PTQUBE
Final Report
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Excecutive Summary

The contribution of IPE within the PtQUBE project was to address the critical need for a cost-effective sophisticated electronics capable of manipulating and reading out superconducting qubits. Over three years, the project successfully developed a prototype system housed within a single 19-inch chassis, integrating FPGA, analog-to-digital converters, and high-frequency (HF) boards (see Figures 3 (right) and 6). This system was designed to exceed the capabilities of traditional laboratory setups, enabling advanced quantum computing experiments such as simultaneous Ramsey experiment on a 5-qubit device (see Figure 14).

In the first phase, the project focused on developing the DAQ components and a pulse description language in collaboration with KIT-PHI. This language facilitates intuitive programming and control of pulse sequences and was integrated into the proprietary QKIT software, enhancing functionality and allowing for detailed pulse parameter control. The robustness and reliability of the system were also address by thorough evaluations of possible error sources and the implementation of failover mechanisms were made.

In the second phase, big steps forward were made when the QiCode experiment description language was fully implemented. This made it possible to plan and run complex quantum experiments directly from the FPGA platform. This integration allowed for dynamic, real-time adjustments during experiments, increasing the flexibility and utility of the system. Additionally, radio-frequency (RF) electronics necessary for translating microwave signals were developed and integrated, streamlining the setup and reducing external dependencies. These RF boards are significantly smaller than the discrete component setup it replaces (see Figure 3 (left)).

The final phase culminated with the successful deployment of the system on multiple setups and the characterization of the performance of the system employing advanced techniques like randomized benchmarking and quantum-state tomography. Creating the ”Cell Coordinator” and ”Cell Signal Router” firmware parts made it possible to precisely sync signals, which are needed for operations that use multiple qubits. The system was successfully used to read and control a 5-qubit device (see Figure 13). Eventually the platform was integrated with the ADR cryostat and successfully tested.

Throughout its lifecycle, the PtQUBE project tackled numerous technical challenges, including achieving nanosecond-level precision in timing, ensuring reliable operation at cryogenic temperatures, and integrating diverse components into a unified system. Solutions involved innovations in materials science from collaboration partners, specialized cooling techniques, iterative firmware enhancements, and advanced PCB design techniques.

The successful completion of the PtQUBE resulted in a robust, scalable, and highly precise platform that not only meets current quantum research needs, but also serves as the foundation for future developments and projects in this field from our research group.

Part II

Detailed Report

1 Introduction and Background

1.1 Overview of Quantum Computing and Superconducting Qubits

Quantum computing is a rapidly advancing field that leverages the principles of quantum mechanics to process information in ways that classical computers cannot. Central to this technology are qubits, which are quantum bits that can exist in multiple states simultaneously, enabling parallel computation. Superconducting qubits are among the most promising candidates for scalable quantum computers due to their relatively mature fabrication processes and compatibility with existing semiconductor technologies.

However, controlling and reading out the states of superconducting qubits requires highly specialized electronics. Unlike classical bits, qubits must be manipulated with precise sequences of microwave pulses and read out in environments cooled to near absolute zero. The need for ultra-low noise, high-speed processing, and integration of various electronic components within a cryogenic environment presents unique challenges that are not encountered in classical computing systems.

1.2 Historical Context and Motivation for the Project

The Institute for Data Processing and Electronics (IPE) at the Karlsruhe Institute of Technology (KIT) has a long history of developing advanced electronics for cryogenic applications. Since 2016, IPE has been working on adapting its expertise in cryogenic electronics, originally developed for metallic magnetic calorimeters (MMCs), to the field of quantum computing. MMCs, which operate at millikelvin temperatures, share operational similarities with superconducting qubits, particularly in terms of their readout requirements. Both systems operate in the microwave frequency range (4-8 GHz) and require low-noise electronics to achieve high-fidelity measurements.

This project was initiated to leverage the existing knowledge and hardware from MMC readout systems and apply it to the development of integrated manipulation and readout electronics for superconducting qubits. The goal was to create a user-friendly, compact, highly precise, and cost efficient system that can be housed in a single 19-inch chassis, integrating an FPGA board, converter board, and RF board. Such a system enables advanced quantum computing experiments that are currently beyond the capabilities of standard laboratory equipment.

2 Year 1: Foundation and Initial Development

2.1 Objectives and Rationale

The first year of the project focused on laying the groundwork for the development of integrated qubit control and readout electronics. The primary objective was to assess the feasibility of adapting existing MMC electronics for qubit applications, with a particular focus on FPGA firmware development. Given the stringent timing requirements for qubit manipulation, this phase was critical in determining whether the MMC-based approach could meet the necessary specifications.

Key Objectives

- Adapt existing MMC electronics for qubit manipulation and readout.
- Develop FPGA firmware capable of generating precise microwave pulses.
- Establish a collaboration with quantum computing experts to guide the development process.

2.2 Firmware Developments for Qubit Control

During the first year, significant progress was made in adapting the FPGA firmware to meet the needs of superconducting qubits. The collaboration between KIT-IPE and the Physics

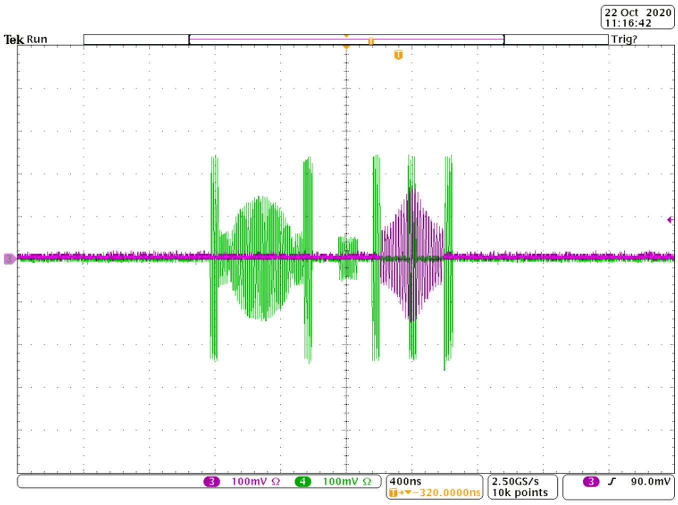

Figure 1: Oscilloscope recording of a complex pulse sequence.

