QuiX QUANTUM

CARINA

UNIVERSAL PHOTONIC QUANTUM COMPUTING

Built for Customer Deployment

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Executive Summary

Quantum computing is moving from scientific promise toward engineered systems that can be deployed, integrated, and used in real-world computing environments. Within this transition, QuiX Quantum photonic quantum computing offers a compelling path: it operates naturally with telecom-compatible technologies, supports modular architectures, and has the potential to scale efficiently while aligning with the energy and infrastructure requirements of modern data centres.

Carina marks a major milestone in this evolution. Developed by QuiX Quantum, Carina is positioned as the world's first universal photonic quantum computer designed for customer deployment. It brings together the critical building blocks required for universal, measurement-based photonic quantum computing in a system architecture intended to move beyond laboratory demonstration and into an operational customer environment.

The significance of Carina lies in the combination of two capabilities that have historically been pursued separately. Some quantum computing approaches have focused on near-term commercial deployment but rely on architectures that are not designed to scale toward universal, fault-tolerant computation. Others pursue universality and long-term scalability but remain dependent on specialized laboratory conditions that limit practical deployment. QuiX has chosen the more demanding path: building room-temperature, customer-installable photonic quantum systems while solving the engineering challenges required for universality.

This white paper describes how Carina advances that path. The system integrates a set of core technologies developed by QuiX, including on-chip photon generation, high-speed switching and multiplexing, cluster-state generation, real-time feed-forward control, and scalable photonic integrated circuit control through the Photonic Assembly Control Unit. Together, these technologies enable the execution of a universal gate set and establish the foundations for measurement-based quantum computing using photonic qubits.

Carina also represents an important step toward fault-tolerant quantum computing. Universality is a prerequisite for generating the resource states, logical operations, and adaptive measurement patterns required by fault-tolerant measurement-based architectures. QuiX's progress in photon indistinguishability with photon distillation, feed-forward control, and data-centre-compatible photonic control directly addresses several of the key bottlenecks on the route to scalable quantum systems.

Equally important, Carina reflects QuiX Quantum's long-standing focus on delivering real photonic hardware to customers. Building on its track record in quantum photonic processors, QuiX is extending its leadership from special-purpose photonic systems to a universal architecture designed for deployment. This milestone does not change QuiX's identity as a hardware company; it raises the bar for what deployable quantum hardware can be.

By bringing universality, photonics, and customer deployment together in one system, Carina establishes a new benchmark for the quantum computing industry. It demonstrates that the path toward useful, fault-tolerant quantum computing is not only a scientific challenge, but an engineering challenge: one that requires scalable components, robust system integration, and architectures that can leave the lab. Carina is QuiX Quantum's decisive step toward that future.

Table of Contents

Executive summary 2
Towards Universal Fault-Tolerant Measurement-Based Quantum Computing 4
Carina - The World's First Universal Photonic Quantum Computer 6
System Architecture 7
Components Level 8
Photon Generator 8
Multiplexer 9
State Generator 10
Feed-forward Control Unit (FFCU) 11
Photonic Assembly Control Unit (PACU) 12
Outlook 13
Conclusion 13
References 14
Appendix A, B 15

Towards Universal Fault-Tolerant Measurement-Based Quantum Computing

Quantum computing promises computational capabilities far beyond what classical machines can achieve for certain classes of problems. The path to realising that promise at utility scale — meaning systems large and reliable enough to tackle industrially relevant problems — depends critically on both the choice of physical platform and the computational model used to operate it. For photonic quantum computing, measurement-based quantum computing (MBQC) is not merely one option among many; it is the most natural and technically compelling route to scale.

In MBQC, computation does not proceed through a sequential application of quantum gates to a register of qubits, as in the circuit model. Instead, the process begins by preparing a large, highly entangled resource state — typically a cluster state, in which qubits are entangled according to a graph structure [1] — and then driving the entire computation through a sequence of adaptive single-qubit measurements [2]. Each measurement outcome classically informs the basis choice for subsequent measurements, a mechanism known as feed-forward [1]. The computation is therefore consumed through measurement rather than constructed through gate sequences, and the entanglement of the resource state serves as the fuel.

This model is particularly well suited to photonics for several interconnected reasons. Photons are naturally mobile and interact weakly with their environment, making them highly resistant to decoherence — one of the central enemies of quantum information [3]. However, that same weak interaction makes deterministic two-qubit gates between photons extremely difficult to implement directly. MBQC sidesteps this problem elegantly: the entanglement required for computation is built into the resource state through probabilistic entangling operations, which can be attempted repeatedly and heralded [4], while the computational step itself — measurement — is something photonic systems perform natively and with very high efficiency [5]. Furthermore, photons travel at the speed of light, which means the classical feed-forward operations required by MBQC can in principle be performed within the coherence time of the system, a constraint that is naturally manageable in integrated photonic architectures [3]. The combination of intrinsic decoherence resistance, room-temperature operation, and measurement-native computation makes MBQC on photonics a uniquely credible path toward utility-scale quantum computing.

Reaching utility scale, however, requires more than the right computational model. It requires that the underlying hardware be capable of implementing any desired quantum operation — a property known as universality. A quantum architecture is universal if it can realise, to arbitrary precision, any unitary transformation on its qubits using the operations available to it [6]. In practice, this means the hardware must support a gate set that is computationally complete: typically, an entangling two-qubit gate such as a controlled-Z or controlled-phase operation, combined with arbitrary single-qubit rotations. Together, these operations can approximate any quantum circuit to any desired accuracy, a result guaranteed by the Solovay-Kitaev theorem [7].

A non-universal photonic processor — one restricted to, say, a limited set of linear optical transformations or a subset of two-qubit gates — can demonstrate quantum phenomena and even quantum advantage on specific tasks such as boson sampling [8], but it cannot be reprogrammed to address an arbitrary computational problem. It is, in a precise sense, a special-purpose device rather than a general-purpose quantum computer.

Universality is therefore not a luxury but a prerequisite for computationally complete fault-tolerant MBQC. It ensures that the hardware can synthesize arbitrary resource states, support the logical operations needed for encoded computation beyond the Clifford group [9], and adapt measurement bases in real time without running into expressibility limits. In short, universality is what transforms a fault-tolerant architecture into one capable of delivering the full promise of quantum computation.

