of photons. We therefore push a two-pronged approach that advances both hardware and algorithms:

a. Bright single photon sources (QUA, C2N). We aim to reach 75% fibred brightness.
b. Near-unity-efficiency detectors (SQ). We aim to reach >90% efficiency.
c. High-efficiency optical coupling for the chip packaging (µA). We aim to reduce the fibre array pitch accuracy to better (less) than 0.1 µm, corresponding to theoretical fibre-to-chip coupling losses of less than 0.1dB for every fibre.
d. Compilation (QUA). We will develop tailored noise-mitigation techniques and demonstrate boosted quantum information processing fidelities.
e. Computational capabilities. We will identify useful applications (Qbit, QUA), define prototype NISQ protocols and provide numerical evidence for utility (classical simulations, time/energy analyses, QPU demonstrations).

## II. We will develop building blocks for scalable quantum computing:

To move towards fault tolerance (FT), we again push a two-pronged approach. On the hardware side, we will leverage the development efforts from the NISQ objective, while supplementing them with the additional technological ingredients required to enable the implementation of MBQC on large resource states (fast-reconfigurability, feedforward, and number-resolution). Taking advantage of the consortium's unique combined hardware expertise, our software and theory participants will develop architectural blueprints and error-correction strategies that are optimally tailored to the platform. Software tools will allow for quick testing and evaluation of emerging results from error-correction to identify the most favourable thresholds, and to identify precise performance and resource targets for a range of landmark quantum algorithms, applications and use cases requiring fault-tolerance.

a. Bright sources of cluster states (C2N, QUA). We aim to reach a 6-photon linear cluster state.
b. Feedforward (UPB, SWA). We aim to reach 100 ns detection and reconfigurability speed.
c. Photon number resolution (SQ, SWA). We aim to resolve 2-photon detections with success probability > 80%.
d. Software for efficient threshold calculations (QUA). We aim for realistic modelling of cluster states, feedforward and photon-number resolution, integrated with Perceval.
e. Resource estimation software (QUA, QBIT). We aim for concrete requirement specifications for quantum phase estimation and a roadmap of minimal requirements for targeting relevant molecules.

## III. We will integrate both approaches in functional prototypes:

The project will gather the expertise of all partners in the consortium in order to develop components with new functionalities and state-of-the- art performances that will be assembled into two distinct quantum computer prototypes

a. A NISQ platform where at least 10 single photons will be manipulated to implement tailored algorithm demonstrating a quantum utility (assembled at QUA)
b. A prototype machine gathering key building blocks for fault tolerance, that will be used to obtain a logical qubit (assembled at C2N)

## 2. Added Value gained from International Cooperation / Relation to EU funding

Thanks to the synergy of expertise from technology leaders and researchers from the three partner countries, we are proposing a comprehensive approach to addressing the complex challenges involved in photonic quantum computing by considering interdependencies between hardware and software components. This holistic perspective is crucial for developing integrated solutions that are more effective and resilient in the face of evolving technological landscapes and international competition for quantum computing. Compared to a more isolated national project approach, this cross-border collaboration will foster much stronger networking and collaboration opportunities, both within the project consortium and with external stakeholders. This not only enriches the project with diverse perspectives but also enhances its visibility and impact on the global stage, facilitating future partnerships and opportunities for knowledge exchange and dissemination.

What is more, this project will generate the momentum to not only tackle short-term technology bottlenecks but to overcome long-term challenges. This full duality, not commonly achievable through conventional EU funding schemes, will be instrumental for all partners to understand actual limitations and to shape fault-tolerant photonic quantum computing on a very concrete and sound basis.

We now briefly present our main national and EU-funded projects, highlighting the differences, added value, and gaps filled by the TUF-ToPiQC proposal, which federates a unique combination of expertise that is best positioned to accelerate development of a photonic QC platform towards utility and fault-tolerance.

**OQULUS (France) - C2N & QUA**: Pushes both discrete and continuous variable approaches to photonic quantum computing at the academic level – supporting mainstream technologies while also exploratory approaches such as new quantum light sources, new photon-photon gates etc. In comparison, TUF-ToPiQC is specifically for discrete variables, with a direct roadmap to applications, leveraging the industrial capabilities of start-ups, and builds strategic development with one of the most advanced industries in quantum grade PICs.

**QUDEM (France) - QBIT**: iNov programme to use the latest advances in quantum machine learning to develop sorting algorithms based on polarizable force fields to create the first complete workflow dedicated to these highly complex targets representing the new frontier for pharmaceuticals. TUF-ToPiQC will also draw on quantum machine learning techniques, but taking a hardware-aware approach to develop variational NISQ algorithms specifically tailored to photonic processors, and as preparation techniques for inputs to quantum phase estimation in the fault-tolerant regime.

**PhoQuant (Germany) - UPB & SWA**: PhoQuant develops lithium niobate based Gaussian boson sampling devices at 1550 nm. PhoQuant also investigates the NISQ applications of Gaussian boson sampling. TUF-ToPiQC will benefit from exchange of ideas on the usage of photonic NISQ devices, with potential for cross-over ideas on loss compilation, error mitigation and algorithms. The added value of comparing and benchmarking the different approaches on photonic quantum computers between PhoQuant and TUF-ToPiQC will be instrumental for new adopters from industry.

**Spinning (Germany) - SWA**: BMBF project on detection and control electronics for a quantum computer based on NV centres. Within Spinning, SWA develops feedback loops based on photon count rates. The platform developed in Spinning can be a starting point for more complex analysis algorithms and faster feedback times. In TUF-ToPiQC the focus is rather on discrete variable photonic quantum computing

**QPIC-1 (Germany) - UPB**: BMBF project on quantum processors and technologies for quantum computing. QPIC-1 develops lithium niobate circuits for 1550nm to feed-forward a two-dimensional cluster state. The cluster state is generated using parametric down-conversion sources. TUF-ToPiQC will benefit from the infrastructure and cleanroom facilities as well as expertise to process lithium niobate, theory cross fertilisation, and photon-loss management. TUF-ToPiQC will target a different target wavelength (925 nm) which raises different challenges in the design of the circuit, fabrication tolerances and device characterization. The aim of this proposal is to generate a different cluster state, requiring new research on the photonic chip geometry, the algorithm, and the feed-forward operations.

**NXTGEN-Inlite (Netherlands) - µA**: National project for boosting the Dutch Integrated Photonics supply chain. 2023-2020. µA participates with a feasibility study on multi-fibre alignment applications and building contacts within the Dutch integrated photonics supply chain.

**EPIQUE (EU): C2N, QUA, SQ and UPB**: This project with 18 European partners aims to develop NISQ CV and DV quantum computing laboratory prototypes, benchmarking, and proof-of-concept building blocks, without any addressing error-correction. In contrast TUF-ToPiQC directly focuses on a DV platform, taking an industrial approach to rapidly advance towards specific applications with utility on the NISQ side and a fine-grained blueprint development and resource estimation for applications on the fault tolerant approach.

**SEPOQC (EIC) - QUA**: Scalable Entangled-Photon based Optical Quantum Computers is a project funded in the framework of the EIC program. QUA aims to improve the brightness, purity and reproducibility of the single photon sources, to develop opto-electronic modules for the core quantum computing platform and for efficient routing and manipulation of photons, to produce a library of algorithms, and software for simulating and controlling Quandela's quantum computer, and to prepare the commercialization of quantum computers. TUF-ToPiQC builds on this via a community approach, that adds additional capabilities on top of the SEPOQC developments, to accelerate towards utility and fault-tolerance.

**QUONDENSATE (EU) - QUA**: EIC Pathfinder project to explore the capabilities of quantum reservoir computing and deliver first proof-of-concept demonstrations. QUA is the only industry partner and participates in the development of algorithms and benchmarks, tools which can be useful for the utility aspects of the TUF-ToPiQC project.

**ResourceQ (EU) - QUA**: QuantERA II ERA-NET which builds tools to unify and optimise algorithmic resources for advantage in quantum computing. Case studies in photonic quantum computing with variational algorithms can complement developments of TUF-ToPiQC, which however aims at practical near-term utility rather than advantage.