Institute at KIT (KIT-PHI), was instrumental in this effort. The team developed a novel FPGA firmware capable of generating highly precise manipulation pulses with nanosecond accuracy. This precision is crucial for ensuring the fidelity of quantum operations, as even minor timing errors can lead to significant decoherence in qubit states.

The initial experiments focused on generating simple pulse sequences, as seen in Figure 1, and evaluating their impact on qubit states. These experiments provided valuable insights into the timing and control requirements for qubit manipulation, guiding further development.

These experiments yielded in a first version of the firmware providing the ability of generating simple pulse sequences and experiments, as well as the readout of a qubit state. Key elements such as a simplified processing core allowing for exact determination of required clock cycles for certain steps, dedicated modules for pulse generation or modules for decoding were already part of that particular approach. This version of the platform also used the same hardware and base firmware infrastructure as the platform for superconducting sensors. While first experiments showed positive results, various downsides in the firmware architecture and usability were detected.

Based on this experience the final architecture design was made, which had simple usability as one of the key targets. Therefore individual modules of the platform have been thoroughly revised and the structure has been adjusted. In particular, a regrouping took place so that all sub-modules that are necessary for controlling a qubit can be found in an encapsulated module. A representation of the work carried out at module level can be seen in Figure 2. For example, the modules implemented on the FPGA were connected to each other with a wishbone bus. This enables the control unit (the sequencer) to control

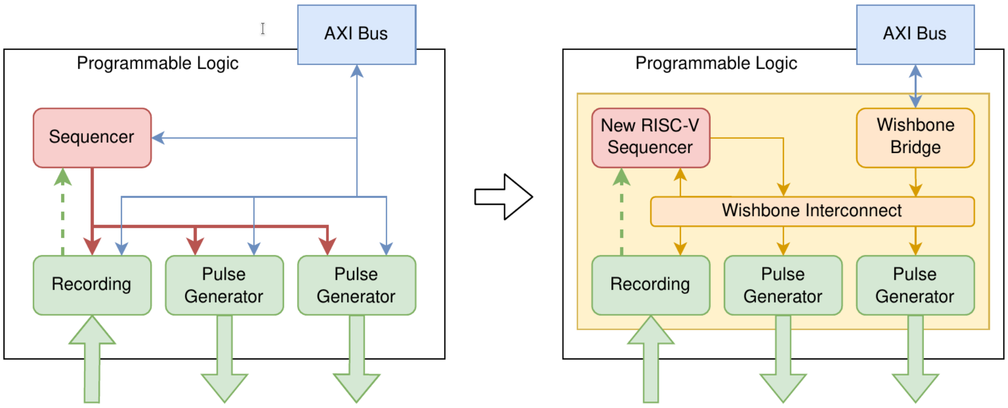

Figure 2: Firmware reorganization.

the other modules and reconfigure them at runtime. Such feature is of particular interest for qubit characterization measurements, in which parameter variations are implemented with minimal time delays in the nanosecond range. The platform can adapt all properties of pulses such as frequency, phase, length or amplitude, but also settings of the data acquisition unit (the recording module), such as demodulation frequency or length of the recording. At the same time, the sequencer was re-implemented and now has significantly more functionality.

As the internal complexity of the system continues to grow, it now resembles that of a standard processor. The decision was made to adopt the RISC-V open source architecture for the instruction set architecture, benefiting from its established framework which simplifies programming by allowing the use of existing concepts. It's anticipated that, eventually, existing RISC-V compilers might be utilized. The innovative architecture includes the wishbone bus to handle memory access commands, facilitating data and configuration exchanges among modules. This enhancement significantly boosts flexibility, enabling the sequencer to adjust all attributes of the sub-modules. Furthermore, the bus is extended (in contrast to regular bus system approaches) to handle parallel writes to several modules. For example this feature can be used as a parallel trigger of modules, yielding in very resource efficient and highly configurable implementation of that particular feature.

The activities in firmware development were complemented by porting the infrastructure to the novel RFSoC device. This new class of devices integrates not only a processing system and FPGA, but also several multi-gigabit analog-to-digital and digital-to-analog converters in a single circuit package. As result not only the hardware is simplified, but also robustness is added and latency shortened. Furthermore it bears the potential of reducing system costs. An evaluation board featuring an RFSoC was for these reasons chosen to be the fundamental hardware for our PtQube contribution.

2.3 Experiment Description Language Concept

Efforts were made to create a high-level easy-to-use experiment description language tailored for the platform. This new language is designed to leverage the full capabilities of the updated sequencer and structure. Developed in close collaboration with the project partner KIT-PHI, this language extends the foundational work done on the pulse description language. The objective is to integrate this into the PHI-KIT laboratory environment, QKIT, enabling a comprehensive description of experimental processes. Like QKIT the description language is created utilizing python that is widely used in the community. A primary challenge lies in automating the translation of Python descriptions into sequencer code, particularly with an emphasis on achieving precise time control within the range of single-digit nanoseconds. A prototype of a custom compiler, that has full knowledge about the platform is also implemented in python. It analyzes the so called QiCode program and transforms it into configurations for the individual modules and the corresponding sequencer program. While some groundwork for that language/compiler could be done, the full implementation of this language was later concluded in subsequent years.

2.4 Radio-Frequency (RF) Heterodyne Mixer board

Alongside the digital electronics, radio-frequency electronics are essential for converting microwave signals from the baseband (up to several hundred megahertz) into the radio-frequency range (typically four to eight gigahertz). Using the designs originally developed for the readout of cryogenic metallic magnetic calorimeters (MMCs), a circuit board has been crafted specifically for handling these tasks with superconducting quantum bits.

A distinctive feature of this board is the integration of the required mixers, filters, and local oscillator signal sources directly onto the board itself. This integration eliminates the need for additional cost-intensive radio-frequency electronic components for operation. Furthermore, the board uses a heterodyne mixing approach, which allows to use easily available commercial off-the-shelf components. The initial version of this circuit board has been assembled and undergone preliminary testing. Another key factor is the size reduction with respect to discrete components. Figure 3 displays an image of the discrete component setup (being a 19 inch rack) and the first version of the RF board.