Photonic quantum computing has yet to demonstrate universality in an operating system for customer deployment. QuiX is set to achieve this milestone with Carina - the world's first universal quantum computer designed to implement a universal gate set enabling any quantum operation.


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Introducing deployable quantum computing at scale: designed for today's data centers

Carina - The World's First Universal Photonic Quantum Computer

Carina [a] is set to demonstrate universality by overcoming long-standing challenges in quantum computing such as feed-forward electronics and on-chip single-photon sources at room temperature. It is a pivotal step towards fault-tolerant universal quantum computing, strengthening Europe's leadership in the quantum computing landscape.

The capabilities of Carina are designed to range from being able to execute single- and two-qubit operations [b] and demonstrate a universal gate set, to utilizing technologies that are required for universal quantum computing at a larger scale. These technologies that QuiX is developing are, for example, integrated photon generators that operate at room temperature, high-speed electro-optical switches, integrated spatial/temporal demultiplexer, cluster state generation and feedforward mechanisms.

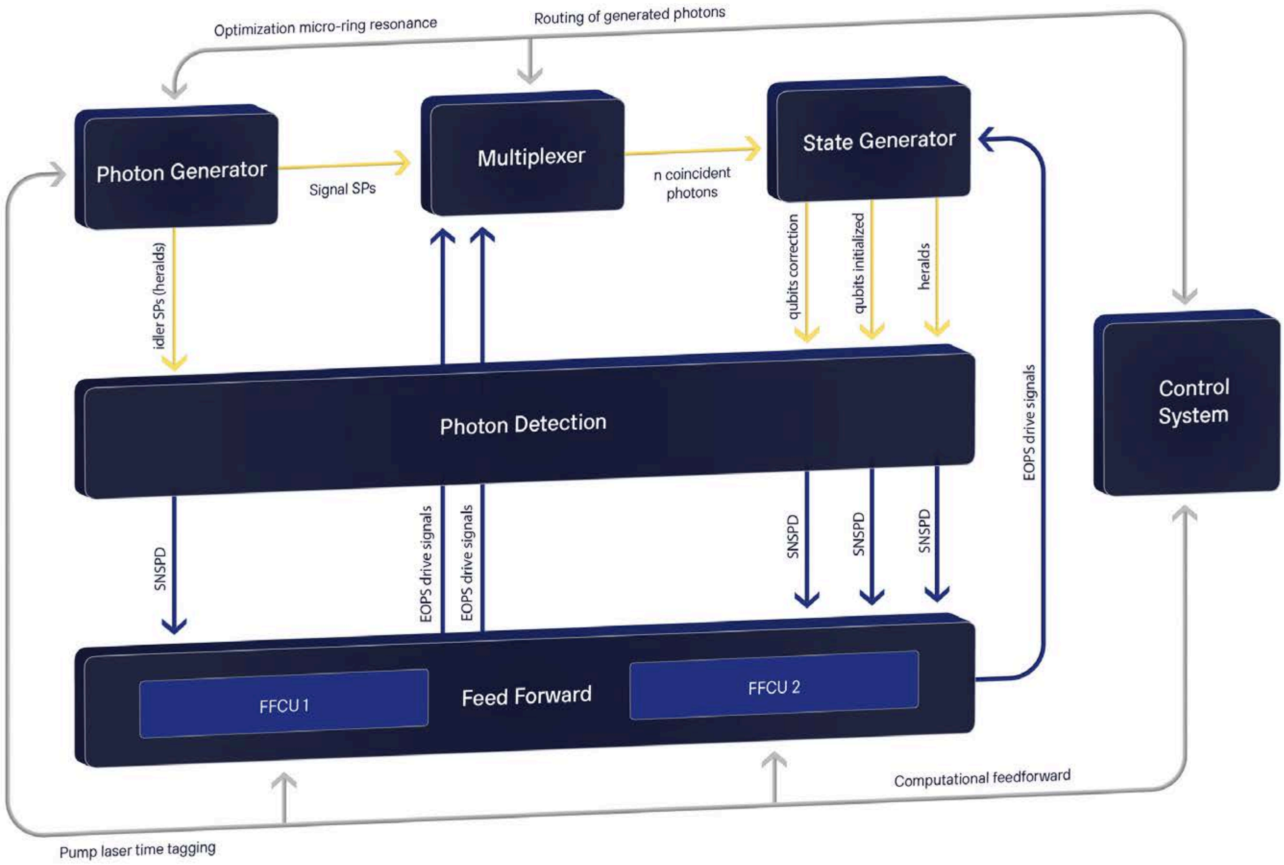
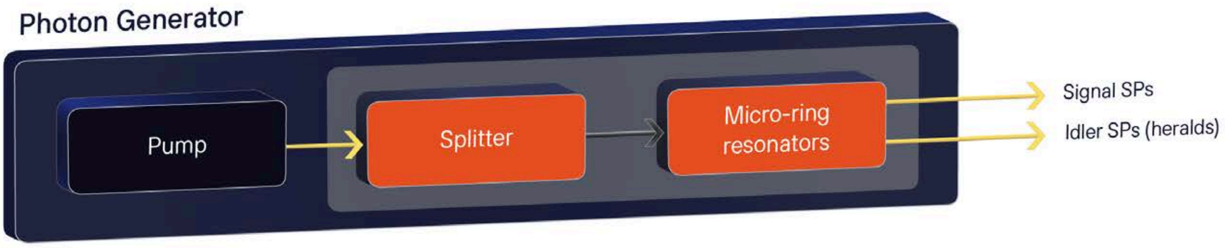


Figure 1 Legend: Yellow arrow = optical fiber, blue arrow = coaxial cables, grey arrow = ethernet cables