**Qu-Pilot (EU) - QUA**: Horizon project that gathers 21 partners from 9 different countries aiming to develop and provide access to the first, federated European fabrication (production) capabilities for quantum technologies. QUA's use-case within the project focuses on the development of large and efficient interferometers based on photonic integrated circuits. TUF-ToPiQC will focus on smaller PICs development with fast reconfigurability for feedforward applications.

**Qu-test (EU) - SQ & QUA**: Horizon project with 26 partners that brings together competences and infrastructure across Europe to offer testing and validation services. QUA and SQ are use-cases in the project. Quandela's use-case aims at integrating SNSPD's on a photonic circuit. In TUF-ToPiQC the development will focus on the photon-number resolving capabilities of SNSPDs and the integration of low-latency SNSPD read-out systems.

**Atlas (EIC) - QBIT**: Development of Quantum Algorithms into Qubit Pharmaceutical drug discovery platform. By optimising hardware implementation and error modelling in TUF-ToPiQC, we aim to demonstrate that these techniques can be made more efficient using QPUs rather than classical computers leading to a global cost reduction.

**SURQUID (EIC) - SWA**: Initial development of a time-to-digital conversion ASIC for a quantum LIDAR system. The prototype for the ASIC has been tested successfully, in TUF-ToPiQC the development will focus on the integration in low-latency systems.

**LiNQs (ERC) - UPB**: ERC starting grant 2021. Lithium-niobate integrated quantum photonics platform. Exchange of nanofabrication and integration expertise. LiNQs develops lithium-niobate circuits for 1550nm as a platform to integrate building blocks such as quantum light sources and memories. TUF-ToPiQC will benefit from the infrastructure and cleanroom facilities as well as expertise to process lithium-niobate but does not require hybrid integration as envisioned in LiNQs. The different target wavelength of 925 nm in our projects will impose additional challenges in the design of the circuit, fabrication tolerances and device characterization.

**EU-adoption (Horizon-CL4-2021) - μA**: ADOPTION works toward the goal of proving a low-power and low-cost solution for intra-data centre networks employing co-packaging of the optical (CPO) transceivers with the packed switch chip. μA supplies a multi-fibre to PIC solution with lower losses at a wavelength of 1310 nm. The approach of μA's solution within ADOPTION is based on the simultaneous alignment of multiple loose fibres to the photonic chip. Such a solution and related activities are the basis to develop further μA's actuation technology, to be employed within TUF-ToPiQC to create high-accuracy fibre arrays. In the latter case, the fibres attached to the chip are encapsulated in a glass block. In TUF-ToPiQC, a shorter wavelength of light is considered, requiring further development of the control hardware supporting μA's actuator.

## 3. State of the Art in Science and Technology and Preliminary Work

### Hardware

In recent years, there has been notable progress in the demonstration of photonic quantum computing, with experiments showcasing on the order of tens of physical photonic qubits [3,4,5,6,7,8]. However, the number of usable qubits remains constrained, primarily by the transmission and efficiencies of the various system components, including single photon emitter efficiencies, optical element transmissions, and detection efficiency. To achieve utility-scale quantum computing capabilities, a significant augmentation in the quantity and quality of system components is imperative. This includes the development of high-efficiency and entangled photonic qubit emitters, rapid and efficient photonic processors, efficient fibre interconnects, low-latency on-chip processing electronics for feedforward operations, and high-efficiency photon-number resolving detectors.

**Single photon & Cluster state sources**

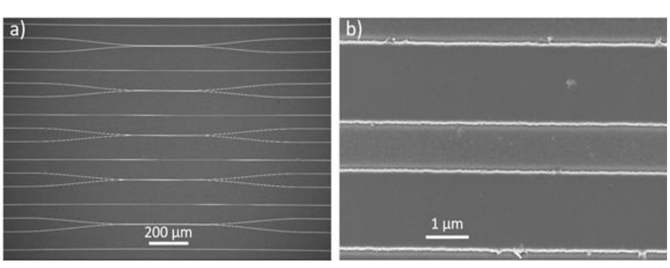
The efficient generation of photonic qubits, such as single photons, is a great challenge that has limited the development of photonic quantum computing platforms for a long time. Semiconductor quantum-dot single-photon sources have brought a solution to this roadblock, with the demonstration of unparalleled efficiency and quantum purity [9,10], with no fundamental compromise when optimising both properties simultaneously. The C2N team has been leading this source development since 2010 by introducing a reproducible and scalable technology for the source fabrication [11,12], which QUA, since 2017, has transformed into a plug-and-play device, today routinely integrated in QUA's quantum computers.

The path to error correction builds on the generation of resources states – i.e. many entangled photons on which measurement-based protocols are implemented. Here again, the quantum dot sources have emerged as a fantastic asset for allowing the generation of entangled photons at the quantum dot level [13]. This protocol builds on the entanglement of the spin degree of freedom and the polarisation of the emitted photons. Recently, C2N and QUA have demonstrated the generation of entanglement between an electron spin and two photons, at an unprecedented rate, using the same devices as the ones used for single photon generation [14].

**Accurate industrial PIC packaging**

Recent advancements in Photonic Integrated Circuits (PICs) technology, particularly exploiting industrial foundries, have led to substantial improvements in transmission losses, particularly with materials like silicon nitride [15], lithium niobate [16], and laser-written glass [17]; some of those demonstrations have also shown near-unity input/output chip-coupling losses [18,19]. Their implementation in large-scale photonic quantum computers, however, requires robust and industrial packaging solutions which are still lacking today. Present fibre-array technologies, such as V-groove configurations, do not meet the requisite accuracy levels and do not permit correcting for bow and warp of wafers (Figure 1). µA has invented a patented [20,21,22] micro-actuation system capable of fast and simultaneous alignment of closely placed multiple optical fibres, allowing for the fabrication of ultra-high accuracy fibre arrays with a core position accuracy better than 0.1µm.

**Feedforward** is a crucial operation in quantum computing, where the outcome of one quantum operation is used to inform subsequent operations dynamically. In the context of photonic quantum computing, feedforward involves adjusting subsequent quantum gates based on the measurement outcomes of previous gates, enabling conditional operations and adaptive quantum algorithms. This requires high-quality optical systems with low latency and fast reconfigurability. Several demonstrations [23,24,25,26,27,28] have been carried out using free-space optics components which are, however, not suited for a large-scale platform. UPB has demonstrated worldwide unique broad expertise in the design and fabrication of tailored integrated-photonic quantum devices in lithium niobate allowing for ultra-fast reconfigurability required for feedforward. UPB has demonstrated interferometrically stable and reconfigurable photonic circuits [29,30] as a promising platform for the large-scale implementation of universal quantum information processors. UPB is designing their own BiCMOS ultra-fast electronic chips using Cadence software, resulting in electronic rise-times below 50ps.



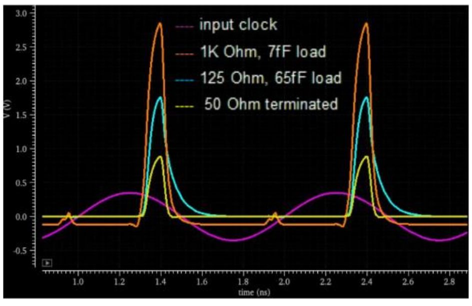



*Figure 1 - **Right**: a) Directional 50%/50% couplers in thin-film lithium niobate waveguides. b) Zoom-in of a thin-film lithium niobate, **Left**: Chip simulation data. The chip was completely simulated with the components of the Chip Foundry process design kit. The pulse heights of the output signal can be adjusted by different impedance and load.*

### Efficient PNR detectors

Recent advancements in single-photon detection technologies have demonstrated near-unity detection efficiencies [31], yet often lack photon-number resolving capabilities. Transition-edge sensors (TES) afford discrimination of energy and photon number with the pulse response, albeit characterised by long recovery periods [32]. Alternatively, employing multiplexing to channel photon flux onto threshold detectors, such as superconducting nanowire single-photon detectors (SNSPDs), enables photon-number resolution (PNR) through spatial, temporal, and multi-pixel strategies [33,34]. Nevertheless, the integration of these techniques and the augmentation of efficiency and repetition rates pose significant challenges. Recently, a novel methodology centred on time resolution, specifically single-pixel-based [35], has emerged, mitigating hardware overhead for integration. Notably, this approach has yet to be validated with quantum-dot single photons, with their length posing a challenge for temporal PNR.

