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QICK workshop 2023 summary

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The first open source Quantum Instrumentation Control Kit (QICK) workshop was held at the Fermi National Accelerator Laboratory (Fermilab) on January 12, 2023. The workshop had an attendance of about 150 participants from Department of Energy laboratories, over 30 academic institutions, and over 10 companies. The workshop was also attended by international research institutions and companies from 10 different countries. The goal for the workshop was to invite most of the leading labs and companies working in Quantum Information Science (QIS) who also have a strong interest in open source, highly integrated control and readout systems, such as QICK. Although QICK is in use in many of those labs and companies, a growing interest from the community in the QICK platform poses new challenges for the development team. The workshop aimed to highlight recent accomplishments at the labs and companies as well as to make a roadmap for controls based on QICK. Outlining these achievements, new challenges, and priorities are the main goals of this document.

CONTENTS

I. INTRODUCTION

This document summarizes some of the highlights and priorities for the QICK open source qubit control and readout system, as found and requested during the workshop held at Fermilab on January 12th, 2023. The QICK workshop brought experts in QIS (Quantum Information Science), including quantum computing, quantum networking and quantum sensing, to Fermilab to outline a roadmap of their R&D and determine requirements and priorities for QICK. A roadmap for QICK and collaborative efforts are being developed. Some of the priorities are clear and outlined in this document. Other priorities, collaborations and opportunities continue to come up and need more time to be developed and consolidate. As a consequence, there is a part of the roadmap that includes clear deliverables for labs and institutions to make use of the system with minimal interface with the QICK team. There is also part of the roadmap that includes the evolution of QICK to suport new initiatives, e.g. new qubits, larger systems and new requirements and functionality. We expect and are aware that new ideas are in development due to presentations and discussions that happened during the workshop.

For those who are less familiar with the platform, a guide to QICK can be found in the first-generation QICK controller publication in the Review of Scientific Instruments [1] (the arXiv version is available here).

The QICK workshop featured presentations from key speakers from academia, DOE labs and invited companies, as well as time for discussions and new ideas. Workshop registration was open to the entire community, but the academic talks and company talks were by invitation only due to preparation time constraints. We expect a follow up workshop, likely a year from the first one, with a different organization depending on the evolution of the rapidly-growing QICK community. The workshop priorities and requests could be itemized in several ways. For instance, requests could be itemized by area of application, e.g. for quantum computing, quantum networking and quantum sensing. We could also include in that list the non-quantum sensors that require very similar readout (e.g. MKIDs, fMUXed TES, broadband RF, etc.). Alternatively, we could itemize requests based on the specific qubit or sensor technology, e.g. superconducting qubit and sensors, atom and ion systems that require laser feedback control and atom manipulation, and systems that require time critical measurements such as quantum networks and detectors based on SNSPDs. Finally, we could itemize requests based on the main components needed in a specific application, or technology, e.g. hardware, firmware and software. This summary will outline the status of the development of QICK in several areas of applications and then move to an itemized list based on hardware, firmware and software.

A main objective of the workshop was to allow for collaborative efforts to evolve. We should use the findings in this document, and the information presented by the speakers as a guide to fulfill that objective. For convenience, we have extracted some relevant information concerning controls from the talks and added as an Appendix to the end of this document. For detailed information about experiments and applications, please see the workshop talks, which can be found at the QICK workshop Indico page [2]. Here we have only extracted what we considered essential to shape a roadmap for QICK development.

II. STATUS OF THE QICK PROJECT

QICK currently supports three hardware platforms that use AMD-Xilinx evaluation boards holding an RFSoC FPGA: the ZCU111 (8 in/out channel), the ZCU216 (16 in/out channel) and the RFSoC4x2 (2 out/4in channels) [3]. Only the ZCU111 has an analog RF- and DC-coupled companion board, designed by Fermilab, that allows the QICK to be connected to an experiment practically without requiring any external components at room temperature. A similar companion board is under design at Fermilab for the ZCU216 board. Current hardware, firmware, and software files and documents can be accessed in the QICK Github repository [4], and documentation through the QICK Read the Docs site [5].

QICK started as a collaboration among Fermilab, University of Chicago and Princeton with the majority of the hardware and firmware developed at Fermilab and the software development shared by all collaborators. The original experiments were run at the laboratories of Professor David Schuster (U. Chicago, now Stanford) and Professor Andrew Houck (Princeton). Since the main focus of those labs is on superconducting qubits, most QICK applications were developed for that area of QIS. Although the QICK team is strongly committed to continue the development of that area, it has been made clear at the workshop that the QICK team wants to make progress in the other areas such as AMOs, trapped ions, critical time sensing, and quantum networking. Given the high degree of overlap in the functionality of hardware, firmware and software for the various QIS platforms, we can more rapidly develop QICK for new platforms by building off of our original work for the superconducting qubit platform.

For instance, controlling a tweezer with AOMs requires many of the firmware blocks already developed for superconducting qubit control (e.g. DDS, memory tables, AWG, tPROC, etc.). Most importantly, the hardware needed is the same. AOM systems require high number of channels for open and closed loops using RF or DC coupled ADCs and DACs, and custom design logic. They are also favored by using the same embedded processor and the PYNQ system. A similar analysis can be done for the large multiplexed arrays of sensors needed for quantum sensing (quantum capacitor detectors, SNSPD arrays coupled to resonators, MKIDs, etc.) for dark matter axion and CMB experiments. In the case of detector applications, QICK already supports working test stands for detector R&D and first physics runs. A similar analysis covers critical time sensor applications for which the QICK system has already demonstrated fast sampling with jitter of 2ps (RMS) for quantum networking and detector applications.