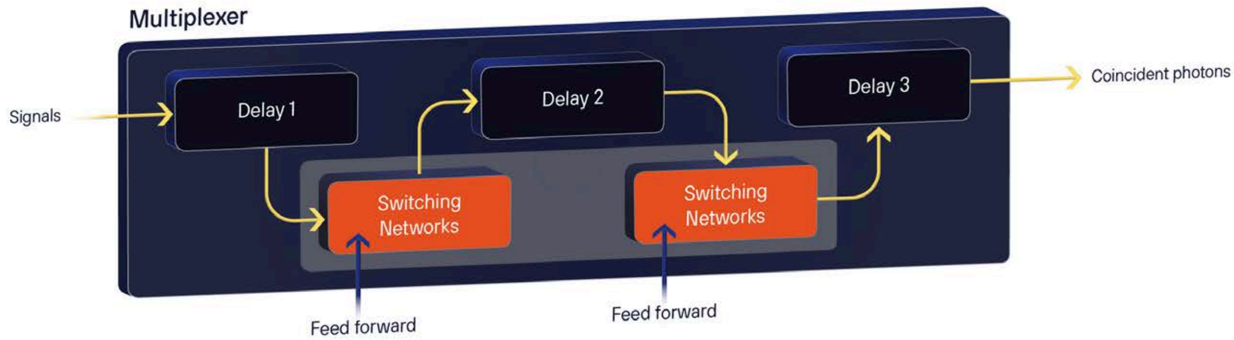
[a] Carina is developed as part of the UPQC project of the DLR Quantum Computing Initiative (DLR QCI), funded by the German Federal Minister of Research, Technology and Space.
[b] Carina is designed to initially operate with computation, i.e., measurements, at specific time steps that are not always sequential. By lowering the overall losses of the system the probability of generating k-coincident photons increases (exponentially with k) and error correction overhead gets lower: as a result, a larger cluster state can be generated and used for sequential measurements.

System Architecture

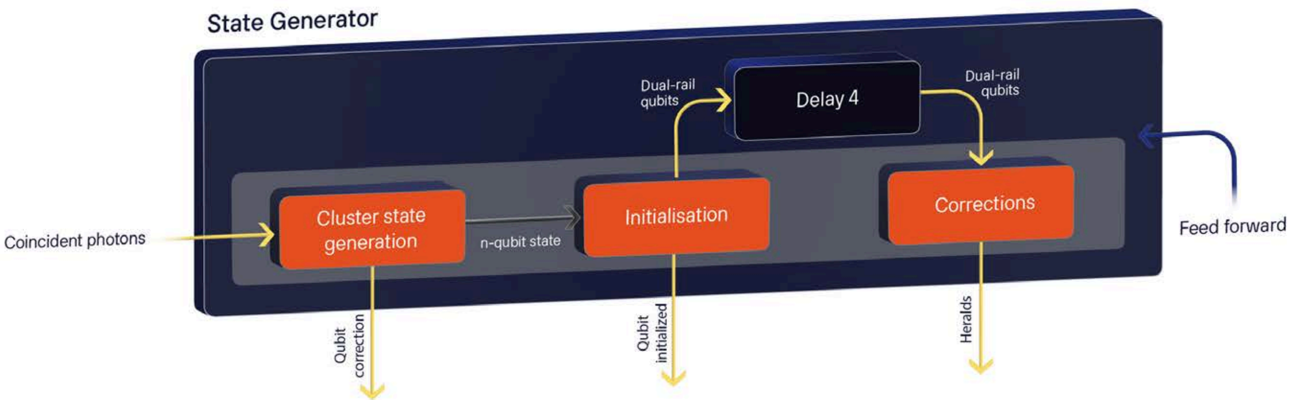
First, the photon generator subsystem generates k single photons by pumping k on-chip micro-ring resonators with a pulsed laser pump. Each micro-ring generates a signal and idler photon pair probabilistically, and by detecting the idler of each pair one can herald on the creation of the signal single photon.



Second, the k signal single photons enter the multiplexer subsystem that delivers m synchronous single photons[1]. The multiplexer consists of an on-chip fast switching network combined with off-chip delay lines (fiber coils) and its function (in combination with the feed forward feature) is to select m out of the k micro-rings that have generated single photons at the same time and route them to the m output channels synchronously.



Third, the m coincident photons from the multiplexer enter the state generator subsystem that entangles such photons on-chip and supply a n-qubit cluster state (n-GHZ state). In this subsystem the cluster state is generated, the preparation layer initialized (i.e., set to the alpha angles – see Appendix in [10]) and the fast MZI used for determining what correction[2] to apply



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[c] The reduction from k to m single photons is due to the probabilistic nature of the micro-ring sources that don't all generate a photon pair at the same time every time they are pumped with laser light.
[d] The measurements we take are probabilistic, and in order to ensure deterministic implementation of a given gate by measurement we need to apply a classical correction on the output, depending on the measurement result.

classically to the measurement results. **Carina will provide the first demonstration ever of an on-chip cluster state generator, unlocking a fundamental functionality for practical implementation of measurement-based QC.**

Fourth, the photon detection subsystem (Fig. 1) is where measurements are performed to execute a user-defined operation. In this part of the architecture are included the photon detectors for heralding both the generated signal photons (from the photon generator) and the cluster state, in addition to the detectors measuring the result of the correction eventually implemented.

Last, the control subsystem has the primary scope of allowing for a universal gate set by featuring fast feed-forward capabilities that not only control the photon generator but most importantly the state generator.