### Utility

We focus on variational algorithms and applications in materials and chemistry. The Variational Quantum Eigensolver (VQE) for finding molecular ground state energies is an emblematic example [36], which was originally demonstrated on photonic processors. Key challenges to extracting utility on near-term devices relate to finding clever strategies to encode more complex problem instances and more expressive ansätze. Methodologies for finding ultra-compact, hardware-efficient ansätze have been pioneered by Qubit Pharmaceuticals [37,38]. Multi-qubit gates are particularly interesting for such ansätze. Research from QUA has shown it to be advantageous on photonic platforms to work with multi-controlled qubit gates [39], while research from QBIT found optimised decompositions of such gates [40]. VQE and other variational algorithms have been demonstrated on QUA's cloud quantum processors [41], which have also been a testing-ground for the development of photon-native ansätze for variational algorithms which can be more hardware-efficient by bypassing qubit encodings [42].

### Fault-tolerance

A crucial stepping stone for the long-term scalability of all quantum computing platforms is the implementation of error-correcting codes, which make use of additional resources to redundantly encode information across many qubits, but are capable of dynamically detecting and correcting errors due to loss, decoherence and other systematic processor errors. Error-correction techniques are measurement-based, requiring feedforward capabilities to correct for errors on the fly. They also require low error rates to begin with. In order to reach break-even point, at which the extra resources pay off by reducing error rates of encoded 'logical' qubits compared to raw 'physical' qubits, requires that physical error rates be below *threshold* values. Thresholds vary according to codes, as do the additional resources required. To date two detailed architectures have been proposed for fault-tolerant photonic quantum computing: FBQC [43] and the SPOQC architecture developed by QUA [44] Thresholds and resource estimation remains to be carried out in a systematic way for these architectures, as well as for variants combining aspects of both.

## 4. Brief Description of the Project Partners

**Quandela (QUA) -** Quandela is a European leader in the field of quantum computing, exploiting semiconductors and photonic technologies. Leveraging the world's most efficient single-photon emitters, the company has developed and commercialised state-of-the-art photonic quantum computers. With more than 80 employees, the company gathers experts in semiconductors, optics, electronics, quantum information theory and computer science, with headquarters located in the Paris region, a subsidiary in Munich (DE) and offices worldwide.

QUA's extremely efficient, high-quality single-photon source technology is based on the use of semiconductor quantum dots in micropillar cavities, a technology developed at the Centre for Nanoscience and Nanotechnologies (CNRS, Univ. Paris-Saclay). These sources have been on the market since 2017 and have been delivered to customers worldwide.

Since 2023, QUA has been supplying its product MosaiQ, a modular, scalable, energy-efficient photonic quantum computer that can be accessed in the cloud or can be delivered as standalone systems directly to customers, with particular suitability for colocation with HPC centres. QUA is specialised in the development of software and hardware solutions for a variety of quantum computing applications. The aim of the proposal is to bring together important commercial and academic knowledge from Germany, the Netherlands, and France in order to advance photonic quantum computing towards fault tolerance and utility (useful industrial applications in the NISQ regime). The project addresses these two goals holistically, encompassing software, hardware, and algorithms with solid expertise at QUA on these three parts and with complementary expertise from the partners of the consortium.

**C2N -** CNRS is the biggest French public research institute with more than 12,000 researchers covering all fields of science. The CNRS-C2N laboratory is a major nanoscience and nanotechnology centre at the French and European level with more than 400 staff members, PhD and postdocs. The C2N hosts a 2800m$^2$ micro-nano technology platform that gathers state-of-the-art III-V semiconductor nano-processing with all technological tools for the present proposal, including 4 molecular beam epitaxy machines and all conventional nanofabrication techniques such as e-beam lithography, reactive-ion etching, wet benches, thin-film deposition, photolithography, as well as optical and SEM imagining. For all the administrative aspects, the CNRS provides a secretary service familiar with managing European projects and the reception of international researchers.

The C2N team is a leader in the development of semiconductor single photon sources for applications in quantum technologies. The team invented a unique technology allowing reproducible fabrication of single photon sources by deterministically positioning a single quantum dot in an optical cavity. By constantly adding knobs to the device, the C2N succeeded in reducing strongly the decoherence induced by the solid-state environment to obtain high purity and near unity indistinguishability photons. This technology was transferred to Quandela who has been commercialising both single photon sources and photonic quantum computing solutions since 2017.

**Qubit Pharmaceuticals (QBIT)** - Qubit Pharmaceuticals is a drug discovery company with headquarters located in Paris and subsidiaries in Boston & Montreal. Close to 60 people contribute to the company's effort and to the management and development of its drug-discovery portfolio, consisting of 6 drug discovery programs in oncology, immuno-oncology and inflammatory diseases. The company is a spin-off from 5 universities and research centres: The University of Washington in St Louis, the University of Texas at Austin, Sorbonne University, CNAM and CNRS. The company has developed an end-to-end drug discovery computational approach, Atlas, leveraging 4 technologies: hybrid quantum inspired, physics based and Neural Network (NN) polarisable force fields allowing us to address any type of target, next generation molecular dynamics software specifically dedicated at accelerating polarisable force fields (physics based or NN based) to generate millisecond-long target simulation in order to identify novel pockets or modes of action, state of the art AI-ML generative tools to design novel molecules and predict their adme-tox and phys-chem property and last, quantum computing accelerated algorithms. While these algorithms are not in production yet due to the limitation of current quantum computers, they will be embedded in hybrid QC-HPC workflow within the next 24-48 months based on the hardware partners.

**Single Quantum (SQ) -** Single Quantum is a market leader in the emerging field of high-performance single photon detectors. The company was established in 2012 as a spin-off from the Delft University of Technology and has since developed, designed, built, and commercialised single-photon detection systems based on superconducting nanowires. A strong market pull for SQ's technology is reflected in a >30% annual growth rate. SQ is continuously developing new detectors to meet the required specifications of researchers and quantum technology companies by expanding its R&D team with highly specialised employees as well as its investments in state-of-the-art testing, calibration, and production equipment and facilities.

In TUF-ToPiQC, SQ will push the detection efficiencies of its single-photon detectors even closer to unity while targeting the emission wavelength of Quandela's single-photon source. With QUA's continuous feedback, SQ would be able to provide a highly specialised single-photon detector that is perfectly optimised for the emerging photonic quantum computing ecosystem. Beyond near unity efficiencies, SQ and SWA will join forces and use high precision timing to extract reliable and efficient photon number information from a single superconducting nanowire. Photon number resolving abilities are necessary for some photonic quantum computing approaches that are becoming increasingly widespread within the ecosystem. These developments will be pursued with higher-yield processing and larger-capacity detection systems in mind to allow for reduced production costs which in turn would lower the entry price of photonic quantum computers, making them more accessible for future customers. Lastly, µA would ensure that almost no photon (information) is lost between Quandela's source and SQS's detectors to push the performance limits of photonic quantum computers.

**MicroAlign (µA)** - µA was born from a PhD project performed at TU/e and part of the MEMPHIS II program funded by the Dutch Research Council (NWO) in 2019. µA was founded in 2021 as a spin-off of the Eindhoven University of Technology. Our core expertise and technology are based on the invention of a micro actuation system capable of accurately aligning multiple optical fibres in a fibre array. The focus for the coming years is to further develop our technology to improve the optical coupling performance of testing and assembly processes for photonic devices and support the packaging activities for photonic technologies like quantum computing, co-packaged optics, and sensing.

Quantum is the market with a major need for the highest optical coupling efficiency, motivating the great fit of this project to our company roadmap. This project allows µA to speed up development and achieve early penetration of the market. Furthermore, it will speed up market validation and product expansion to the different flavours of Ultra-high Accuracy fibre Arrays (UAFA's) and specifications (different types of fibres, wavelengths, etc.) based on market demand.