III. PRIORITIES AND REQUESTS FOR QICK

QICK will keep making progress on all fronts depending on available funding and manpower available from the team and collaborations. The main priorities will be evaluated by the QICK team according to:

- Specific QIS areas that need to achieve milestones. We will put emphasis in developing control functionality to help projects meet their deadlines.
- Collaborative efforts. We will prioritize developments in which collaborative efforts with counterpart manpower are in place and it is likely to make QICK and QIS grow.
- Availability of funds and or resources from the team.
- New ideas and opportunities to improve controls.

The list above does not mean to be comprehensive. Below, we detail an itemized list of requests based on hardware, firmware and software.

A. Hardware

1. 16 channel analog frontend for the ZCU216

Hardware design for this project has started. The schematics are complete. The next step is the layout of the boards. The hardware has been split in a motherboard and daughtercards that can be used for RF or DC coupled output and input. The daughtercards each have 4 output channels and 2 input channels. RF and DC coupled outputs and inputs can share a motherboard with up to 16 outputs and 8 inputs.

- A motherboard compatible with the ZCU216. The motherboard will host ZCU216 mating connectors, most power management devices, SPI control, system safety circuitry and 8 channels of 20 bit DACs for qubit/sensor biasing with a dynamic range of 0-10 volts per output.
- RF DACs output daughthercard (with 4 channels). Includes RF amplification up to 10GHz, step attenuation and band-pass filtering.
- DC DACs output daughtercard (with 4 channels). Includes amplification up to 1.5GHz and filtering.
- RF ADCs input daughtercard (with 2 channels). Includes RF amplification up to 10GHz, step attenuation and band-pass filtering.
- DC ADCs input daughtercard (with 2 channels) . Includes amplification up to 1.5GHz and filtering.

Our hardware timeline is to have prototypes ready and tested by mid 2023, and production of 50 boards within 3-6 months after that. There is risk associated with our timeline: due to the worldwide IC shortage, parts need to be purchased before production. It is also not clear how to centralize the hardware production, distribution and payment.

2. RFSoC evaluation boards

The QICK team will continue supporting firmware and software for the three RFSoC evaluation boards (the ZCU111, ZCU216, and ZCU4x2).

B. Firmware

1. *QICK-AMO*

The workshop has made clear that there is a strong interest in QICK from the atom/ion community. We need improved support for optical experiments. This includes feedforward and feedback loops for tweezers and laser system control (e.g. laser actuators, EOMs and AOMs). Some new IP blocks are needed to control AMO systems, but most of the new blocks can be based on modifications of existing blocks. That makes the task simpler.

2. *New IP blocks*

An important goal for the firmware is to keep creating an IP block library that can be shared among applications (e.g. tPROC, complex (I,Q) RF and DC signal generators, FIR and IIR filters, PID and other type of controllers, timing blocks, data buffers, data averagers, multi-board communication and synchronization, etc.). Some of the blocks that have yet to be developed or improved include:

- FIR filter for fast flux. We need to define filter parameters.
- Multi-board experiments. A communication protocol needs to be adopted (e.g. White Rabbit or a simpler open source protocol). We need to demonstrate a multi-board system working with qubits. Currently, the ZCU216 can be used to control up to 16 non-multiplexed outputs. A QICK system with 100 control lines or more should be easily achieved in 2023. Devices with 100 qubits are already available at some companies (IBM, Rigetti) and could be implemented in the near term by some academic labs (Schuster lab at Stanford).
- Interpolated, parameterized signal generator waveforms. The advantages of interpolated, parameterized waveforms is compactness in memory use and that the same template waveform can be used for arbitrary pulse lengths and amplitudes. Examples have been developed for Gaussian pulses using third-order splines. Output noise needs to be characterized with qubits and compared with performance from table based waveforms.
- Direct to RAM saving of ADC data. We need to define the amount of data buffer needed. Large data buffers may need to use the DDR4. The DDR4 throughput is limited to $\approx$ 12Gb/s.
- Better trigger engine. We need to define “better". More outputs? Better management from tPROC?
- Use of realtime processors. Define the need for real time and compare vs. the new (soon to be released) tPROC. If the R5 RISC processor is used, what would be the function and interface with the tPROC(s) and the ZYNC processor?
- Reconfigurable modules. That is doable but it will likely require compilation using Vivado or other AMD-FPGA software.
- Crosstalk compensation. This is a high priority function. It requires a new IP block in the form of a complex matrix among channels that experience crosstalk.
- Optimal filter to accelerate readout. Simulations exist. The goal is to speed up readout and minimize the effect of qubit relaxation or excitation during the readout.
- Pulse generation and control for fast timing. Those functions have been implemented in the context of quantum networks at Fermilab. That framework needs to be expanded to multi-channel and other configurations.
- Improved SNSPD detection. New IP blocks to be able to readout SNSPD arrays.
- QICK VNA / Signal Analyzer. This application has been developed with up to 512 channels. It is being tested at U. Wisconsin (McDermott lab).
- Fast real-time scope. The rudiments for a real time scope are developed. More specifications are needed.
- Analog noise performance. The current analog noise is given by the noise of the first LNA on the RF board and its noise temperature is $\approx$ 150 K.
- More DDR/bandwidth. Limited to $\approx$ 12Gb/s on ZCU216 and ZCU111.
- Temperature stabilization. Can be achieved using temperature controlled racks (e.g. used in accelerator RF electronics), RMS $\Delta T \approx 0.5$ C.

C. Software

The current QICK software (based on PYNQ and Python notebooks) is user-friendly and allows the user access to the full firmware functionality. Basic and low level Python programming allows the user to execute medium complexity experiments. The software has been optimized for speed. New drivers have or are being developed for the new tPROC (soon to be released). A nice software accomplishment has been a collaborative effort between Amazon AWS and the QICK team that has enabled remote serving through the AWS cloud. We expect this project to continue being supported. This project also shows how DOE labs and companies can work together in open source controls for QIS.

Software is the QICK component that currently requires the most development given the large scope of QIS tasks, layers, and applications. On the other hand, software is the QICK component that can most easily be developed by collaborations, sometimes even without access to the hardware. Some of the current software tasks are to develop interfaces and middleware that enable access to QICK from existing powerful open software for quantum (e.g. OpenQASM 3, Qiskit and Amazon Braket).