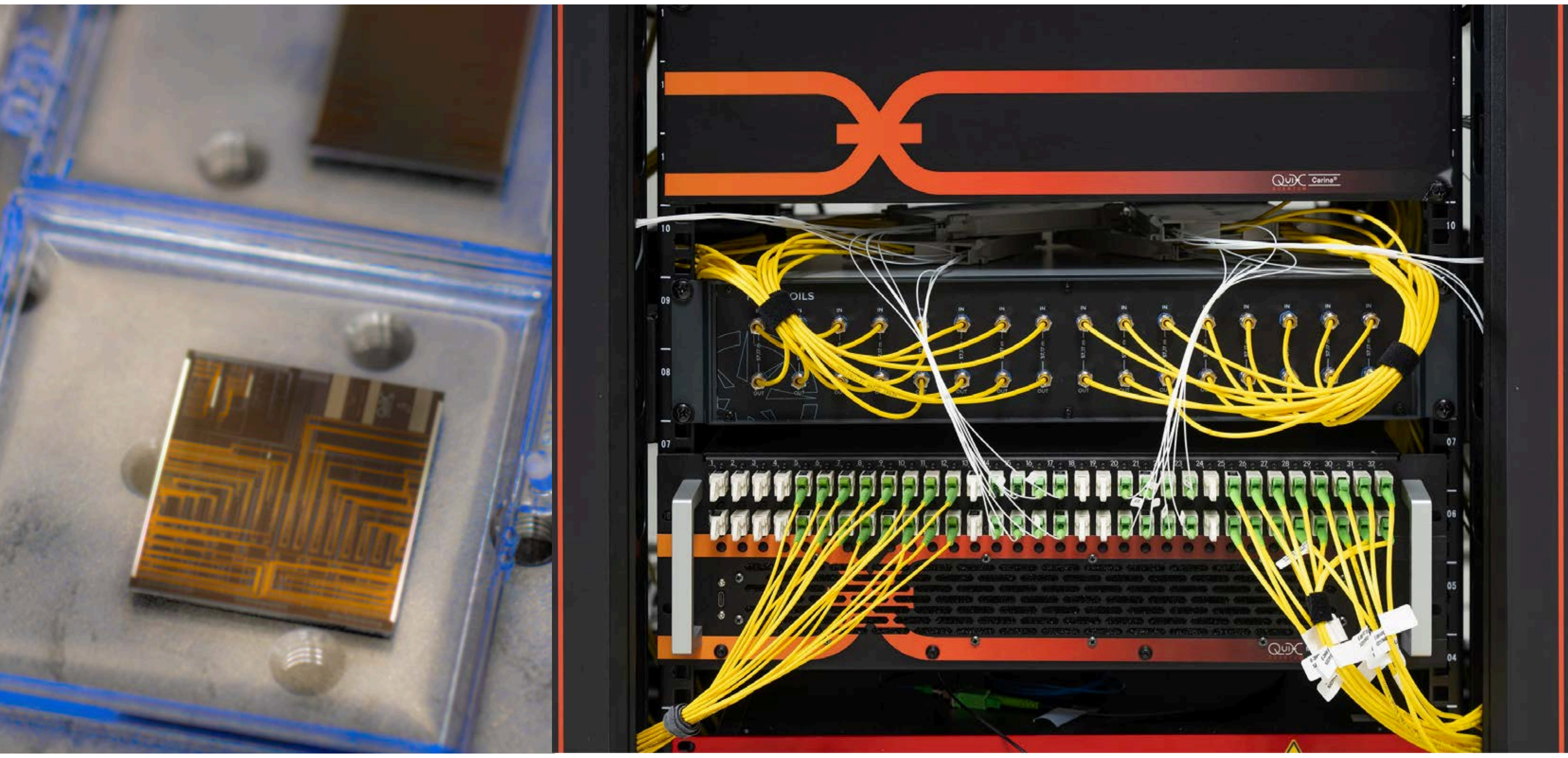
Building Carina involves the development of five major technologies: the photon-generation photonic integrated circuit (PIC), the multiplexer PIC, the state generator PIC, the Photonic Assembly Control Unit (PACU) that can control any PIC with both slow (thermo-optic) and fast (electro-optic) modulators and the Feedforward Control Unit (FFCU) to drive PICs with fast modulators. All these need to be integrated with third-party equipment such as pump laser, pulse pattern generator, photon detectors [e] (with cryostats), and control computer. In total Carina consists of ~88U rack-mounted pieces of equipment with max power consumption ~9 kW.

Components Level

Photon Generator

QuiX Quantum designs and implements chip-integrated single-photon generation components based on the spontaneous four-wave mixing (SFWM) [f] phenomenon in optically- pumped ring resonators. This technology is based on mature silicon photonic materials that are compatible with standard wafer scale CMOS foundry processes. Therefore, offering an easy route to mass production of single photon generation chips for scalable photonic computing [11].

Our sources offer several advantages compared to other photonic-based sources such as spontaneous parametric down conversion (SPDC) and quantum dots. For example, unlike quantum-dot (QD) emitters [12, 13], SFWM sources can be engineered to emit indistinguishable photons and be densely integrated without cryogenics. Furthermore, SFWM sources are monolithically integrated in photonic circuits, which is still significantly more challenging for SPDC materials. Additionally, SFWM in micro-ring resonators can exploit resonant enhancement to achieve high brightness and narrow linewidths with a small footprint.