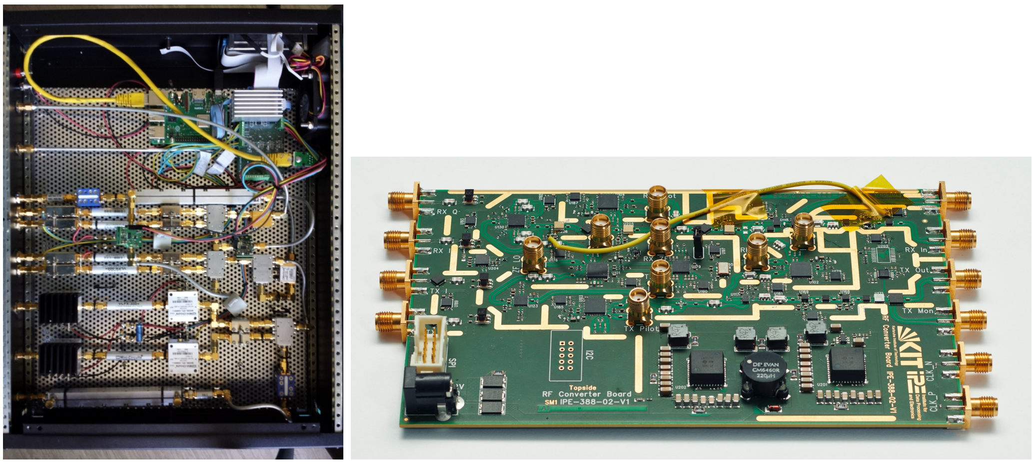

Figure 3: Discrete components radio-frequency mixer (left). Integrated heterodyne mixer board developed in the project (right).

2.5 Platform Technical Challenges and Solutions

Reliability and robustness are critical in the electronic systems used for physics experiments. Any operational failures can cause the system to stall, leading to unwanted delays in the experimental timeline. Consequently, significant emphasis was placed on these qualities from the early stages of the PtQUBE project to ensure the FPGA platform operated reliably.

Potential errors were analyzed and several proactive measures were developed to detect and correct errors early. For instances where errors could not be preemptively managed, a failover system was implemented, allowing the platform to be remotely restored to an operational state most of the time. This involved revising the boot process so that in case of a persistent issue, the platform would not attempt to restart the faulty system but instead switch to a predefined failover mode. Concurrently, a watchdog mechanism was established to monitor the system's operational status continually and trigger a system restart to initiate the failover process when an uncorrectable error occurs.

Furthermore, system monitoring capabilities were integrated to continuously oversee critical platform metrics such as temperature, processor load, and memory usage. This monitoring allows for the automatic generation of alerts and the implementation of necessary countermeasures to maintain system stability and performance.

3 Year 2: Platform Expansion and Integration

3.1 Expanded Objectives and Strategic Direction

With the foundation established, the second year of the project aimed to expand the platform's capabilities and begin integrating the various components into a cohesive system. The strategic direction of this phase was informed by the lessons learned in the first year, with a focus on creating a more versatile and user-friendly system that could support a broader range of quantum computing experiments.

Key Objectives

- Integrate the FPGA board with analog-to-digital converters and radio-frequency (RF) boards in a single chassis.
- Refine the FPGA firmware to support more complex pulse sequences.
- Begin integration with the QKIT software framework for data analysis.

3.2 Progress and Achievements in System Integration

The second year saw the successful integration of the FPGA board with the analog-to-digital converters and radio-frequency (RF) boards, resulting in a compact and efficient system housed within a single 19-inch chassis. This integration was a critical milestone, as it marked the transition from a proof-of-concept platform to a fully functional demonstrator capable of supporting advanced quantum computing experiments.

The integration process involved several key steps

- **Hardware Integration:** The FPGA board, analog-to-digital converter board, and the radio-frequency (RF) board were integrated into a single chassis, with careful attention to thermal management and signal integrity. The system was designed to minimize electromagnetic interference and ensure reliable operation with cryogenic environment.
- **Firmware Refinement:** The FPGA firmware was further refined to support more complex pulse sequences, enabling a wider range of quantum operations. This included the development of new control algorithms and the optimization of existing code to reduce latency and improve timing accuracy. Furthermore, a real-time

processor on the RFSoC device was integrated into the platform approach by implementing a software stack named taskrunner. It adds an intermediate layer, which is capable of first level processing of the measured data, e.g. for statistics or data reduction. The taskrunner also allows to perform more complex sweeps of experimental parameters.

- **Software Integration:** The platform was integrated with the QKIT software framework, which is widely used at KIT-PHI for quantum computing experiments. This integration allowed for seamless data collection and analysis, making it easier for researchers to conduct experiments and interpret the results.

3.3 Advanced Demonstrations and Experimental Successes

One of the most significant achievements of the second year was the successful demonstration of quantum feedback using the integrated platform. Quantum feedback is a process in which the state of a qubit is measured within its coherence time, and the control sequences are adjusted in real-time based on the observed state. This capability is essential for many advanced quantum computing algorithms, including error correction and quantum state stabilization.

The quantum feedback demonstration involved several key steps

- **State Measurement:** The qubit's state was measured using the integrated readout electronics, with the results processed in real-time by the FPGA firmware.
- **Real-Time Control:** Based on the measured state, the control sequences were adjusted in real-time to drive the qubit into the desired state or to correct errors.
- **Validation:** The results of the quantum feedback experiment were validated through repeated trials, demonstrating the platform's ability to perform complex quantum operations with high fidelity.