- Develop middleware for multi-board quantum programming. IBM will release open source QSS. This is an interesting approach that we want to pursue. It will enable high level software (e.g. Qiskit) to control multi-board QICK systems.
- Develop middleware for interfacing to OpenQASM 3, Qiskit and Amazon Braket.
- Develop software for low latency program switching.
- Improve remote serving (AWS/direct).
- Develop experiment libraries. Those libraries could include typical calibration procedures, no proprietary data.
- Develop software framework for VNA and fast scope instrumentation.

IV. QICK DOCUMENTATION

The QICK documentation is available on the QICK GitHub and Read the Docs webpages [4, 5]. More documentation will be added and released as it becomes available. At the workshop, users requested more comprehensive documentation for both the QICK software and the QICK firmware IP blocks.

V. HIGHLIGHTS OF REPORTED EXPERIMENTS USING QICK

From the project's origins, the QICK team has not only sought to make a cost-effective open source qubit control system but also to enable new QIS experiments. QICK aimed to add new functionality and improve the outcome of measurements by designing a system that intimately integrated classical control with a quantum system. In this section we highlight only few comments from the most experienced QICK users and results at their labs.

Professor David Schuster (Stanford, formerly at U. Chicago): "I can certainly say that using the QICK has not just let us do experiments more cheaply but has changed the way we think about control and that we do things differently now". Professor Michael Hatridge (U. Pittsburgh): "With QICK we can now do long experiments, detailed data, no recalibration (as long as the quantum device itself is stable). Reset in DDS eliminates 'history' of phase in virtual generators. It is important that the DDS implementation not inherit flaws from previous hardware. QICK succeeded where other control systems failed" (see pictures below). Professor Jeff Thompson (Princeton): "QICK achieved laser pulse stabilization with rapid convergence, negligible drift. Long term stability limited by optical components used to pick off reference beam for stabilization."

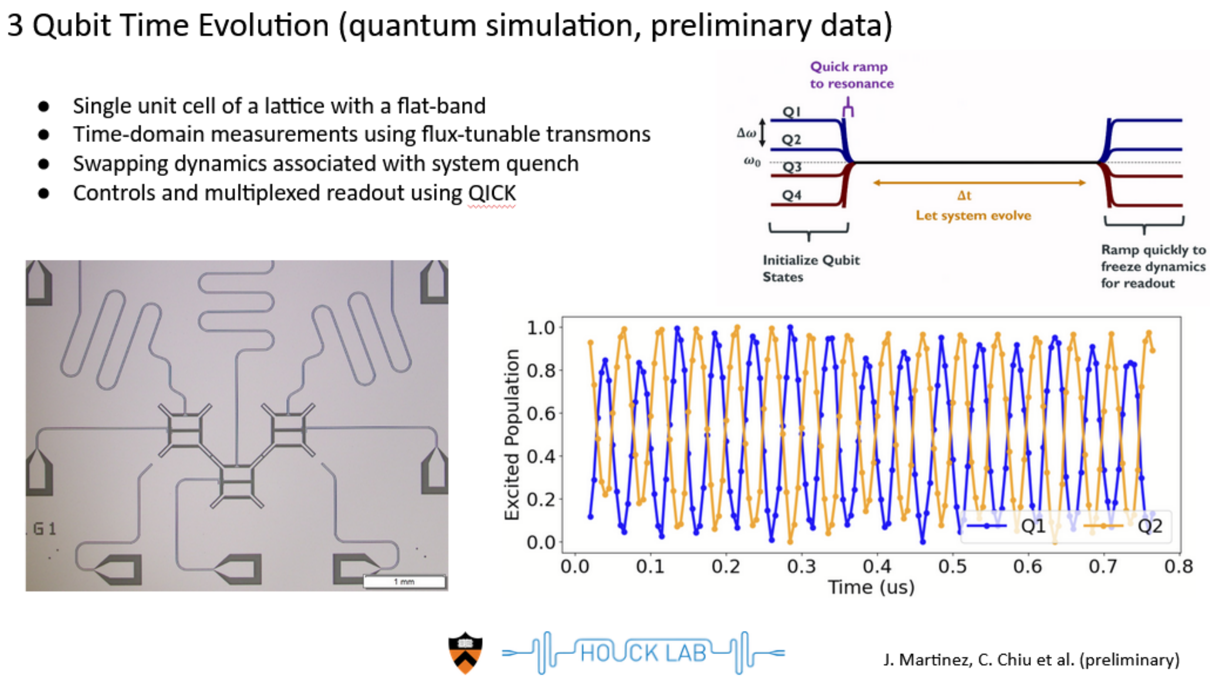

FIG. 1. The picture shows a three-qubit system from the Houck lab that was measured with the QICK ZCU216 board. Most recently, a four-qubit system has been measured. Fast-flux step pulses are used to quench the system (upper right), resulting in SWAPs within the qubit system. The high time-resolution of QICK allows for custom pulses to compensate for fridge line distortions. The SWAPs shown on the right are done with uncompensated fast flux pulses.