**Paderborn University (UPB)** - With its mission as a University for the Information Society, Paderborn University (UPB) embodies the concept of a modern profile university. In 2006, the central research facility "Centre of Optoelectronics and Photonics Paderborn" (CeOPP) was founded to further strengthen UPB's excellence in the fabrication of integrated optical elements, cryogenic optoelectronics, and solid-state quantum optics. In 2020, the newly founded Interdisciplinary Institute for Photonic Quantum Systems (PhoQS) consolidated UPB's position as an international centre for photonic quantum technologies. Prof. Dr. Klaus Jöns leads the chair for Hybrid Quantum Photonic Devices with more than 20 members at the Department of Physics of Paderborn University. The group is engaged in the development of integrated quantum photonics and electronics for quantum technologies. Klaus Jöns was the youngest coordinator of a European Quantum Technology Flagship project, co-chair of the European quantum photonic integrated circuit working group and holds an ERC starting grant on the lithium niobate integration platform. Prof. Dr. Christine Silberhorn group of more than 40 members covers novel optical technologies based on integrated quantum optics for use in quantum information processing. Her group has 15 years of experience on lithium niobate integrated photonics. Christine Silberhorn has received several awards, including the prestigious Leibniz Prize of the DFG and the election as member of the German National Academy of Science Leopoldina, as well as Fellow of the Optical Society of America.

In a joint research effort, both groups develop thin-film lithium niobate integrated circuits for feed-forward operations, combining ultra-fast electro-optical modulators on photonic integrated circuits with BiCMOS ultra-fast electronic chips. Both principal investigators have established long lasting collaborations with different partners of the consortium during several quantum technology projects, for example: Qurope (SQ), EPIQUE (CNRS, QUA, SQ, UPB), PhoQuant (SWA).

**Swabian Instruments (SWA)** - Swabian Instruments is a company for scientific measurement and control equipment based in Stuttgart, Germany. Since the founding of the company in 2016, the Time Tagger Series has become the world's leading solution for time-tagging applications, ranging from quantum optics to synchronisation analysis. Currently, SWA has 40 employees, including two subsidiaries (USA and China).

SWA's most relevant expertise is the combination of high-precision hardware and highly efficient and flexible software solutions for data processing. This approach matches the needs of the leading

research institutions worldwide, making SWA not only a supplier of lab devices but also a renowned partner in research activities. The research team of SWA is currently (March 2024) involved in eight research projects in Germany and the EU. These research activities include tackling challenges in quantum optics by exploring new technologies. For instance, a first time-to-digital ASIC prototype has been developed to go beyond the limitations of the current Time Tagger Series based on high-end FPGAs. Low-latency data processing based on FPGA has also been a focus of recent years.
For SWA's market position, superior timing resolution is a fundamental requirement. FPGA-based time-to-digital conversion has been pushed to its very limit around 1 ps. Timing resolution below the picosecond timescale requires a dedicated architecture. Developing such ASICs, while keeping the data analysis generic, will strengthen SWA's leading position in the market and enable new applications. ASIC-based Time Taggers promise to provide significantly reduced cross-talk and flicker noise, opening also new markets like high-end frequency analysis. On a system level, integrating time-to-digital converters in complex systems is one of the key challenges for further development. Together with partners like SQ, SWA has made efforts to create new read-out algorithms for SNSPDs, for example for photon number resolution [35]. Analysing the individual history of a single event is a novel approach to extracting information from large data sets.

## 5. Preliminary Work performed and networking within the Community

The project sets its basis on established interactions among most of the partners, based on previously shared research and commercial projects.
Towards reaching utility and fault-tolerance with photonic based quantum computers, the present project aims at filling the gaps on both scientific and engineering development, strengthening the links among France, Germany and the Netherlands.
When links among partners were initially not present, the proposed project completes them by bringing together the European leaders in the field of photonic quantum computing and ultimately moving closer to a fully European supply chain, of both hardware and software technologies
C2N and Quandela have been maintaining their strong links since 2017, the year of incorporation of Quandela, together innovating and closely collaborating for deploying a new device-generation of quantum-light sources into real-life applications. The fruitful research work among the two entities is ongoing, with more than 10 peer-reviewed articles published in the highest-impact factor journals to date. Similarly, Single Quantum and Swabian Instruments were created by spinning out state-of-the-art technologies of single-photon detectors and ultra-fast time-tagging electronics from Delft University and the University of Stuttgart, respectively. Similarly, Qubit Pharmaceutical utilises French scientific know-how from Sorbonne University.
All these start-ups and SMEs continue to foster science in Europe by developing high-level research and by publishing in the highest-level scientific journals within their respective fields. SQ, SWA and QUA, since their incorporation, have been at the forefront of commercialisation of quantum technologies for the academic community, with devices delivered into hundreds of research laboratories worldwide, many of which combine the three technology platforms in the same system.

Ongoing interactions in between SQ and QUA, first as a customer and later as an R&D partner have led to active development projects, privately funded or through EU projects (EPIQUE), that aim to generate added value by combining Quandela's single-photon sources with SQ's single-photon detectors with ~90% efficiency. Through TUF-ToPiQC, SQ will push the efficiency even closer to unity while increasing the detection capacity of the systems, improving yields, and reducing production costs.
Furthermore, a third institution (Friedrich Schiller University Jena) has shown first demonstrations of photon number resolving abilities using Swabian's time taggers and SQ's detectors. SQ has been exploring a few approaches to use timing resolution for resolving photon numbers. As SWA and SQjoin forces through TUF-ToPiQC we aim to offer reliable and industry-ready photon number resolving solutions. Finally, SQ and µA have engaged in preliminary discussions to explore collaboration using the precision positioning of µA to minimise further optical losses in SQ's detection systems. Through TUF-ToPiQC, we aim to deepen these collaborations.

SWA has developed Time Taggers that reach a single-shot precision of 2 ps and up to 18 channels on a single FPGA. The know-how of the company includes calibration algorithms as well as a data streaming architecture that allows on-the-fly analysis of detected events. While the commercial toolset focuses on software-based data analysis, on a research-level also platforms for FPGA-based, fast, and high-throughput analysis have been developed. Fundamental IP blocks such as time-tag-based coincidence detection, histogramming, and count rate monitoring are already included. With the current platform, feedback latencies of a few microseconds have been achieved. For latencies in the range of 10 to 100 ns, we will combine this knowledge with dedicated time-to-digital conversion chips. In recent research projects (SURQUID, SINPHOSS), we have developed the first application-specific integrated circuit (ASIC) for time-to-digital conversion TDC. This prototype that includes a coarse and a fine TDC element already provided sub-picosecond timing-resolution. We strive to continue this research to bring the TDC ASIC to a commercial level, which will open the pathway for a new generation of Time Taggers with superior cross-talk, noise, and timing resolution specifications.

Starting from 2019, QUA enlarged its scope building the first European based photonic quantum computer. Integrating cutting edge technologies from SQ and SWA among others, developing middle-ware and software platforms, an important milestone was reached in 2021 with the release of the first cloud-available reconfigurable photonic quantum computing system worldwide. Via the open-source programming framework (*Perceval*) and free access plans, the platform counts today more than 600 users, both from academic institutions and industries.
It is widely adopted to experiment and develop new algorithm tools – the first step towards reaching quantum computing utility – but also for training and education. The cloud has been in fact included in educational programs in France (University of Paris-Saclay, Centrale Supelec, Epita) and South Korea (KAIST, KIST institutes), while it's expanding in more countries.
The scientific efforts towards development of novel photonic quantum computing algorithms and tools is also supported at the European level, within the quantum flagship project "Epique". The most prominent European academic groups, start-ups and companies in the fields, reunite to develop new photonic quantum computing technologies. C2N, UPB, QU, SQ and SWA work on the project jointly.