3.4 Experiment Description Language Update

The QiCode experiment description language has been fully deployed and is continuously being enhanced to facilitate the formulation and execution of intricate experimental procedures on the platform. At the core of QiCode is a custom compiler designed to convert

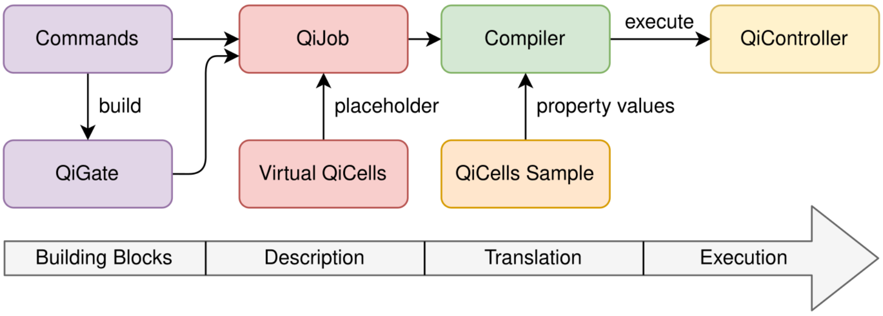

Figure 4: The concept of the QiCode experiment description language.

the language into specific machine instructions for the sequencers and configuration settings for the platform. A critical aspect of this development has been the precise timing requirements and full deterministic behavior of the generated machine code. Even slight delays of a few nanoseconds can significantly impact experimental outcomes. Deviations in different compilation runs of the very same code would hinder any repeatability.

An overview of the conceptual framework of QiCode is provided in Figure 4. The language is structured around several fundamental commands that form the basis for all operations, such as the Wait command, and the Play and PlayReadout commands, which control the emission of manipulation and readout pulses. These commands can be assembled into more complex quantum gate operations known as QiGates. An experimental procedure, known as QiJob, is constructed from these commands and QiGates. QiJobs employ a virtual reference to qubits, known as QiCells, which abstracts from the actual physical qubits to maintain a generic description that can adapt to include specific qubit properties like frequency before execution. For this purpose, the compiler processes a sample object containing the real values to replace the virtual QiCells in the QiJob. Post-compilation, the QiJob is loaded to and executed on the platform.

The capabilities of QiCode have been expanded to allow direct modification of various experimental parameters, such as the interval between pulses or their frequency, through a sequence executed by the platform's sequencer. This enhancement supports the execution of more complex experiments directly on the platform without the need for additional instrumentation, such as conducting basic frequency scans to identify qubits or their corresponding readout resonators. Additionally, the language now supports the collection and bundling of multiple experimental results in a single execution. For instance, several hundred consecutive measurements can be executed in a loop and presented to the user in sequential order.

```python
with QiJob() as job:
    q = QiCells(1)
    length = QiVariable()
    with ForRange(length, start, stop, step):
        Play(q[0], QiPulse(length, frequency=q[0]["manip_frequency"]))
        Measurement(q[0], save_to="result") # Gate defined earlier
        Wait(q[0], 5 * q[0]["T1"])
```

Figure 5: Example of a Rabi experiment description using the experiment description language “QiCode”.

An example of how QiCode is used in practice is illustrated in Figure 5, where a Python script is employed to define a Rabi experiment. In this script, a variable is used to parameterize the length of the manipulation pulse, which is then varied in a loop through successive passes. The script also uses a QiGate named ”Measurement,” which integrates the generation of a readout pulse with the subsequent recording and evaluation of the response, encapsulating multiple functions into a single command.

3.5 Radio-Frequency (RF) Heterodyne Mixer board (version 2)

The RF mixer board, developed by the end of the first project year, underwent detailed characterization where several issues were identified and opportunities for optimization were noted. These enhancements were integrated into a new version of the board, which was subsequently designed and manufactured.

This updated radio-frequency circuit board was rigorously tested, successfully addressing the shortcomings of its predecessor. Following initial tests, this second version is now actively employed in experiments involving superconducting qubits. Figure 6 displays the now fully operational board. Moving forward, the project aims to integrate this board directly with the platform’s digital electronics, facilitating configuration through the platform itself for a more seamless and integrated solution.

3.6 Experimental Results

To evaluate the platform effectively and enhance its assessment, extensive characterization measurements were performed. The signal quality of the platform matches that of commercial laboratory electronics, making it highly suitable for use with superconducting qubits. Figures 7-10 provide a brief overview of the key characterization results. These tests were conducted entirely in baseband, ranging up to a few hundred megahertz, and did not require separate radio-frequency electronics.

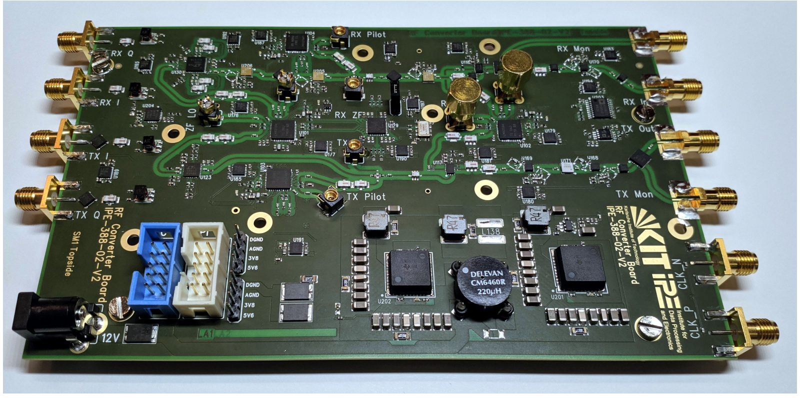

Figure 6: Second version of the analog radio-frequency board.