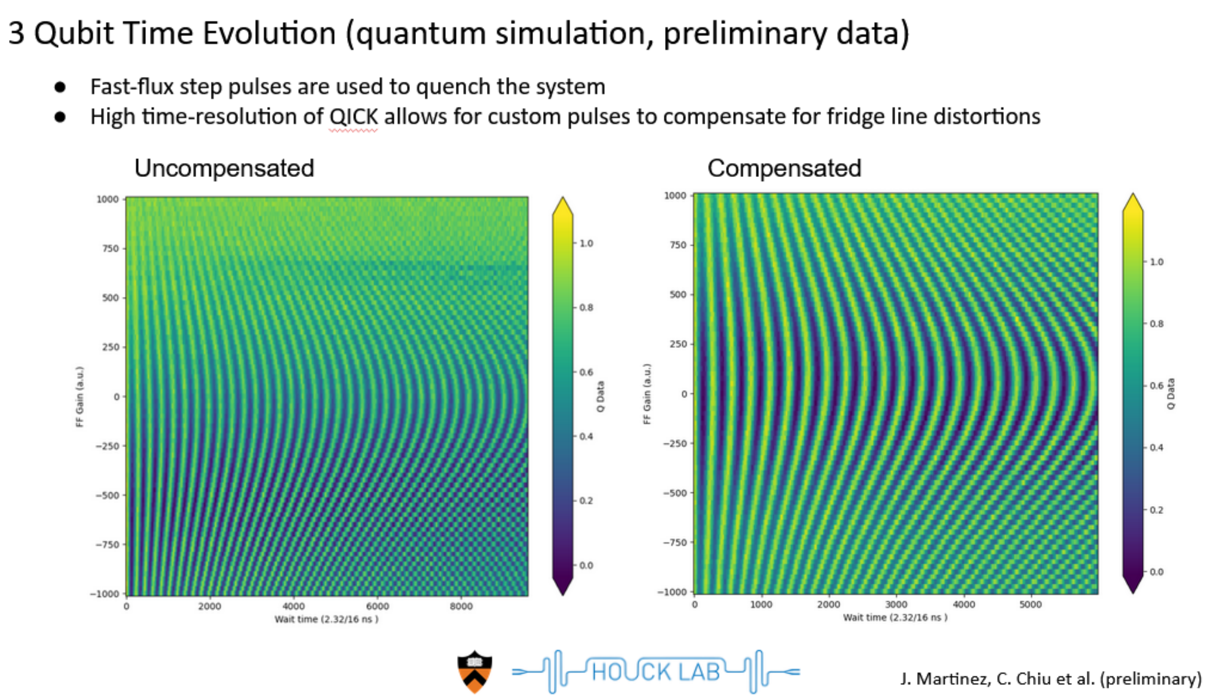

FIG. 2. Also from the Houck lab four-qubit sample that was measured with the QICK ZCU216 board. a) SWAPs between qubits with uncompensated fast flux pulses. b) Fast flux pulses used to SWAP qubit population are now compensated using QICK fast time resolution.

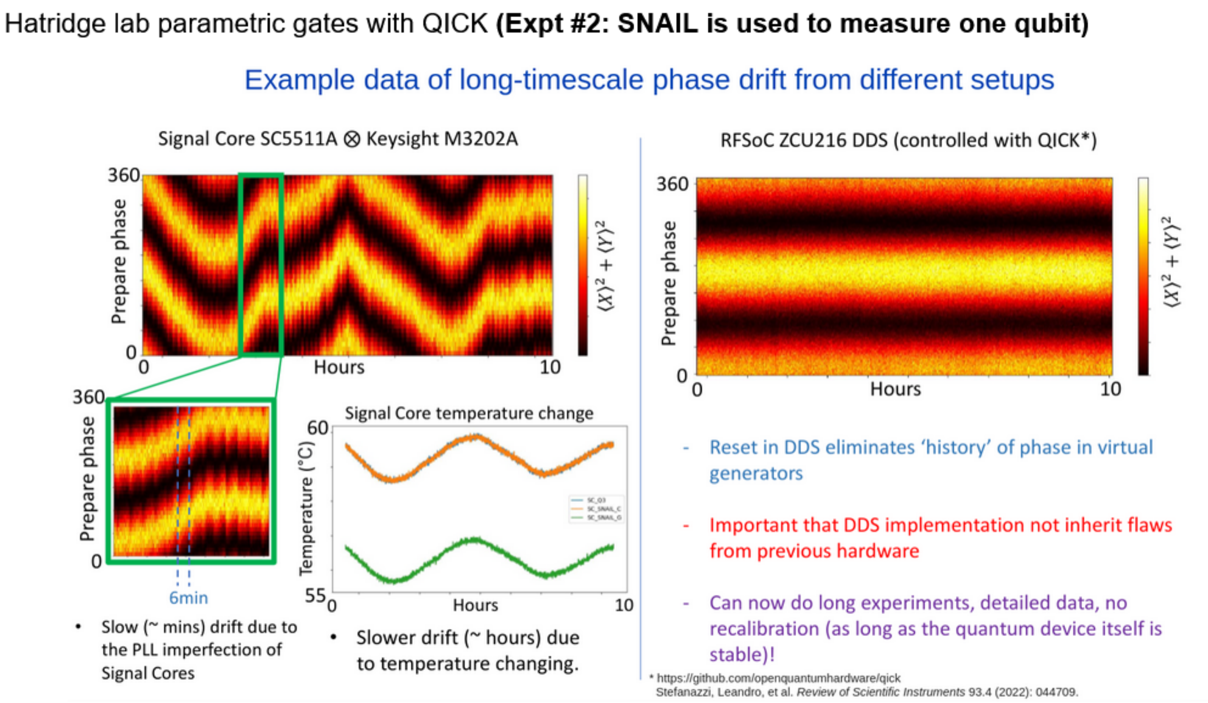

FIG. 3. Functionality added to the control of the phase in the QICK system allows for very long time stabilization. The new phase control requires careful design of clock boundaries in the FPGA firmware. This functionality is only found in the QICK. A comparison at the Hatridge lab shows the problem of phase drift (left) and the performance of QICK phase drift (right) for a measurement spanning 10 hours.