The effort in federating the most advanced quantum technologies in Europe continues with the current proposal. The presented project and consortia, in fact, proposes to tackle specific technical challenges bringing photonic quantum technologies into a new regime of performance, setting the basis towards fault-tolerance, passing through utility. While QC companies and research groups worldwide focus on parts of the value chain, or on specific computing regimes, the project takes a different approach, unifying the efforts.
Uniting Micro-align and Paderborn University, we close the gap in the engineering of more efficient photonic integrated circuit modules, including novel features (feedforward), necessary for implementing error correction protocols. The unique expertise of Qbit, on the application perspective, permits to bridge to industrial applications and users with tailored algorithms in the field of drug design.
Looking at both near-term applications with noisy quantum computing systems, and long-term error corrected machines, Qbit and Quandela join efforts in developing a unique set of software platforms to empower end-users. While the main technologies and intellectual property will be based in Europe, the resulting achievements will have an international reach exploiting the established commercialization activities and visibility of each of the startups, through their hubs worldwide: in North America (Boston, Quebec region) and Asia (South Korea).
The unification of enabling technology developers, forefront academic research groups, algorithms developers and integrators in TUF-ToPiQC is motivated by the necessity of expanding the adoption of industry grade quantum computing solutions, to make its assimilation more effective within organisations, from industries to governments, academic institutions and ultimately society.

## 6. Consortium Structure and Work Programme of all Partners involved

### 6.1. Solution Path / Approach

The overall solution path adopted in this project is illustrated by the figure below. All partners work to the overall effort covering hardware, software and algorithms to bring the photon-based quantum computing platform to a new level of computational capability. Each hardware partner develops new features or enhanced performances to bring the platform into the utility regime and prepare the path toward fault tolerance. Both algorithm partners join their expertise to advance near-term algorithms for useful applications, in particular pursuing the development of tailored variational algorithms, and develop tools for resources and threshold estimations for error corrected architectures, providing a rigorous long-term algorithms roadmap for photonic platforms. All partners work together with strong connections between hardware, software and algorithms.

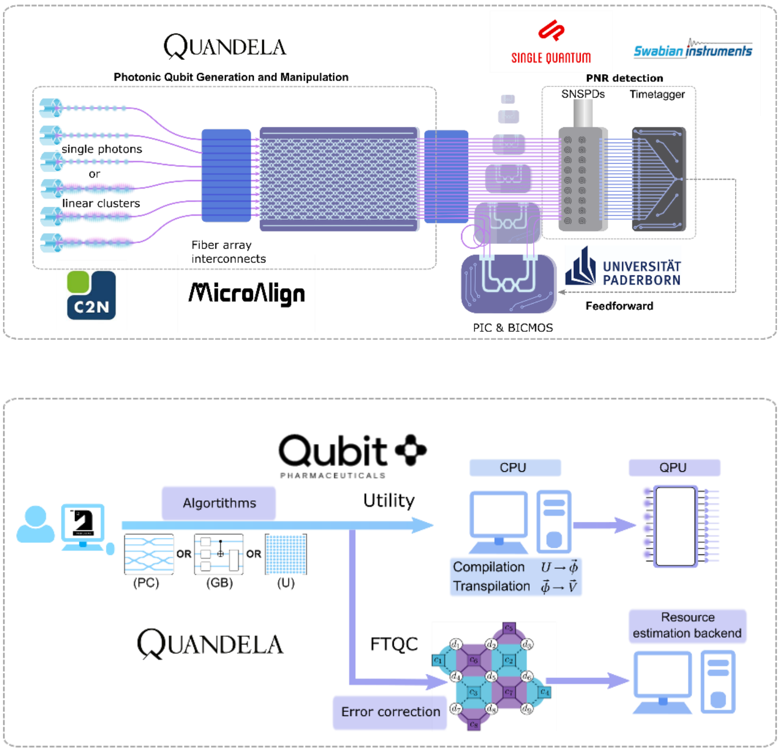
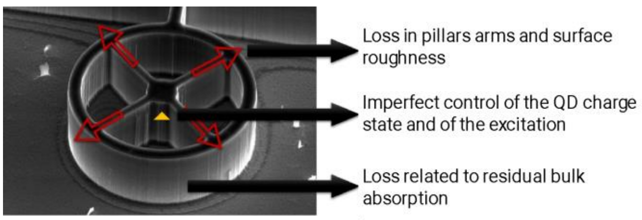



*Figure 2 – overall solution.* ***On the top****: the targeted prototype with individual contributions from each partner. The two assembled prototypes will share the same functional structure. From left to right, brightest single photons or linear clusters are generated from C2N. The generated photons are demultiplexed in space and send it a first large photonic chip through µA fibre array interconnects. At the output of the chip some modes are sent to SQ SNSPD and state are analysed through Photon Number Resolving SWA fast electronic modules with very low latency in order to control secondary fastly reconfigurable photonic chip processing the remaining output modes and sending them to detection therefore achieving a circuit with feedforward.* ***On the bottom****, the logical workflow controlling the prototype through Perceval developed by QUA. Algorithms designed by Qbit and represented as logical qubit circuits, photonic circuits or unitary transform are optimally compiled taking into account individual component imperfections to control the first photonic chip and the mapping allowing to decide on the configuration of the feedforward chip that will be set upon the detection of the main modes. The new capabilities offered by linear clusters and feedforward will be also integrated in Perceval and used for demonstration of a logical qubit and a resource estimation.*

We briefly list the main concepts behind each studies:

### Single photon sources




We take advantage of the deterministic emission of single photons by semiconductor quantum dots in micropillars [45]. We will reduce the optical losses by an ambitious factor of 2, in order to reach a first-lens brightness higher than 75%. To do so, we will track every source of loss as sketched in the inlaid figure: losses relate to the geometry of the cavity, roughness introduced in the semiconductor fabrication process, as well as charge control of the quantum dot. In parallel, charge noise will be reduced and new excitation schemes and setups will be developed to increase the source indistinguishability.

### Sources of linear cluster states

In 2023, the team of Prof. Pascale Senellart at C2N demonstrated the efficient generation of entangled photons with the spin inside the quantum dot coupled in the cavity[46]. We will develop techniques to increase the coherence time of the spin by two orders of magnitude, using new sample designs and exploiting spin echo techniques. Together with technical development permitting a greater brightness, C2N and QUA will generate streams of entangled photons. By shaping the entanglement sequence with various spin gates, we will create graph states of various structures and topology. These states are critical for the large-scale manipulation of quantum information in photonic circuits. Within this project, they will be used to demonstrate first error correction steps.

**Feedforward**
Thanks to their unique broad expertise in the design and fabrication of tailored integrated-photonic quantum devices in lithium niobate UPB will fabricate and characterise Photonic Integrated Circuits and design BiCMOS ultra-fast electronic chips using Cadence software. Fast reconfigurability will be achieved through a proper RF design targeting impedance matching between the electronic driver and photonic integrated modulators.
Interfacing ultra-fast electronic chips with on-chip lithium niobate modulators will allow us to perform feed-forward operations on cluster states in the MHz regime.
**Fibre interconnects**
µA will use their fibre control technology to fabricate near-perfect fibre arrays (12 modes and 24 modes) that will be tailored for the photonic integrated circuits involved in this project, taking into account their characteristic and imperfections. Quandela will perform loss characterization and packaging of large photonic integrated circuits and measure packaging loss. The packaged photonic integrated circuits will then be incorporated into the NISQ prototypes used in this project.