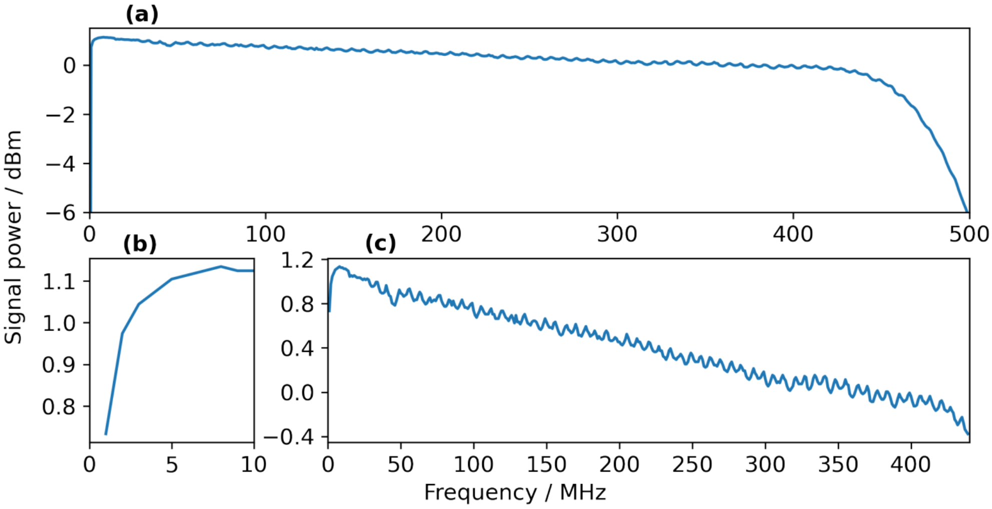

Figure 7: Platform power output in baseband. (a) shows the complete range, (b) onlythe low frequencies and (c) the excerpt of the linear mid-range.

Figure 7 illustrates the output power of the platform across baseband frequencies. As anticipated, there is a slight monotonic decline in power from 10 to 420 MHz. At frequencies below and above this range, signal suppression occurs due to filtering and sample rate limitations, which is expected.

Figure 8 depicts the phase noise across various carrier frequencies generated by the platform. When compared to commercial laboratory electronics such as Arbitrary Waveform Generators (AWGs), the phase noise levels are similar. Additionally, the impact of using an external reference clock on phase noise close to the carrier frequency was examined, revealing significant improvements as shown in Figure 9. The performance of the platform in terms of spurious free dynamic range, as depicted in Figure 10, also aligns well with that of commercial laboratory electronics.

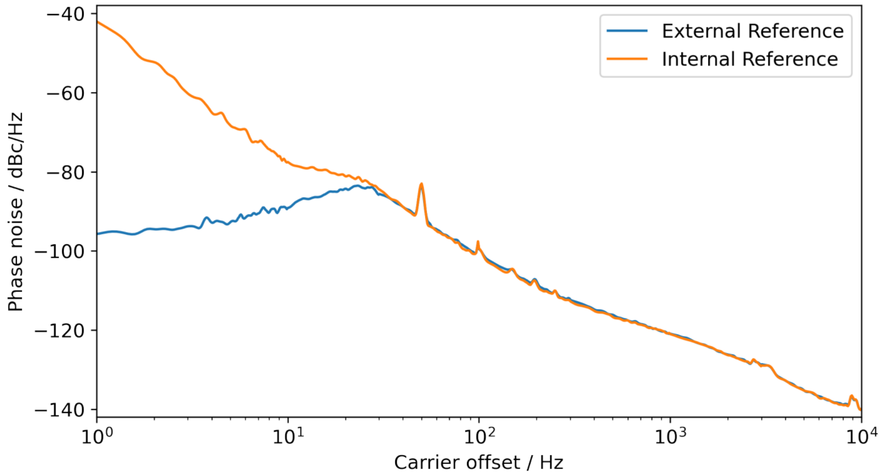

Figure 8: Phase noise of a carrier tone with and without an external reference.

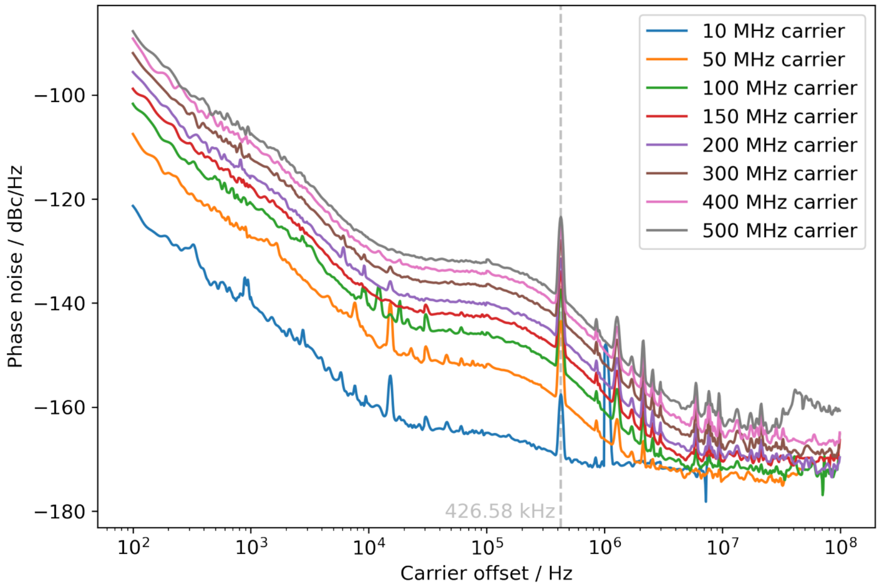

Figure 9: Phase noise of different output tones (carrier) of the platform.