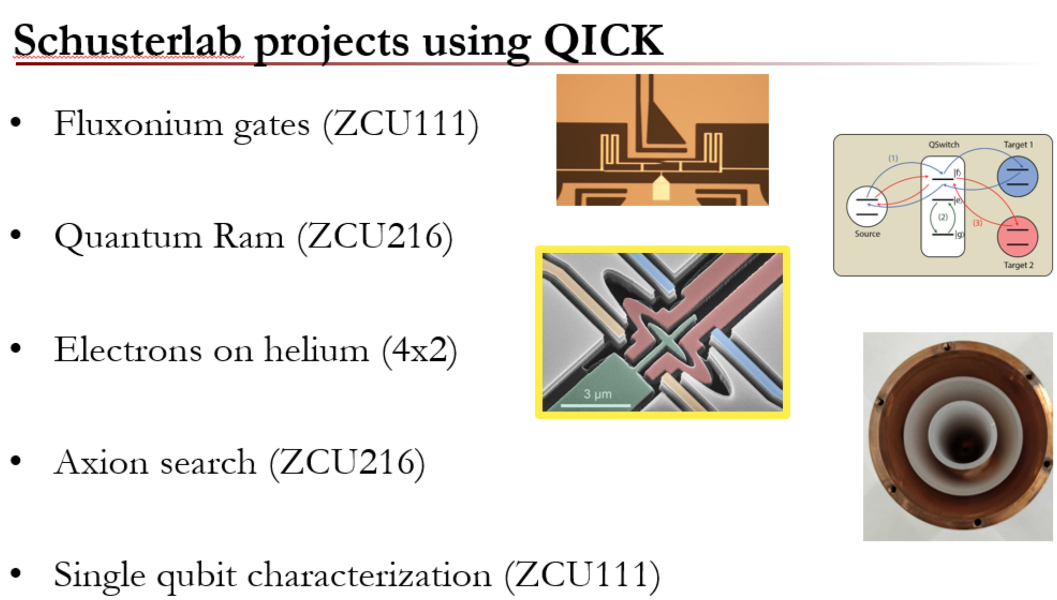

FIG. 4. The Schuster lab projects that currently are controlled by QICK boards.

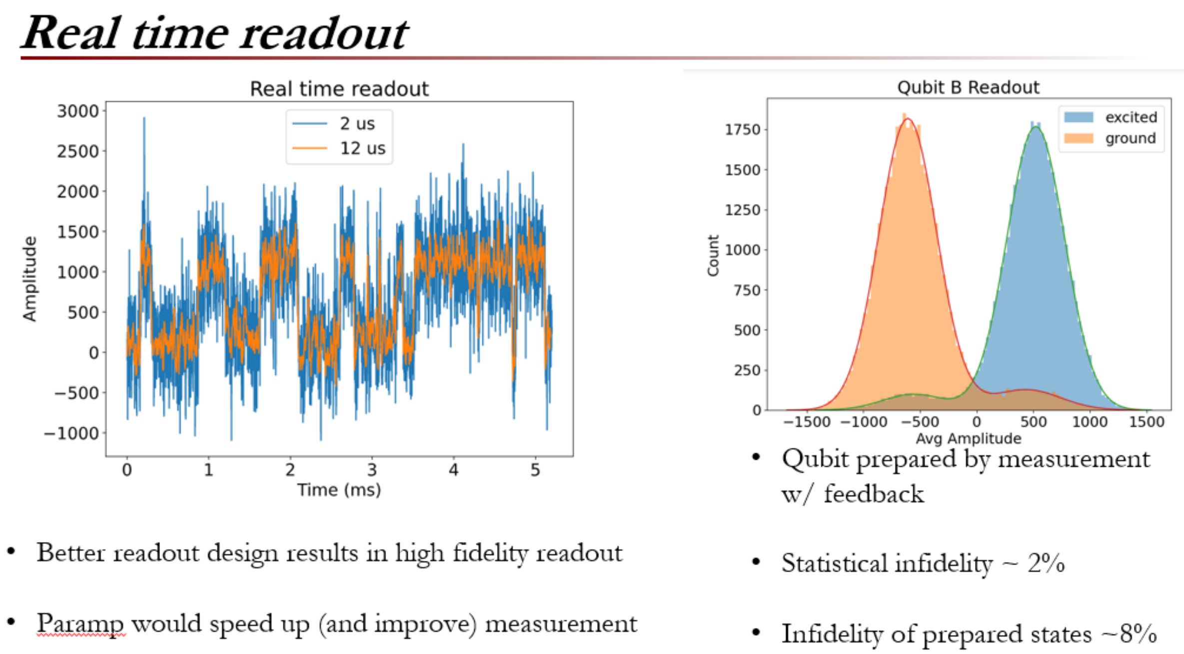

FIG. 5. This data is from a Schuster lab parametric gate project for fluxonium qubits using an inductive coupler. It requires three flux drives and two readouts. All the control was implemented using a single QICK ZCU111 board. Each qubit is read out with high fidelity.