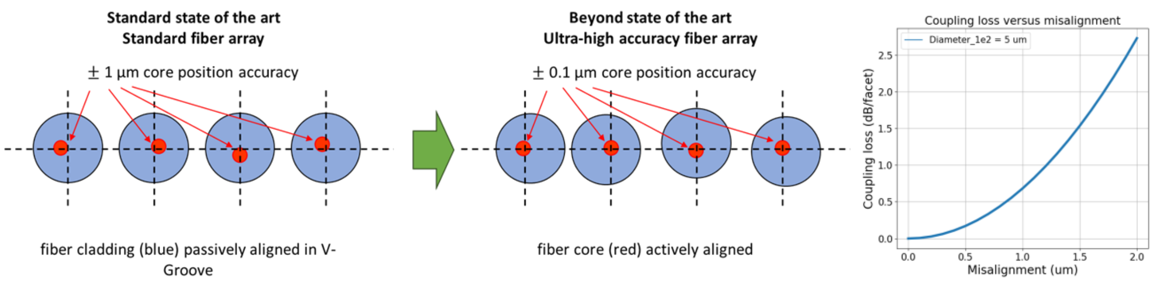



*Figure - Left: Standard fibre array core position compared to: Micro Align fibre array Right: Theoretical fibre to chip coupling loss as a function of the fibre misalignment at 925 nm*

**Detectors**
SQ aims to become the central supplier of single-photon detection systems for the emerging photonic quantum computing market. To that end, efforts have been carried out in the last few years to engage with photonic quantum computing companies, understand their current and future single-photon detection needs, and develop photon detection systems that fill those requirements. Important requirements that were identified by SQ are high efficiencies, photon number resolving abilities, and reduced costs. We have been pursuing development paths to address these requirements and will continue to do so within TUF-ToPiQC.
**Time taggers for SNSPD detection processing PNR and Feedforward**
SWA will combine its FPGA and ASIC technology expertise for high precision time tagging of single photon detectors. They will achieve photon number resolution with Quantum dots single photons, using Single Quantum efficient SNSPDs. They will also implement a prototype timetagging system with low latency output signal for feedforward implementation.
**Utility – Algorithms & Use-cases**
We will build on consortium expertise in both tailoring of algorithms to photonic NISQ platforms and variational quantum algorithms with interest for pharmaceutical applications. We will bring to bear algorithm-specific optimised qubit and gate encodings, which may exploit multi-controlled gates with efficient photonic implementations, photon-native ansätze that exploit the full expressivity of Fock spaces, and the use of photon-number resolution. We will extend work from QBIT on feedforward for VQE [47], to generalise it to arbitrarily large quantum computation. This combined with the overlap-adapt-VQE work [36], will provide an avenue for chemistry applications. We will also study the feasibility of using variational hybrid classical-quantum algorithms to simulate the Lindblad master equation and its adjoint for time-evolving Markovian open quantum systems and quantum observables [48]. This is expected to outperform brute force classical simulations, demonstrating a utility era application of quantum computers. For initial testing we will run both ideal and realistic noisy numerical tests on classical simulation backends running on GPUs through the Perceval software framework. In order to evaluate the utility point we will perform time and energy benchmarking of classical simulation runs. Finally, we will perform QPU runs on the integrated TUF-ToPiQC platform and benchmark classical and quantum performances.

**Fault-tolerance – Algorithms & Resource Estimation**

We will build a software tool for efficient threshold calculations for a variety of error-correction codes running on a variety of architectures. For this we will build on and extend the calculator developed at QUA for the numerical analyses in [49]. We will cover common error correction families including surface and LDPC codes. The architectures will cover both the FBQC and SPOQC architectures, as well as allowing for combinations of fusion and spin-optical architectures. As a second phase the tool will be built-out into a resource estimator capable of evaluating the hardware requirements in terms of numbers of modules and their performance thresholds for specific target algorithms, taking into account error-correction and architecture choices.

The best known FT algorithm for chemistry is the Quantum Phase Estimation (QPE). However, this algorithm to function requires a starting state with >50% overlap with the true state, for which there is currently no known solution. QBIT will determine whether VQE [35] will ultimately be suitable for preparing such an initial state. This also acts as an eventual bridge from the NISQ implementations to fault-tolerant applications. As a useful target for the hardware efforts, QBIT and QUA will also provide simulations, and resource estimation and length of computation for useful application in chemistry. Combining approaches and tools this will lead to a long-term algorithms roadmap with clear resource estimates for milestone applications.

### 6.2. Work Content / Work Packages

The work organisation is aligned with the three main objectives of the project: toward utility, toward fault tolerance and demonstrations developed within Work Packages 1 to 3. A fourth Work Package ensures coordination and management of the actions.

We detail below the work planned in each Work Package and then explain the global organisation.

| **Work package No.** | WP 1 | **WP leader** | **SQ** |
|---|---|---|---|
| **Objectives: Develop hardware and algorithm to reach quantum utility in the NISQ regime.** In WP1, we push all the components at the core of the NISQ photon quantum computing platform to new limits to increase the number of manipulated photons, the size of the computational space and increase the process fidelities. We will develop algorithms in the NISQ realm, with numerical simulation to demonstrate utility for specific applications. | | | |
| **Description of work:**<br>Task 1.1. **Bright single photon sources (C2N, QUA)** – QUA and C2N joint efforts to develop single photon sources with higher performances (brightness, purity, indistinguishability). Studies on cavity design, etching processes, low noise electronics and high purity materials. Starting from a first lens (fibered) brightness of 50% (25%), we target 70% and 50% respectively with indistinguishability above 99%.<br>Task 1.2. **Near-unity-efficiency single photon detection system with doubled channel capacity (SQ)** – SQ will develop single photon detectors based on superconducting nanowires with >90% efficiency at 925 nm and design a full detection system (cryogenics, electronics, and optics) with double channel capacity of SQ's current commercial product.<br>Task 1.3. **High efficiency optical coupling for the chip packaging (µA, QUA) –** µA will deliver fibre arrays (of 12 and 24 fibres) with 0.1µm accuracy that will be designed for specific photonic integrated circuits. Quandela will perform characterization and packaging of several chips and estimate the maximum loss from packaging inaccuracy and wafer bow. We target less than 0.1dB packaging inaccuracy loss for standard 780HP fibre at 925 nm over more than 10 input modes.<br>Task 1.4. **Modelling and Compilation (QUA, C2N, µA, SQ, SW)** – With input from C2N, µA, SQ and SW - QUA will develop a unique framework allowing to model noise and hardware imperfections all throughout the photonic lifecycle, and tools for reducing the impact of these imperfections through advanced compilation techniques. | | | |

| | |
|---|---|
| Task 1.5. **Utility with NISQ algorithms (QUA and QBIT)** – We develop variational algorithms tailored to photonic platforms with pharmaceutical use-cases, first running classical numerical simulations, then performing time/energy analyses to identify utility point, and ultimately QPU demonstrations | |
| **Half-time milestones:**<br>**HM1.1**: 35% fibered brightness single photon source.<br>**HM1.2**: Design and demonstrate a high performance single photon detection system with doubled channel capacity.<br>**HM1.3**: Ultra-high Accuracy fibre Array - 24 channel version, 250µm pitch, for room temperature<br>**HM1.4**: Noise modelling software integrated in Perceval including contributions from different hardware modules<br>**HM1.5**: Numerical simulations | |

| **Work package No.** | WP 2 | **WP leader** | **UPB** |
|---|---|---|---|
| **Objectives: Develop building blocks for fault tolerant quantum computing.** In WP2, we develop important technological building blocks required to progress toward fault tolerant computing. We will also develop softwares for estimating the relevant hardware threshold depending on the computing architecture as well as resource estimation. | | | |
| Task 2.1. **Bright sources of cluster states (C2N, QUA)** – C2N and QUA co-develop sources of entangled photons based on the entanglement of the spin degrees of freedom of a charge in the quantum dot and the polarisation or time degree of freedom of the photons. C2N will push the spin coherence time with various optical techniques to mitigate the decoherence induced by the nuclei. QUA will optimise the doping structure of the source as well as the excitation scheme. QUA algorithm teams will provide tools for characterisation of cluster states of continuously large size.<br><br>Task 2.2. **Feedforward (UPB, SWA)** – UPB will design, simulate and nanofabricate a lithium niobate chip with modulators to implement feed-forward operations based on the output signal of the time tagging devices of SWA and the detectors from Task 1.2 and Task 2.3.<br><br>SWA will develop a hardware platform for analysing photon events and generating control signals for feedforward. The analysis will be based on time-tagging where we compare two approaches: Firstly, in a single FPGA, time-to-digital conversion and data processing are combined. This approach provides higher development flexibility at the cost of inter-channel cross-talk and lower timing resolution. Secondly, we will develop an application-specific integrated circuit (ASIC) for time-to-digital conversion. An already existing prototype will be optimised for low latency. This approach promises better timing-resolution and reduced cross-talk at the cost of long development cycles.<br><br>SWA and UPB will together design the electronics chip necessary for feed-forward and use Cadence software to simulate and optimise its performance. UPB will send the chip design to a BiCMOS foundry. UPB will characterise the electronics as well as the photonic lithium niobate chips.<br><br>Task 2.3. **Photon number resolution (SQ, SWA)** – SQ and SWA will study and co-develop single photon detection and timetagging analysis compatible with quantum dot single photons characteristics.<br><br>SQ will develop, validate and benchmark photon number resolving single photon detectors based on superconducting nanowires. | | | |

| Work package No. | WP 2 | WP leader | UPB |
|---|---|---|---|

SWA will develop FPGA IP blocks for analysing SNSPD events, especially with respect to photon-number resolution (PNR). These processing blocks will be executed within the time-tagging and control hardware unit. First software-based observations on detectors provided by the partner SQ have shown promising results [35]. Besides PNR, error identification and counter-measures are a second goal of the analysis of IP blocks.