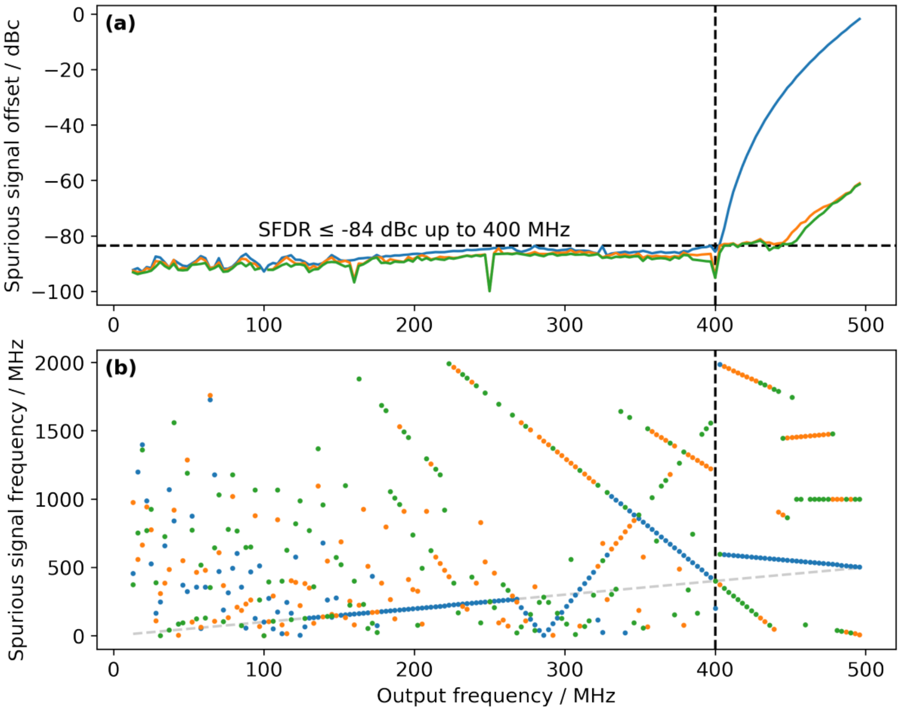

Figure 10: Spurious free dynamic range as a function of carrier frequency without harmonics.

4 Year 3: Optimization and Advanced Demonstrations

4.1 Objectives and Strategic Focus

The third year of the project was focused on optimizing the integrated system and demonstrating its capabilities through a series of advanced qubit experiments. This phase had as a goal the refining the performance of the system and the expansion of its functionality to support more complex quantum computing tasks.

Key Objectives

- Optimize the data acquisition system for high-speed, high-fidelity measurements.
- Implement advanced qubit characterization techniques such as randomized benchmarking and quantum-state tomography.
- Demonstrate the system's capabilities through a series of advanced quantum computing experiments.

4.2 Advanced Experimental Demonstrations

The third year also saw the successful demonstration of several advanced quantum computing experiments, showcasing the system's capabilities and validating its performance.

- **Randomized Benchmarking:** This technique was used to evaluate the fidelity of quantum operations by applying random sequences of gates to the qubits and measuring the resulting state. The platform demonstrated its capability to entirely characterize qubits by performing all the full set of standard operations. The results also provided valuable insights into the system's performance and identified areas for further optimization.
- **Quantum-State Tomography:** This technique was used to reconstruct the quantum state of the qubits based on a series of measurements. The high precision of the data acquisition system enabled accurate state reconstruction, demonstrating the system's potential for use in complex quantum computing tasks.
- **Multi-Qubit Operations:** The system was tested with multiple qubits to evaluate its scalability and performance in more complex quantum computing scenarios. The results showed that the platform could reliably handle the increased complexity of multi-qubit operations, paving the way for future experiments involving larger qubit arrays.

4.3 Optimizing Firmware and enabling Multi-Qubit Operation and Synchronization

While performing experiments with qubits and platform characterization optimization potential in the whole platform stack, including the Qicode compiler, was identified. Whenever possible optimizations were directly implemented and tested. In general optimizations targeted bug fixes, additional features, or improved usability. However, none of those changes was disruptive in the sense of changing the overall platform concept. Adding a first version of multi qubit support was a natural extension of the existing system.

To enhance multi-qubit support, key firmware components were developed in an initial version: the "Cell Coordinator" and the "Cell Signal Router", as seen in the overall firmware architecture depicted in Figure 11. These components synchronize signals from digital unit cells, central to our firmware architecture, ensuring coherent operations across multiple qubits.

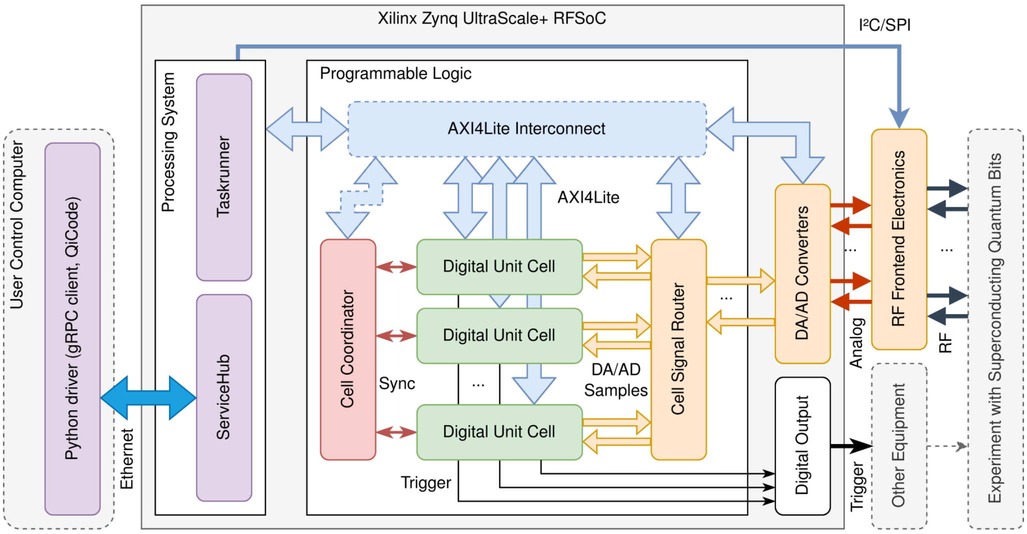

Figure 11: Firmware architecture of our heterogeneous electronics platform.

Each unit cell, equipped to control and read a single qubit, can also handle multi-qubit interactions. With a dedicated cell coordinator, each cell can start operations and exchange data simultaneously, streamlining communication. This system allows for the combination of signals using frequency-division multiplexing (FDM), reducing the need for multiple channels, and distributes digitized signals efficiently across cells.

The system's configuration is adjustable via the AXI4Lite register interface, facilitating dynamic changes and real-time response. This setup not only supports various quantum processor architectures by adapting to different external microwave line requirements but also enhances operational efficiency and synchronization across multiple unit cells, crucial for executing complex quantum computing tasks.

Qubit architectures vary and now standard interface exists. Some architectures necessitate two microwave lines for each qubit, whereas others employ frequency-division multiplexing to merge control or readout signals onto a single line. To accommodate these varying requirements, a versatile cellular signal router was developed. This router effectively combines and distributes signals among the digital elementary cells and conversion channels.

