

Electronic Control Systems for Ion Trap Quantum Computers

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Abstract—Ion trap quantum computers are complex optoelectronic systems that require several electronic subsystems orchestrated to sub-1ns precision, both low-noise and high speed. WUT developed a modular control system in EEM/DIOT form factor called SINARA [1].

(Standardised Instrumentation Architecture for Research Applications). SINARA became the de facto standard in atomic and Molecular laboratories worldwide; a few leading quantum computer manufacturers also use it. Its success, which can be attributed to the open-source, open-hardware licensing model, has significantly advanced the field of quantum computing by providing a reliable and adaptable control system. SINARA was primarily developed for lab applications but recently has been transformed into an industrial form factor (DIOT[5]) because many lab projects have turned into spin-offs and startups.

The scaling of quantum computers creates several technological issues. Most topologies are enclosed in a vacuum and use cryogenic temperatures. Future quantum computer architectures need to implement electronic control systems capable of steering hundreds of thousands of electrodes with high precision and relatively high voltage of a few dozen V. Within the framework of the Quanteria SIQCI [3] project, a collaborative effort aimed at advancing the field of quantum computing, we are building a demonstrator of such a scalable control system. An essential step of the design process is characterising a standard 180nm high voltage process at temperatures below 10 K. The next step is updating the process PDK and designing the test structures using updated models. This paper presents the requirements for such a control system, the first results of the measurements and the design methodology.

Furthermore, this talk will unveil the first coherent operations results performed on ions trapped in the WUT labs using the SINARA system, marking a significant milestone in our system's practical applications.

Keywords—FPGA, ASIC, Cryogenics, AMO, Trapped Ions, ARTIQ

I. INTRODUCTION

Scalable, fault-tolerant quantum computers (QCs) will solve certain classes of problems significantly faster than their best classical counterparts. While the ultimate realisation of a fault-tolerant device is considered a long-term goal, noisy intermediate-scale quantum (NISQ) devices are already

available today and are expected to be used, for example, in optimisation tasks, novel material design, or critical processes in logistics, healthcare, and finance. However, current quantum devices cannot be scaled to 1000 qubits or efficiently programmed due to the lack of suitable control systems and software. As a result, the roadmap for building large-scale, universal computing devices faces a key technological “bottleneck.” **The WUT team develops dedicated control systems for ion trap quantum computers. Since 2022, our quantum computer infrastructure has been built based on developed technology[5].** Several key technologies are necessary to create a multi-thousand-qubit ion trap quantum computer:

Advanced cryogenic ion trap with integrated optics (photonic integrated circuit), ion transport electrodes (QCCD) and readout sensors, capable of trapping and manipulating of hundreds of thousands of ions

Scalable, low-noise electronic circuits tailored for ion transport operations such as moving, splitting, and merging sub-registers within segmented traps at room temperature and under cryogenic conditions;

Efficient compilation of quantum algorithms based on low-level instruction sets for segmented QPU units, optimizing algorithms with more than 100 qubits.

II. SINARA CONTROL SYSEM

A. Introduction

SINARA is a modular, open-source measurement and control hardware ecosystem designed for quantum information processing applications that require deterministic, high-precision timing. It is based on industrial standards and consists of over 50 digital and analogue input and output modules. The hardware is controlled and managed by ARTIQ [2], an open-source software system for experimental control that provides nanosecond timing resolution and sub-microsecond latency via a high-level programming language. The measurement and control systems used in quantum physics experiments suffer several problems. In general, an improvised solution is built in-house without enough consideration for good design,

Several grants and contracts funded this research: NESTER (MAZOWSZE/0153/1900), DOB-SZAFIR/01/A/023/01/2020, IDUB-POB-FWEiTE, QUANTERAI/1/80/SIQCI/2022, POIR.01.01.01000553/20



reproducibility, testing, and documentation. It makes those systems unreliable, fragile, difficult to use, maintain, and reproduce in other labs, and hard to repair. It also duplicates work in different laboratories. Also, the performance and features of the existing systems (e.g., regarding pulse shaping and synchronisation abilities) are becoming insufficient for some experiments.

Sinara and ARTIQ projects address the above issues by providing a collaborative hardware and software environment that is both open-source and commercially available from multiple vendors. The community involved in the Sinara project has successfully developed over 100 boards and modules over the last eight years. Some are already commercially available, with most of the rest to follow. Nearly all modules were developed at the WUT, most of which were designed by the Author. The design of SINARA is indebted to much prior work on control hardware and software by the ion-trapping community. Currently, SINARA is the leading control system in the AOM community, and several quantum computing vendors use it as a foundation for their systems.

B. SINARA ecosystem

The Sinara ecosystem offers a nearly complete set of modules performing the following functions:

- System controllers
- Analogue to digital and time to digital converters
- Digital to analogue converters
- Servos and regulators
- Fast digital Inputs and Outputs
- Camera and optical sensor interfaces
- Arbitrary Waveform Generators (AWG)
- Radio Frequency and DDS synthesisers
- RF, low frequency, and HV amplifiers
- Low-voltage and high-voltage power supplies
- Various adapters and converters

III. ION TRAP QUANTUM COMPUTER SCALING

Practical, real-life problem-solving algorithms require hundreds of thousands of qubits. While the standard, modular SINARA system addresses most quantum computer needs, it fails to deliver signals for future ion trap processing units. Existing and near-term quantum computers up to 1000 qubits are built on the existing SINARA ecosystem, including 32-channel DAC cards, but such a solution is not scalable due to several reasons:

- Difficulty in delivering millions of signals to cryogenic QPU
- Physical space and power needed for hundreds of electronic racks
- Noise limitation of room-temperature electronics, essential for high-fidelity qubits

Due to those constraints, WUT develops dedicated ASICs within the Quanteria SIQCI project.

Those ASICs need to address the following issues:

- Operation at 4K in ultra-high vacuum
- Offer scalability to millions of DAC channels
- Provide high voltage operation of at least $\pm 20V$
- Consume very low power, the entire cooling budget at 4K is a few Watts
- Provide ultra-low noise, at least 16-bit precision and very low drift
- Integrate with the SINARA/ARTIQ ecosystem

The WUT team developed and succeeded in tape-out and cryogenic measurements of the first test ASIC, which includes DAC and test structures. The second, multi-channel DAC is being finalised and will be sent for tape-out in June.

ACKNOWLEDGMENT

I want to thank the entire Sinara and the ARTIQ community, without whom this project wouldn't exist. Special appreciation to: David Allcock, Chris Ballance, Tim Ballance, Sebastien Bourdeauducq, Joe Britton, Ken Brown, Stanisław Hanasz, Tom Harty, Robert Jordens, Anna Kaminska, Marcin Kiepiela, Paweł Kozakiewicz, Paweł Kulik, Jakub Matyas, Jonathan Mixrahi, David Nadlinger, Christian Ospelkaus, Krzysztof Pozniak, Maciej Przybysz, Drew Risinger, Daniel Slichter, Ana Sotirova, Mikołaj Sowinski, Filip Switakowski, Zbigniew Wawrzyniak, Weida Zhang, Konrad Norowski, Krzysztof Siwiec, Dominik Kasprowicz, Tomasz przywózki, Adam Borkowski, and others involved.

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