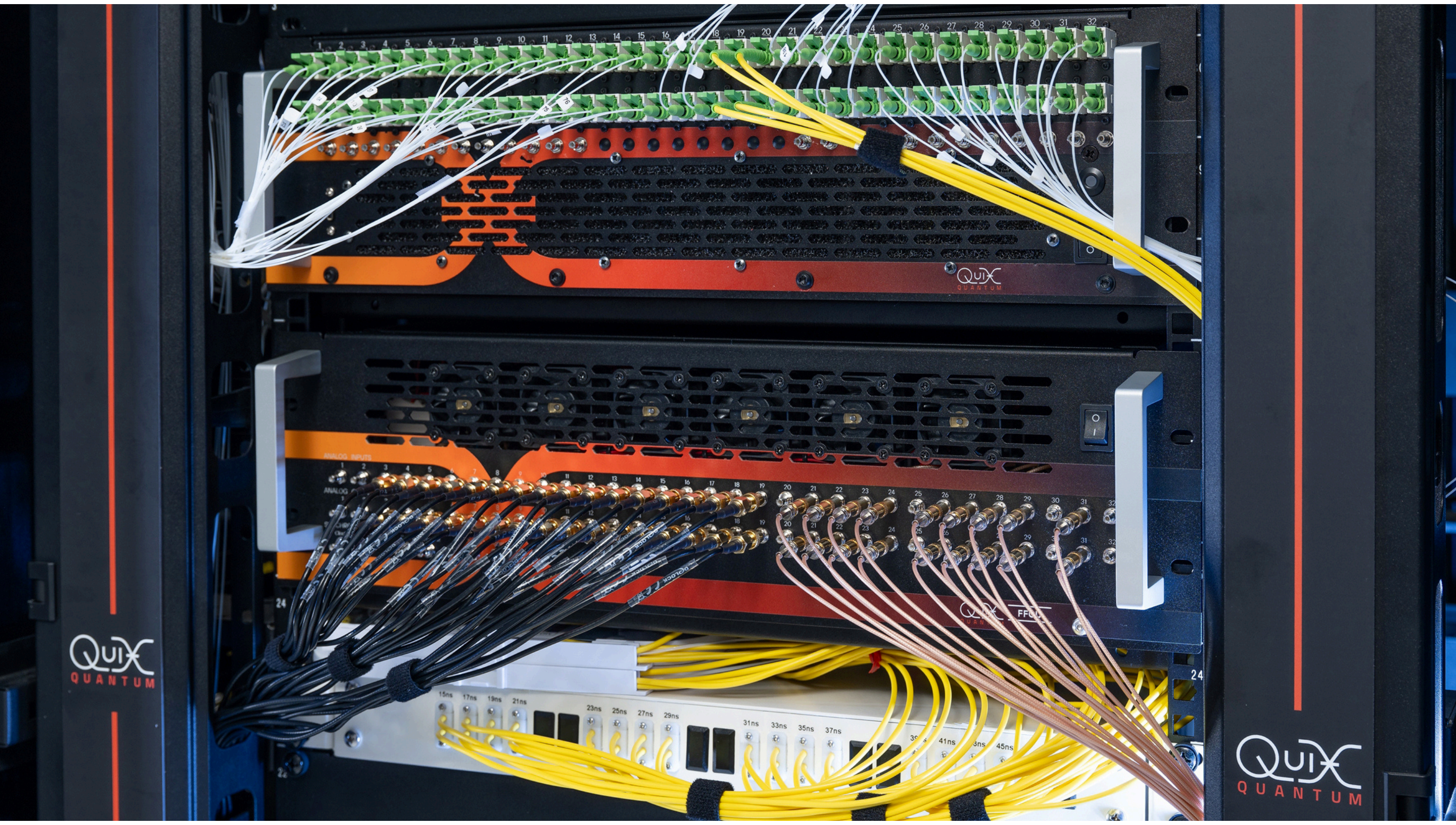
Picture of photon generator chip and its PACU connected to Delay 1

To use the single photons generated by the micro-ring resonators for quantum computation, however, the pump light needs to be suppressed. Micro-ring resonators employed in coupled resonant optical waveguide (CROWs) configurations provide high-extinction filtering. CROW filters can be thermally tuned and locked [14] making them both spectrally selective and resilient to thermal drift. We will use a series of on-chip CROW filters design to achieve > 110 dB reduction in power.

In conclusion, integrating both the single-photon sources and the high-extinction filters using CMOS technology provides a **clear route toward massively parallel, scalable photon generation.** Our focus is now on optimizing the designs and fabrication methods to enable high yield, indistinguishable and synchronous single photon sources as this is the most critical subsystem in the overall photonic quantum computer stack.

Multiplexer

Integrated photonic lithium-niobate ($LiNbO_3$) electro-optical (EO) modulation components are high-performance on-chip devices that convert electrical control signals into precise, ultrafast changes in optical amplitude, phase, or polarization. Lithium niobate EO modulators leverage the material's large second-order nonlinear coefficient (χ^2) to achieve fast, linear, voltage-dependent changes in the refractive index. EO modulators are realized in conjunction with low-loss SiN photonic platform designed to outpace the latency on our control electronics.



Picture of Multiplixer PACU (top) connected to the FFCU (center) and Delay 2 (bottom)

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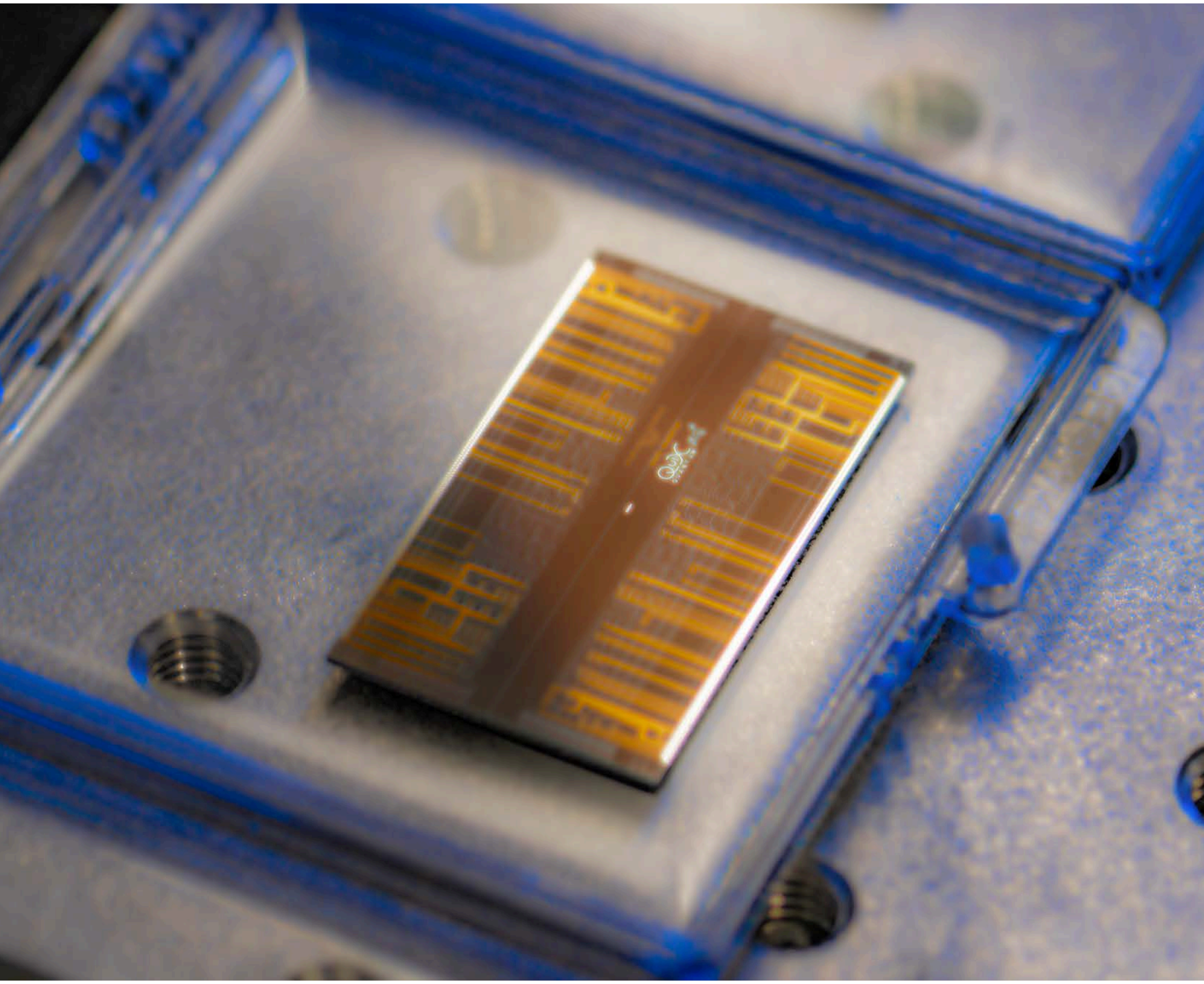
[e] Single-photon detection plays a critical role in optical quantum computing, as photonic heralding protocols depend on idler photon detection events and accurate photon counting to generate, control, and validate quantum states. Key detector parameters, including dead time and detection efficiency, have a direct impact on computational fidelity, error rates, and attainable gate speeds. Currently, arrays of superconducting nanowire single photon detectors (SNSPDs) represent the leading technology for high-performance implementation. Importantly, for SNSPDs, the size and complexity of the associated cryogenic systems significantly influence system scalability. The development of compact, energy-efficient cryogenic detectors is therefore crucial for advancing large-scale, practical photonic quantum computers.