4.4 Demonstration of Multi-Qubit Operation

In a test setup mirroring the AP3.2 demonstrator, a Bluefors cryostat and a qubit chip with five superconducting transmon qubits linked to a common microwave line via separate readout resonators was utilized. This setup leverages frequency multiplexing for control

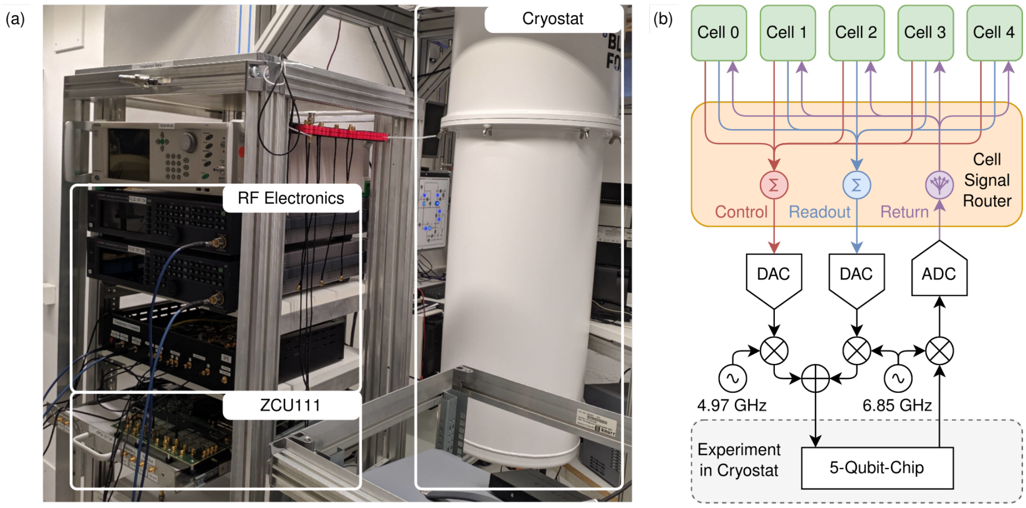

Figure 12: (a) Photo of the experimental setup including the cryostat with the five-qubit chip at approximately 15 mK. (b) Simplified sketch of the signal routing between digital unit cells and the five-qubit chip.

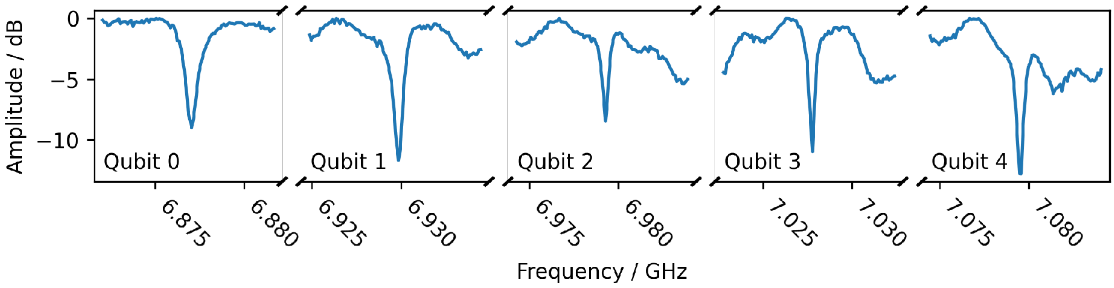

Figure 13: Simultaneous VNA-like measurements to determine the frequency of the readout resonators for all five qubits. The amplitude was standardized to the largest value separately for each frequency section.

and readout pulses across five of the ten available digital unit cells in the firmware, each dedicated to a single qubit. The RF electronics, including two IQ mixers with distinct local oscillators for upconversion, integrate signals from these cells into a single microwave line, as shown in Figure 12.

A frequency sweep is achievable by altering the frequency of the internal numerically controlled oscillator in both the signal generator and recorder. As each qubit operates within its own unit cell, this adjustment can be executed simultaneously across all five qubits, as illustrated in Figure 13. Each cell independently handles signal generation and processing for one resonator cycle, with output signals subsequently combined in the Cell Signal Router and directed to a DAC output.

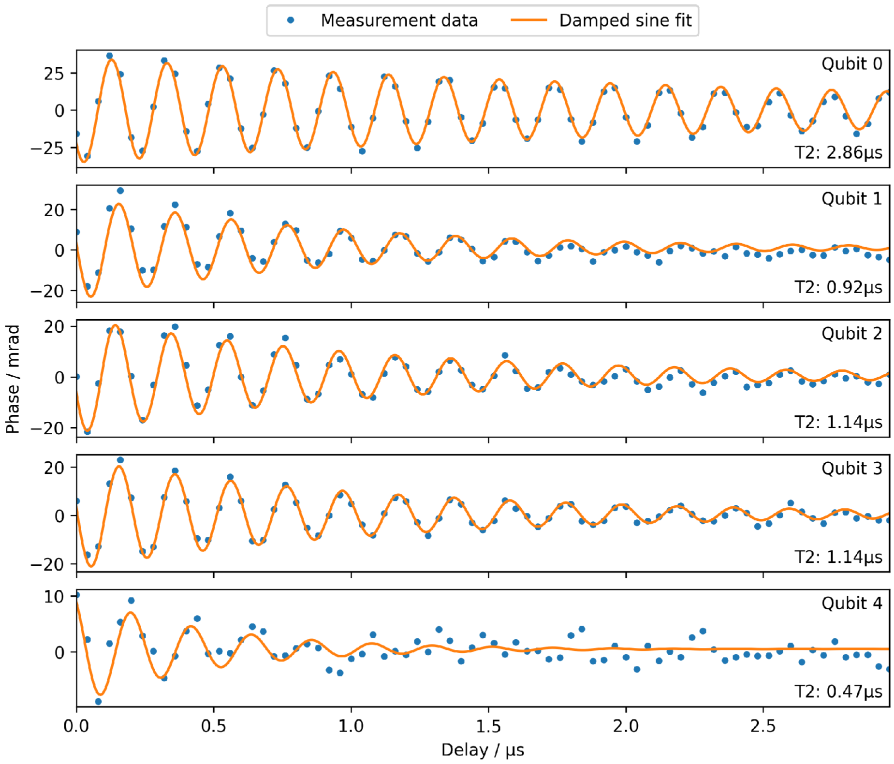

Figure 14: Simultaneous measurements to extract the decoherence time T2 with five qubits using a Ramsey pulse sequence. For averaging, 100000 repetitions were carried out.