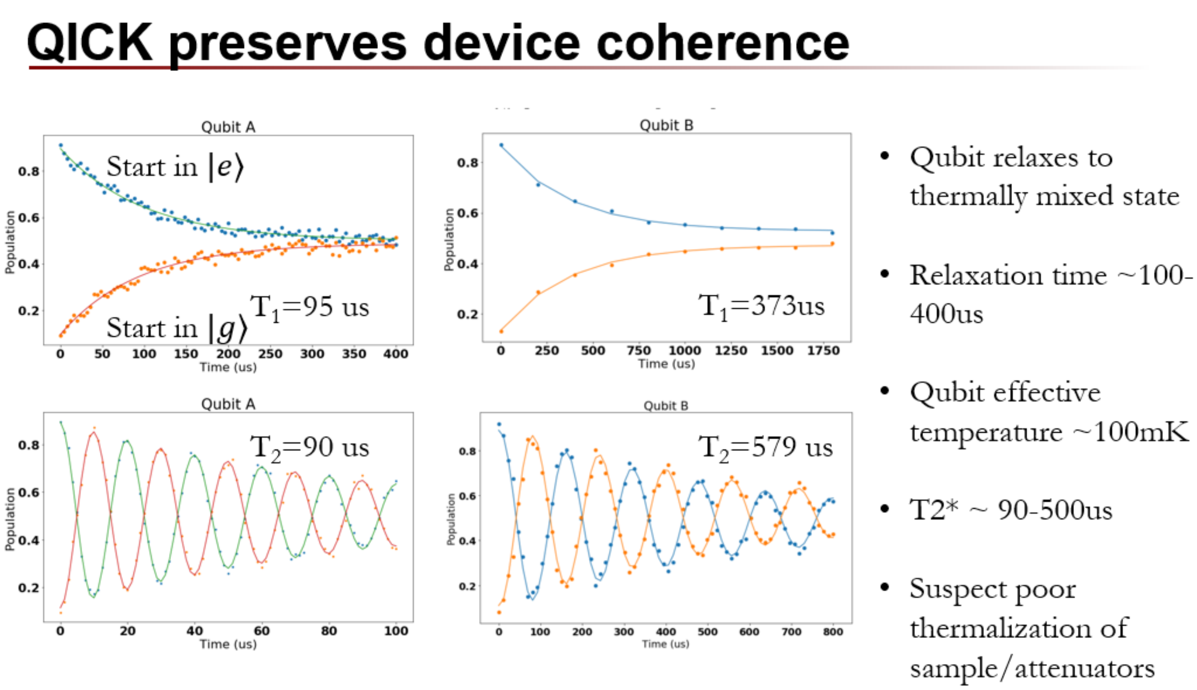

FIG. 6. Also from the Schuster lab fluxonium gate project. The QICK preserves the device coherence, which is thought to be limited by thermalization.

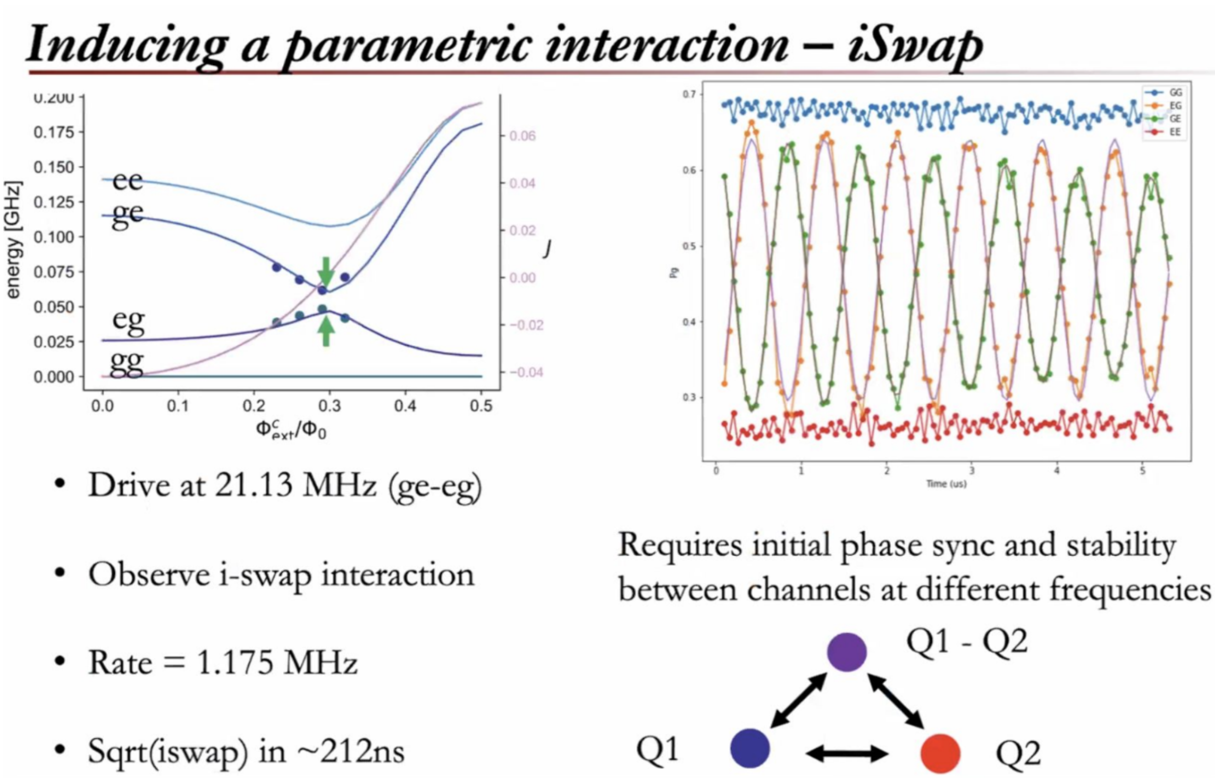

FIG. 7. Also from the Schuster lab fluxonium gate project. Inducing a parametric iSWAP entangling gate in ≈ 212ns.