[f] In implementing SFWM, two pump photons are consumed to generate a photon pair in a ring, respectively called the signal and idler photons. The pair is generated at distinct resonant wavelengths of the ring. The pump light is filtered out by additional resonators and the idler photon is detected, heralding the existence of the signal photon, which is then routed and used to complete quantum computations.

State Generator

In the MBQC regime, on-chip GHZ state generation [17] provides a compact, hardware-native way to unlock the computational power of cluster-state quantum computing by supplying high-fidelity entangled resource states directly in an integrated photonic setting. GHZ states can be stitched together, or grown, into large cluster states via fusion operations whose probabilistic nature directly sets the resource overhead and thus the practical scaling rate for moving to higher qubit-count system architectures. It follows that achieving on-chip state generation requires, on one hand, high-quality, synchronous, indistinguishable single photons and, on the other hand, low-loss, phase stable, precise interferometric circuits to successfully carry out fusion with sufficient fidelity. Regarding the latter, **QuiX already provides an industry-leading solution for the interferometric circuits**, i.e., Alquor quantum photonic processors, that offer unprecedented fidelity of up to F = 99.4% and insertion losses IL < 3 dB.



Picture of State Generator chip, before it was assembled and hosted into PACU

Feed-forward Control Unit (FFCU)

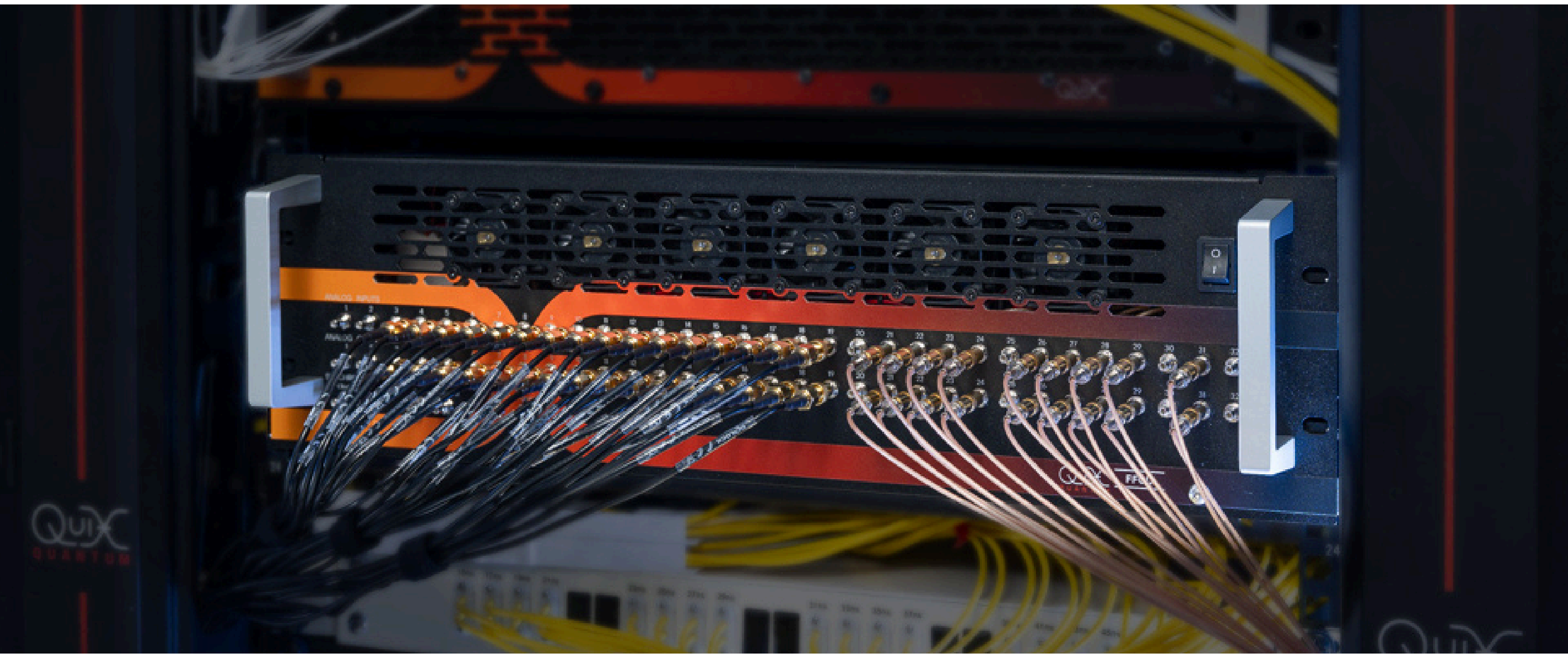
The Feed-forward Control Unit (FFCU) is a high-speed electronics system engineered to support universal quantum computing by providing dynamic, real-time responses to signals received from single-photon detectors. Its core function is to rapidly process measurement outcomes and apply the appropriate operations directly to photonic qubits, ensuring that quantum computations proceed with minimal delay and maximum fidelity.