Task 2.4. **Modelling & simulation (QUA, SWA)** – to support development of feedforward system, QUA will extend simulation framework Perceval to include possibility to introduce new features Cluster State input state, Feedforward, PNR and corresponding Noise Models as defined in Task 1.4. These models will in particular allow us to estimate necessary resources associated with specific levels of noise.

Task 2.5. **Resource estimation (QUA, QBIT)** – Produce software capable of performing threshold calculations for a wide range of error-correcting codes and architectures covering both FBQC and SPOQC. Extend the threshold software to evaluate resource requirements for target algorithms and performances. Perform resource estimation for quantum phase estimation. Roadmap with specification of which relevant molecules can be targeted with which resources.

**Half-time milestones:**
**HM2.1**: Source of 6 entangled photons obtained from spin-photon entanglement.
**HM2.2**: UPB half time milestone: lithium niobate chip with 4 inputs and 4 output spatial modes which can map any input mode onto any output mode using feed forward operation.

SWA: Time-tagging and control output hardware with processing unit and platform-related latency of below 100 ns.

**HM2.3**: SWA: Photon-number resolution module as IP block for the processing unit adjusted to the specific SNSPDs with photon-number distinction (1 photon vs. >1 photons) fidelity of > 85%.
**HM2.4**: Upgrade of Perceval with inclusion of Cluster State modelling, PNR and Feedforward
**HM2.5**: Numerical simulations to evidence whether VQE can be used for producing the initial state for quantum phase estimation of a chemical problem.

| Work package No. | WP 3 | WP leader | QUA |
|---|---|---|---|

**Objectives: Prototype assembly and operation**

Task 3.1. **NISQ Prototype integration (QUA, C2N, SQ, SWA, µA, UPB) –** NISQ - 24 mode chip and 10 photons - Assembly of a reconfigurable quantum processing unit manipulating 10-qubits in the form of dual-rail encoded single photons. The platform will include all the hardware modules and optimised compilation stack developed in WP1, as well as a software platform for user access and programming.

Task 3.2. **NISQ demonstrations (QBIT, QUA)** A demonstration of the feedforward VQE algorithm.

Task 3.3. **FT POC** (**QUA, C2N, SQ, SWA, µA, UPB)** – integration of and demonstration of feedforward with linear cluster states based on a feedback loop between Tasks 2.1-2.3. we will optimise the individual hardware components and make compatibility verification. The individual components will be shipped to C2N to perform proof of concept experiments.

Task 3.4. **Logical qubit demonstration (QUA) –** demo of a Shor-(3,3) logical qubit

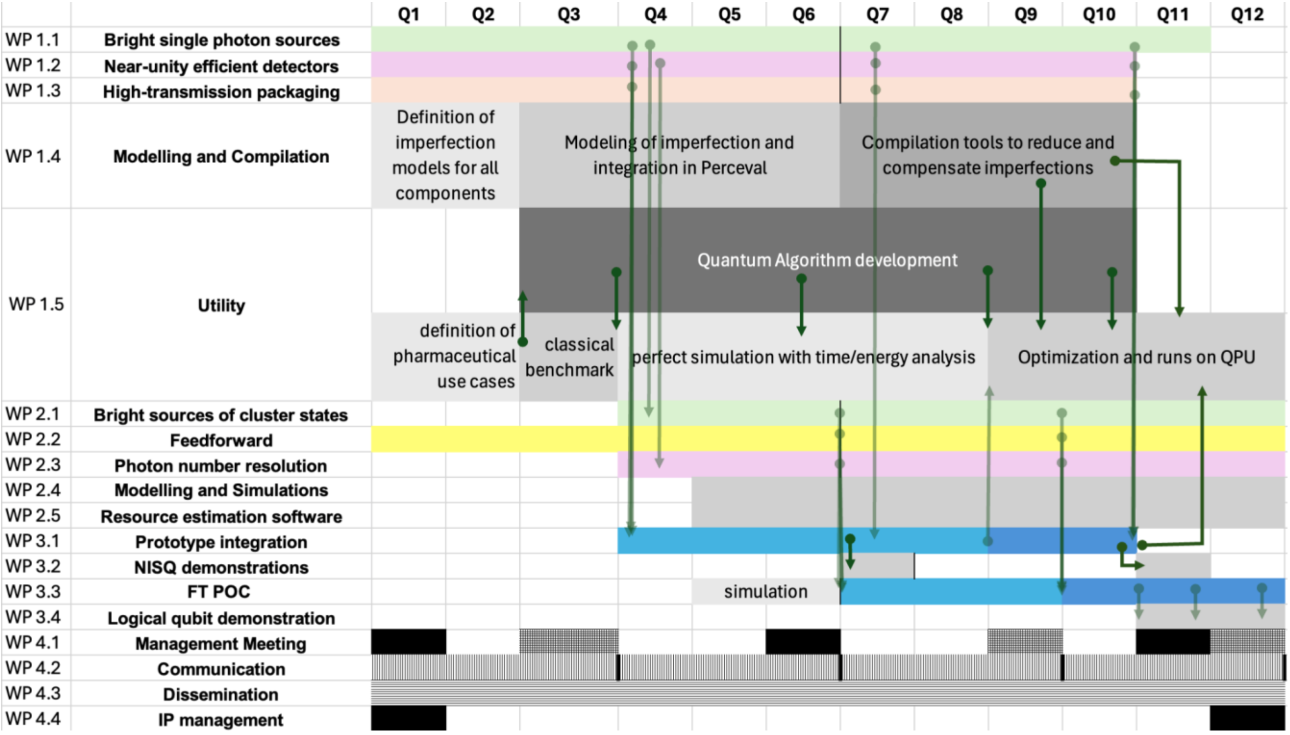
**Half-time milestones:**

| |
|---|
| **HM3.1**: Report on the measured and expected performances of the prototype platform with the included hardware modules and compilation stack developed in WP1.<br>**HM3.2:** Available at Q7, first demonstration on hardware<br>**HM3.3:** Demonstration of feedforward VQE with pseudo feedforward (postselected) and hybrid use of simulator and QPU<br>**HM3.4:** *No half milestone demonstration - the demonstration of WP3.4 will be done at the end of the project* |

| **Work package No.** | WP 4 | **WP leader** | **QUA** |
|---|---|---|---|
| **Objectives: Project management and coordination:** Coordinate and monitor both research and administrative work; Manage the scientific risks and find solutions; Report to the various funding institutions. Support and coordinate dissemination and to prepare the project exploitation. | | | |
| Task 4.1. **Coordination**: An intranet site will be set up to facilitate consortium management. Tele-conference meetings, within each WP, will be organised every 3 months. In-person meetings will take place every six months to discuss the project progress. Scientific progress will be monitored and project reports assembled. Risk assessment and management will be conducted all along the project.(QUA)<br>Task 4.2. **Communication**: Development of project logo, factsheet, leaflets/brochures and project website. Posting of results on the project website and other appropriate sites (e.g., Wikipedia or similar), including videos and non-technical descriptions of scientific results. Other public outreach actions (QUA, all partners involved)<br>Task 4.3. **Dissemination:** Publication in high-ranking scientific journals. Participation and presentations in scientific international and national conferences, lecturing in scientific summer schools. (QUA, all partners involved)<br>Task 4.4. **IP management**: Exploitation of results and IPR protection (QUA, all partners involved) Evaluation of the project results for IPR protection. | | | |

## 3. Time Schedule

The overall schedule is given by the following table:




In this table, each work package activity is represented at the quarter level. Dot and Arrows shows linkages between tasks. Colours (but blue) represent hardware/electronic development, grey represent software development, blue represents integration, and black & white patterns represent management tasks.