Similarly, incoming signals from the ADC are distributed back to the respective cells, leading to an oscillation between states $|0\rangle$ and $|1\rangle$. The results of these simultaneous measurements on all five qubits are depicted in Figure 14, showing the phase response from the readout resonator encoded state of each qubit and the exponential decay of signal envelopes due to prolonged intervals between pulses, corresponding to the coherence time T2.

Additionally, various standard experiments were conducted, all yielding results comparable to previous measurements performed with other systems. This demonstrates that our RFSoC-based setup can replace complex external signal conversion systems without sacrificing accuracy. The unit cell approach significantly enhances the parallel control and readout of all five qubits, reducing execution times by more than 80% compared to earlier experiments. Our system has demonstrated its capability to perform all necessary single and multi-qubit operations with ease and precision, suitable for both superconducting qubit research and as an interface between quantum processors and classical computing environments.

4.5 Modular RF Analog Front-End for Enhanced Scalability and Integration

In anticipation of scaling the system and integrating next-generation RFSoC devices capable of directly synthesizing signals within the desired frequency range, the complexity of the analog front-end was simplified. This was achieved by breaking down the previously used superheterodyne mixer into separate mixer stages. These boards have been designed to be controlled through a single interface using a daisy chain configuration, which facilitates the management of more sophisticated qubit devices.

5 Year 4 (cost neutral extension): Final Integration with the ADR Cryostat and Performance Validation

The fourth year of the PtQUBE project saw a significant shift from development to integration, with a focus on assembling all cryogenic components into the designated ADR cryostat. Originally scheduled for delivery earlier in the project, it was delayed due to supply chain disruptions caused by the COVID-19 pandemic. With the ADR cryostat finally delivered to the PHI Institute, the project entered the critical final stage of integration.

After receiving the ADR cryostat, efforts were focused on integrating the QiController with the qubit device, using protocols similar to those used in the advanced 5-qubit demonstrator. This process necessitated meticulous coordination among all project partners to ensure that each component, designed for the cryostat's low-temperature environment, was installed and configured to work seamlessly within the system.

Following integration, the system underwent a series of qualifying experiments to validate its performance, replicating previous tests to allow for direct comparison. The results confirmed that the integration yielded similar system performance to previous tests as shown in the 5-qubit demonstrator.

The successful integration of all cryogenic components into the ADR cryostat marks a significant milestone in the PtQUBE project and its final realization. Despite logistical challenges, the project maintained its commitment to excellence, laying the groundwork for future phases of quantum computing research and development. The PHI Institute's system is now fully operational and ready to explore new quantum computing frontiers, expanding the capabilities of this cutting-edge technology.

6 Supplemental Information

The key positions in the numerical evidence: An overwhelming majority of the funded costs are related to human resources, focusing on the development of RF boards, FPGA firmware, embedded software, and high-level software. Purchases made, were directed for the extension of measurement equipment that allowed for a more precise characterization of the platform capabilities.

The necessity and appropriateness of the project work performed: The work performed was entirely directed to contribute to the project goals in the most efficient way. The high innovative nature and complexity of the development at the same time made it necessary to explore various approaches before converging to the final system. However, during the project execution there was a clear goal on early sustainable decisions. Latter was also necessitated by the high overall goal to deliver a working demonstrator at the end of the project.

The anticipated benefits, particularly the usability of the results, including concrete plans for the near future, in line with the updated utilization plan: The developed qubit control and readout platform already proves to be a valuable tool for scientists in the field of quantum computing in its current state. As multi-qubit systems gain more attention, platform scalability is of major interest and currently targeted in our developments. This explicitly includes scalability beyond one single RFSoC. Further details can be found in the updated utilization plan.

The progress in the field of the project that became known to the grant recipient during the implementation of the project at other institutions: The necessity of specific instrumentation quantum computing experiments is meanwhile largely accepted in the community. During the execution of the project commercial electronics with a similar scope became available by e.g. Quantum Machines or Zurich Instruments. At the same time also some academic groups started the development of custom platforms.

The completed or planned publications of the results: Various papers and contributions to scientific conferences were made during the execution of the project. An overview is given in the dedicated spreadsheet of the reporting.

7 Conclusion

The development of integrated manipulation and readout electronics for superconducting qubits represents a significant advancement in the field of quantum computing. Through careful planning, rigorous testing, and innovative engineering, the project team has successfully developed a demonstrator system that meets the stringent requirements of quantum computing experiments. The system's precision, scalability, and user-friendly design make it a valuable tool for researchers. By sharing the results through publications and presentations, the team has contributed to the global scientific community.

7.1 Summarized Achievements

The project commenced by establishing a strong foundation with the development of a pulse description language and a robust FPGA platform. These early advancements facilitated precise control and automation of complex pulse sequences, significantly enhancing the capability of the experimental quantum computing platform including QKIT integration.

In the second phase, the project team made significant strides with the full implementation and refinement of the QiCode experiment description language, thereby leveraging the platform's flexibility and utility. The incorporation of radio-frequency electronics streamlined the entire setup, reduced external dependencies, and improved overall system efficiency.

The final phased focused on demonstrating the platform's capability to support complex, multi-qubit operations and integration with the ADR cryostat setup. Precise synchronization of operations across various digital unit cells was added to the system.

7.2 Future Directions

Looking ahead, the PtQUBE project lays a robust foundation for further advancements in quantum computing technology. The platform developed is not only a testament to the collaborative efforts of the research teams but also a critical tool that will facilitate more sophisticated research and development in the field. The next steps involve enhancing scalability, user interface optimization and rolling out the platform.