The FFCU is constructed around a commercial off-the-shelf (COTS) system-on-module (SoM) that enables high-speed digital signal processing, crucial for the demands of quantum photonic control. The system fuses RFSoC-based digital logic with a custom-designed analog front-end, resulting in ultra-fast signal processing capabilities.

Feed-forward logic within the unit is realized through lookup tables generated from measurement patterns. This approach allows for rapid and deterministic control of Mach-Zehnder Interferometers (MZIs) on integrated photonic circuits. The FFCU supports adaptive, measurement-based quantum computing by employing real-time lookup table addressing and dynamically updating MZI configurations based on ongoing measurement results.

This implementation [g] was selected for its extremely low latency, inherent scalability, and strong compatibility with integrated photonic platforms. These characteristics are essential for executing real-time quantum feed-forward algorithms, which are foundational to advanced photonic quantum computing architectures.

Figure 2 Rendering of FFCU rack mount unit with 32 RF I/Os



FFCU rack mounted and connected to SNSPDs (black cables) and Multiplexer PACU (brown cables)

[g] Measured specs: Trigger Output Frequency Range: 1–100 MHz. Latency: 150 ns response to detector signals.

Photonic Assembly Control Unit (PACU)

The Photonic Assembly Control Unit (PACU) is a system that offers reliable control of large-scale photonic integrated circuits (PICs) by its highly optimized design for heat-dissipation and reconfiguration.

Forced-air cooling is used, eliminating the need for water and the associated risks of leakage. Multiple Peltier elements are used in conjunction with a large heat sink and heat pipes to manage thermal loads. Air is expelled from the back of the unit using a fan, and provisions are made to support optical fibers, preventing them from hanging loosely and therefore improving the phase stability of the system.

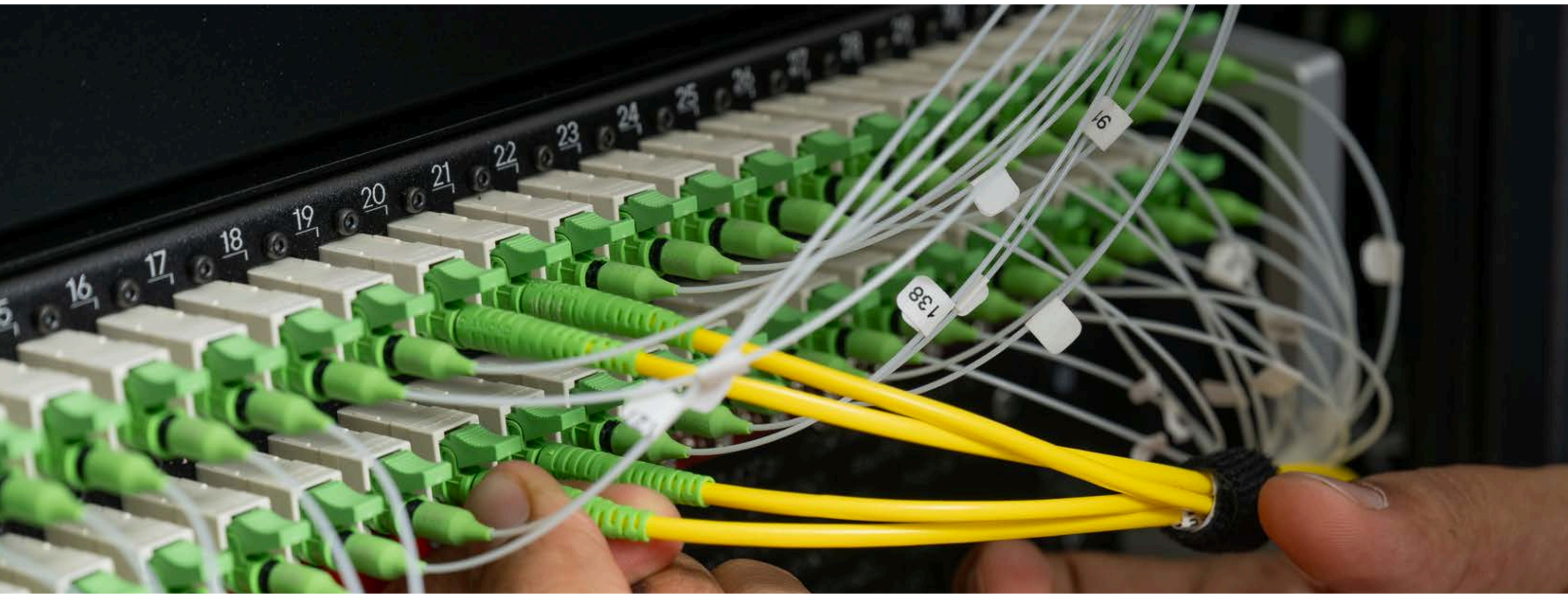
Figure 3 Rendering of PACU as scalable, rack mount unit for quantum computing. PACU also powers QuiX Quantum next generation

The PACU is designed to control up to 1,000 thermo-optic phase shifters using current (I) drivers, thus reducing drastically electrical crosstalk compared to voltage-driven systems. The system offers also the flexibility in configuration and expansion of the driver cards to accommodate different types of phase shifters, enhancing the versatility of the system.

Board-to-board connectors enable fast control signals reducing the reconfiguration speed of the PIC to millisecond time scale. All information related to the Photonic Integrated Circuit (PIC), such as, e.g., its calibration, is securely stored in an encrypted flash memory located on the Photonic Assembly (PA) itself allowing hot-swapping.