The work organisation is pretty straightforward and reflecting the tasks and each partner main role in the project:

- Hardware developers (C2N, QUA, SQ, SWA, UPB, µA) are starting their tasks at the kickoff of the project and incrementally toward the optimization goals. WP2.1 and WP2.3 start at Q4 since their development will be built upon work on WP1.1 and WP1.2. Tasks WP1.1 (resp WP1.2) will benefit hardware development in WP2 with tasks WP2.1 (resp 2.3).
- Hardware integrators (QUA, C2N) will receive components/modules progressively for system integration and will provide platform for software demonstration
- Software development - algorithm and modelling will lead/optimise to demonstration runs
- Overall management meeting in black show in-person meetings (kick-off, mid project, preparation of closure) - and in grid pattern remote meeting.
- Reporting is done quarterly
- Communication and Dissemination are continuous tasks all along the project
- IP management defines rules with consortium agreement at the beginning and happens at the end to sort out new development and created IP (in addition to potential work being done by partners for patenting)

## 4. Half-Time Milestone and Risk Mitigations

We list all half-time milestones in the WP description above. They are all verifiable – supported by measurements on the hardware side, description of algorithm architectures or softwares on the theory side and operation of prototypes on the integration side. Note that WP3.3 has no half-milestones since it is an end-of-project final demonstration of logical qubit and WP3.2 half-milestones is at the end of Q7 and not Q6 since it is at the end of the chain of integration.

We list below the identified risks essentially from hardware production and their planned mitigation strategies:

- WP1.1, WP2.1: On the semiconductor production (QUA, C2N) - the production is contingent on availability of machines in clean-room. Mitigation: QUA and C2N have access to 2 clean-room set-up that allow for redundancy.
- WP1.2: Cryostat cannot contain the doubled number of detectors, fibres, and electronics due to spatial, mechanical or thermal budget considerations. Mitigation: we will be exploring a larger colhead with increased cooling power.
- WP1.5: Numerical simulations are performed prior to QPU runs to test algorithms ahead of the technological readiness. As risk mitigation a combination of ideal simulations, realistic noisy simulations, and approximate simulations allow algorithm development to be verified for readiness and development to be best oriented prior to running on the quantum hardware.
- WP2.2: Reducing resolution to below 100 ns range is an electronic challenge. Mitigation: We follow two approaches for signal detection, in a single FPGA and an ASIC-based solution. We will pick the superior solution with respect to the requirements of the PNR data analysis.
- WP2.3: Technology can't meet expected resolution because of the nature of the Quantum photons. Mitigation: We will collect comprehensive data sets on the specific SNSDPs with a software-based approach that has proven its feasibility. For the HDL code, we will investigate two alternative approaches for latency optimization: Analysis of rising and falling edges of a single event, and tracking for instantaneous count-rates for time-shift compensation. Additionally, if there is no positive outcome (if the QD photons prove too slow for the temporal approach), we will explore multi-element PNR or hybrid approaches.
- WP3.1: The realisation of the NISQ prototype is dependent on the production of photonic chips by a supplier. Mitigation: QUA is doing the designs of these chips and will be sub-contraction to two partners.

We also acknowledge risks linked to the whole supply chain in connection with geopolitical situations and scarcity of some of the core resources (e.g. rare Helium isotope, Titanium, InGa wafers, etc…). As a risk mitigation: this project, together with additional strong partnerships[1] as described in Section 8, is contributing to the development of a strong network of European players toward full autonomy on each component of the photonic quantum computing industry.

## 7. Financial Planning

| **Partners** | **Project Coordinator** | **Partner 2** | **Partner 3** | **Partner 4** | **Partner 5** | **Partner 6** | **Partner 7** |
|---|---|---|---|---|---|---|---|
| Name (group leader) | Shane Mansfield | Pascale Senellart | Alberto Peruzzo | Sander Dorenbos | Simone Cardarelli | K. Jöns & C. Silberhorn | Jan Bruin |
| Institution | Quandela | C2N/CNRS | Qubit Pharmaceuticals | Single Quantum | MicroAlign BV | Paderborn University | Swabian Instruments GmbH |
| Country | France | France | France | Netherlands | Netherlands | Germany | Germany |
| Funding Organisation | BPI | BPI | BPI | Quantum Delta | Quantum Delta | BMBF | BMBF |
| **Project Costs (Euro)** | | | | | | | |
| Personnel | 1,380,000 € | 130,000 € | 825,000 € | 352,000 € | 342,000 € | 536,385.27 € | 380,000 € |
| Consumables | 400,000 € | 190,000 € | | 355,000 € | 20,000 € | 95,000 € | 90,000 € |
| Investments | 250,000 € | 60,000 € | | | 70,000 € | 0 € | 0 € |
| business trips | 20,000 € | 10,000 € | 10,000 € | 16,000 € | 7,500 € | 12,000 € | 6,000 € |
| Overheads | 276,000 € | 52,000 € | 165,000 € | 180,750 € | 108,000 € | 128,677.05 € | 180,000 € |
| **Partner Total Costs** | 2,326,000 € | 442,000 € | 1,000,000 € | 903,750 € | 547,500 € | 772,062.32 € | 656,000 € |
| **Percentage** | 60% | 100% | 50% | 66% | 66% | 100% | 80% |
| **Requested** | 1,395,600 € | 442,000 € | 500,000 € | 602,533 € | 365,000 € | 772,062.32€ | 524,800 € |

[1] For instance, with German company attocube GmbH providing a unique compact cryogenics dry cryostat solution.

The total cost of the project is estimated to be 6,647,312.32 € and the requested budget is 4,601,962.32€ taking into account the percentage following the size of the partner and whether academic or industrial as well as the overhead percentage given by each partner following the indications from the national funding organisations.

## 8. Exploitation of Results, Access for Users

Project TUF-TOPIQC aims to develop innovative solutions to develop photonic quantum computing on a short term and longer perspective.

For the short term perspective, immediately upon the completion of the project, the partners will make the results available in various ways to benefit potential users and target markets:

- All industrial partners will have new competitive technology to provide to their users: new generation of single photon sources, improved single photon detectors, fast electronic solution for feedforward, more robust technology for fibre array micro-alignment, key-turn useful quantum algorithms running on current generation of photonic quantum computers.
- Specially optimised for integration in Quantum Computing, the development done in this projects will also directly benefit other types of application
- Finally, a prototype of quantum computer integrating all of these components will be show-cased and be used to push the limit of photonic quantum computers ready to be distributed.

At the same time, for longer term perspective, work on next generation of photonic quantum computers led by research institute and completed by breakthrough in hardware production will push the boundaries of applications for photonic quantum computing and will pave the way to fault tolerant hardware:

- On one hand, each of these technological modules, assembled in a prototype, will be used for a shared research publication, and be made available to the research community for further exploration.
- On the other hand, the technological advances of this prototype will come with open software enabling the quantum computing community to start exploring new generations of quantum algorithms with these new capabilities and with first precise idea about resource estimation when entering in this era.

It is important to note that this strategic European collaboration, from 3 leading countries in the field of quantum computing will also be contributing to European digital sovereignty and consolidation of the supply chain. Throughout the project lifecycle, collaborations with complementary key European industry players such as QC design and attocube GMBH in Germany, PhiX in the Netherlands, and Ligentec SA and Spark Laser in France will be established to leverage their expertise, resources, and market insights. These collaborations will facilitate the reinforcement of the constitution of full and reliable supply chain integration of project solutions into existing products or services.

Last, from the end-user perspective, this consortium will give access to cutting-edge technology with potential immediate benefit for some specific industry contributing to the necessary quantum transformation of the full industry.