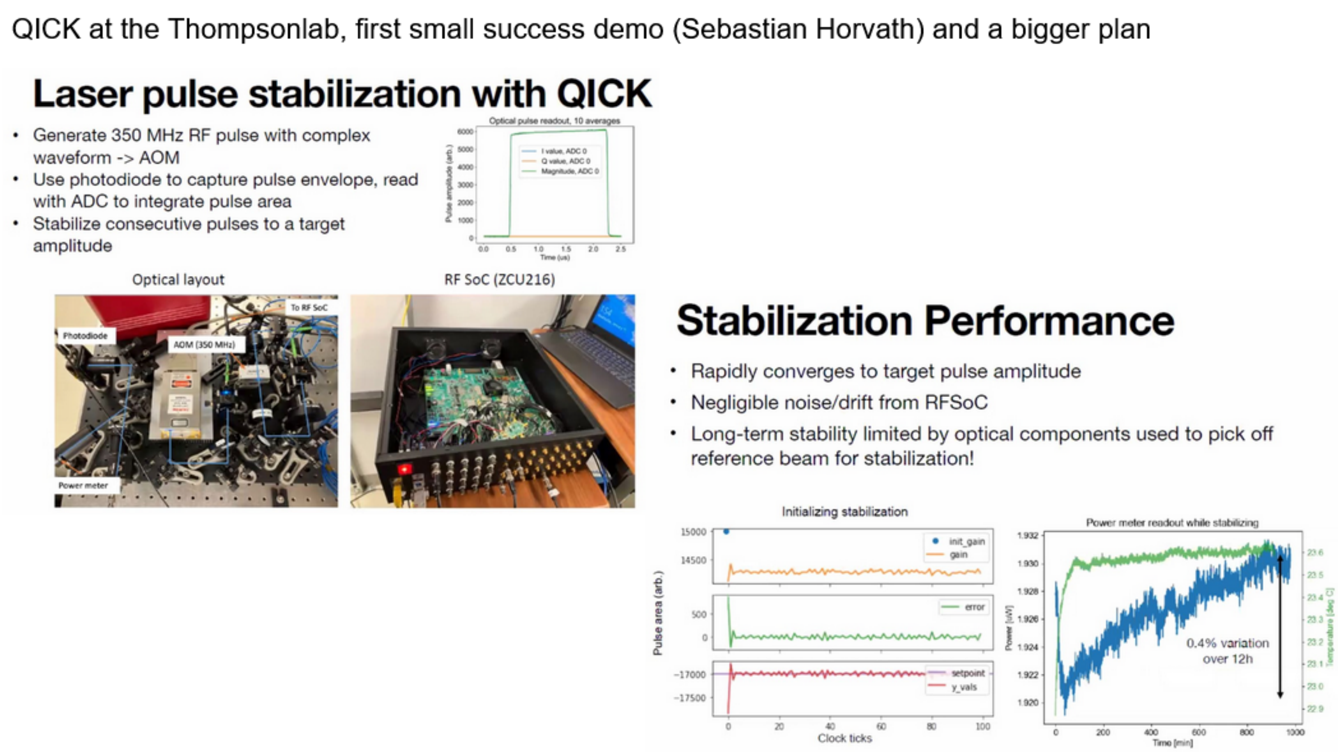

FIG. 8. Pulse to pulse amplitude stabilization achieved at Jeff Thompson's lab (Princeton). QICK achieved laser pulse stabilization with rapid convergence, negligible drift. Long term stability limited by optical components used to pick off reference beam for stabilization.

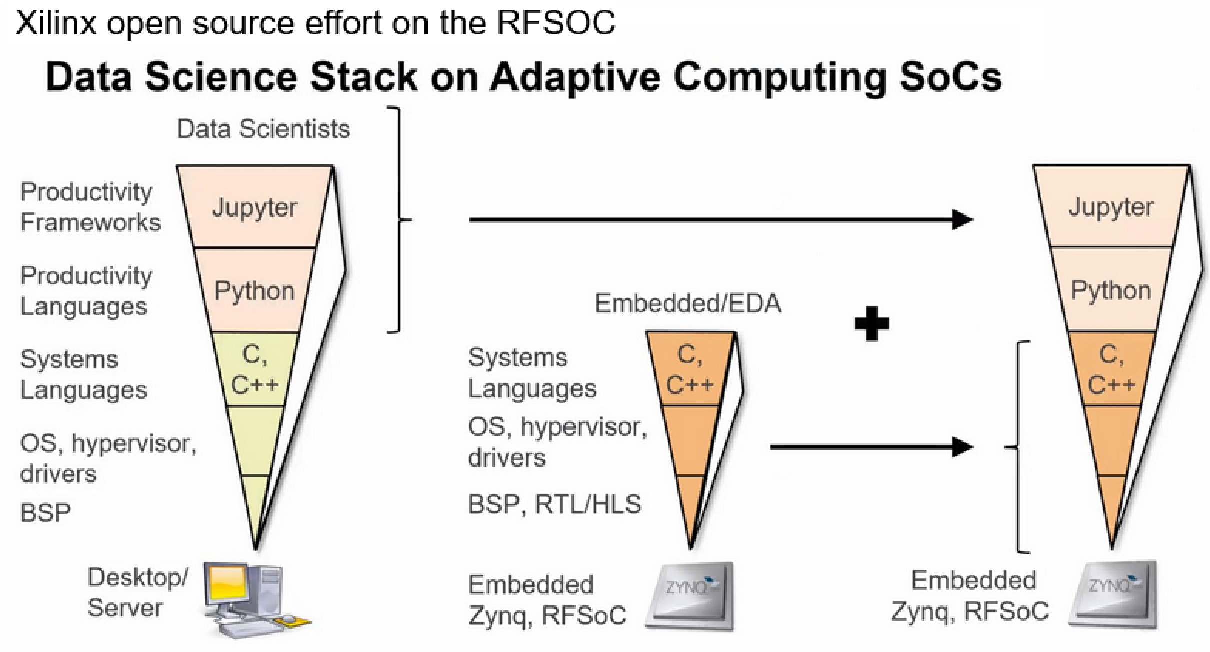

FIG. 9. AMD-Xilinx approach to data science has modified the way we do embedded programming and data acquisition. The company has developed the PYNQ system and migrated Python quantum programs into the FPGA. The RFSoC has a powerful 4-core ARM processor able to run Jupyter notebooks through the PYNQ interface and Linux OS.