External control signals are allowed to directly manage high-speed phase shifters on the PIC, eventually. The PACU features in fact 32 MMC high-speed RF connectors. These fast control signals are routed through the front panel and can be accessed externally via the Feed Forward Control Unit (FFCU).

Low-loss optical connections are ensured via E2000 connectors and a 3U rack form factor is chosen for compactness. The pluggable and hot-swappable PA, with its secure flash memory, and the inclusion of both USB and Ethernet connection further demonstrate the PACU's focus on reliability, flexibility, and data-center readiness.



Close up on PACU E2000 fiber connectors.

Outlook

We intend to run on Carina established protocols and quantum algorithms, including Quantum Teleportation [18], Shor's algorithm [19], Grover's algorithm [20], and Deutsch and Jozsa's algorithm [21]. Initially, computations will be executed on a Carina emulator [h], followed by trials on the hardware demonstrator; this approach enables the assessment of quantum system quality and the impact of noise relative to ideal results. Comparing the emulator with the physical quantum computing system is essential for identifying error sources and evaluating their consistency with theoretical models. A thorough analysis of real versus ideal scenarios will provide valuable insights to optimize future iterations of the quantum computing system.

On the long-term, QuiX will we focus on lowering the errors in the system, especially losses, in order to demonstrate operation with logical qubit in its upcoming system Dedalo, designed to demonstrate loss-error tolerance in a photonic quantum computer [10].

Conclusion

Amongst the various quantum computing modalities, QuiX's photonic quantum computing solution offers fascinating advantages such as native interconnectivity, that allows modularity and rapid scaling, low hardware overhead, thanks to favorable error correction schemes, and data-center readiness, allowed by room temperature and telecom operation.

Photonics quantum computing, however, was lacking the demonstration of universality in an operating system. QuiX is well poised to achieve this milestone with Carina, designed to implement a universal gate set enabling any quantum operation. We show in this white paper QuiX's most recent technological advancements for the critical components of measurement-based quantum computing and its universal architecture including on-chip photon generation, fast network switches, cluster state generation and feedforward.

QuiX's leadership pushes the boundaries of the quantum photonic industry and drives the development of cutting-edge technology. With Carina**, QuiX is set to truly open the pathway towards data-center ready and energy-efficient universal photonic quantum computing for real-world applications.**

For more information, contact: sales@quixquantum.com

[h] The Carina emulator is available on the DLR QCI Connect webpage qci.dlr.de/connect

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Appendix A

Carina Emulator

In the Carina emulator, the computation is done by measuring, in suitable basis, some highly entangled dual-rail encoded state (typically a graph state) which the actual Carina hardware can produce. In this sense, the emulator produces the output samples of a given quantum circuit following the MBQC prescription. More precisely, the computation consists in 3 steps:

1. First a quantum circuit is compiled by using an MBQC compiler which considers all the constraint and peculiarities of the actual Hardware. The result of this operation is a series of settings for all the tunable elements of the Carina architecture.
2. Those settings are used to initialize a simulator, which simulates at photonic level the photonic integrated circuits in Carina, as well as emulate all the control electronics of Carina. The result of this operation is a series of samples (i.e. measurement outcomes), which are the ones they should expect from the actual hardware in ideal conditions.
3. Finally, the samples are post-processed by correcting the randomness introduced by the quantum measurements. This is a fundamental step in any MBQC computation, which allows us to extract the computation result from what would look like noise otherwise. The result of this last step is the samples of the quantum circuit we started.

All those 3 steps are done internally by the Carina emulator.

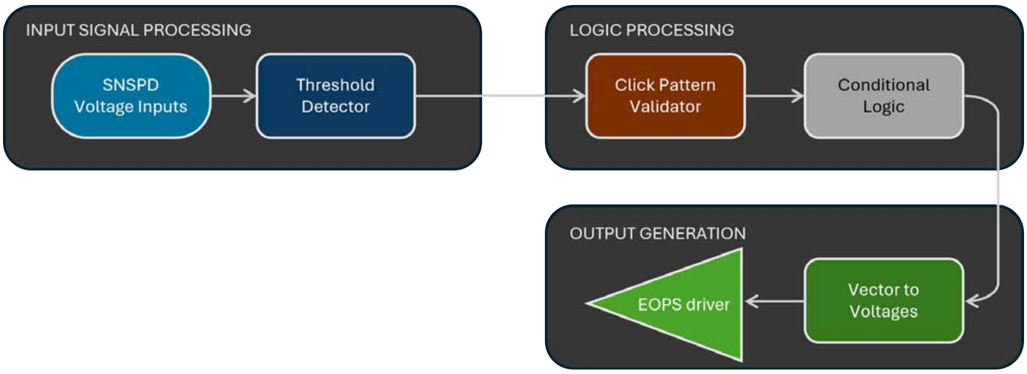
One way to use the Carina emulator is via the QCI Connect developed by DLR QCI [22]. Carina emulator is one of the simulators available in this platform, and the user can send jobs to a dedicated server, where the Carina emulator runs, using this interface. In that case, the use just needs to specify a quantum circuit in openQASM format and send it to the Carina emulator server. Once the computation is ready, the result is returned to the used in the DLR QCI to connect interface as a histogram. Alternatively, one can have directly access to the samples produced (after the post-processing) or, exploring the result metadata, get some insight on the settings produced by the compiler.

[22] Eric Bertok et al. - "QCI Connect: A Modular Full-Stack Quantum Computing Platform" - https://arxiv.org/abs/2606.14456v1

Appendix B

FFCU

Diagram of internal computation of the FFCU:



For the input voltage, a threshold represents the voltage level at the rising edge of the SNSPD output signal. When a certain threshold is exceeded, this indicates a measured photon.

We work in a loss-free scheme, i.e., we only consider measurements where the amount of photons detected is equal to the amount of photons generated; therefore we post-select the detection patterns against photon loss, either because a photon has been truly lost or two photons ended up at the same detector.

Post-selection against the heralding pattern from the state generator (expected vs measured) ensures the use of correct computational resource states only.

A lookup table stores phase shifter output values represented as a vector. The interpretation of this vector in terms of voltage depends on the calibrated values of each Electro-Optic Phase Shifter (EOPS). These values must be characterized initially and recalibrated dynamically to maintain accuracy during operation.