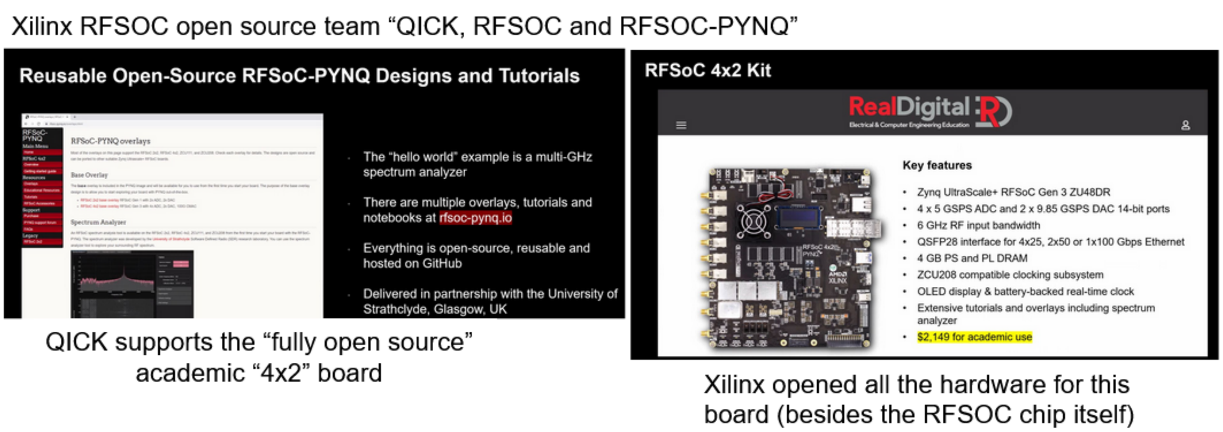

FIG. 10. AMD support is very important for the QICK project since RFSoC FPGAs are used in the QICK design. AMD has decided to open source the 4x2 hardware board that targets University research. All artwork and firmware is open source. The system is accompanied by tutorials and demos.

Appendix A: Workshop registration list

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Appendix B: Workshop agenda

Session	Speaker	Time
Welcome to Fermilab	*Dr Joe Lykken*	08:45 - 08:53
QSC welcome	*Dr Travis Humble*	08:53 - 09:00
Workshop objective	*Gustavo Cancelo*	09:00 - 09:15
QICK overview	*Leandro Stefanazzi*	09:15 - 09:35
Control of superconducting systems	*Dr Andrew Houck*	09:35 - 09:50
control of 3D superconducting qubit systems	*Dr Hatridge Michael*	09:50 - 10:05
Control at Cleland's lab	*Dr Haoxiong Yan*	10:05 - 10:20
Control of 2D and 3D superconducting qubit systems at SQMS	*David van Zanten*	10:20 - 10:35
QICK workshop session: Coffe break		10:35 - 10:50
Future experiments, a path to NISQ	*Dr David Schuster*	10:50 - 11:05
Questions and discussion		11:05 - 11:20
Laser and cavity control for GQuest	*Dr Lee McCuller*	11:20 - 11:35
Controls for atoms and ions	*Dr Jeffrey Thompson*	11:35 - 11:55
Control at Awschalom's lab	*Dr Yeghishe Tsaturyan*	11:55 - 12:10
Discussion and questions		12:10 - 12:25
QICK workshop session: Lunch		12:25 - 13:00

FIG. 11. QICK workshop agenda part 1 of 2 [2]

Time	Session	Speaker
13:00 - 13:15	**Overview of controls for quantum networks**	*Cristián Peña*
13:15 - 13:25	**Activities at Bernien lab**	*Dr Conor Bradley*
13:25 - 13:35	**Discussion and questions**	
13:35 - 13:50	**Quantum sensing control**	*Dr Aaron Chou*
13:50 - 14:05	**Activities at Matt Shaw's lab**	*Dr Matthew Shaw*
14:05 - 14:10	**Discussion and questions**	
14:10 - 14:25	**qolab and U. Santa Barbara**	*Dr John Martinis*
14:25 - 14:40	**QICK workshop session: Coffe break**	
14:40 - 14:55	**Rigetti talk**	*Dr Glenn Jones*
14:55 - 15:10	**AWS talk**	*Dr Jeff Heckey*
15:10 - 15:25	**IBM Controls**	*Dr Thomas Alexander*
15:25 - 15:40	**AMD-Xilinx talk**	*Dr Patrick Lysaght*
15:40 - 15:55	**ColdQuanta talk**	*Dr Ryan Jones*
15:55 - 17:00	**QICK workshop session: Meeting with DOE centers and University PIs and companies**	*Dr David Schuster*
15:55 - 17:00	**QICK workshop session: QICK demo and technical Q&A**	*Chris Stoughton, Leandro Stefanazzi, Martin Di Federico, Sho Uemura*

FIG. 12. QICK workshop agenda part 2 of 2 [2]

Appendix C: Workshop photos

FIG. 13. On site attendance at the QICK workshop for Professor David Schuster's talk.

FIG. 14. On site attendance at the QICK workshop for Dr. Haoxiong Yan's talk.

Appendix D: Extracted from presentations

1. Andrew Houck, Princeton

- Active control of fluxonium: fast flux pulses, post-selection, single shot readout > 90% fidelity. This is the first scientific publication to use the QICK [6]. Following the QICK workshop, this publication was accepted with minor revisions to Phys. Rev. Applied.

- Fast-flux step pulses are used to quench the system in a quantum simulation experiment with four transmon qubits. The high time-resolution of QICK allows for custom pulses to compensate for fridge line distortions [7] (see Figures 1 and 2).

- Houck lab control priorities include: Automated tune-up of qubit systems, consolidating a lab-wide QICK qubit measurement library, moving towards fully automated tune-up for faster sample turnaround, Highly-multiplexed readout (emulating a VNA, measuring many resonators in parallel). The goal for that is to become significantly faster and more reliable than using a VNA for multiplexed resonator chips. Working on establishing better overall SNR even at extremely low drive powers, Compensated fast flux pulses for fluxonium, tunable transmons, etc. and efficient, low-latency two-qubit randomized benchmarking. Continuing collaboration with Schuster lab two-qubit team on this.

2. Michael Hatridge, U. Pittsburgh

- The Hatridge lab quantum router experiment (four transmons with all-to-all coupling through a central SNAIL) is using the QICK in their follow-up work after initial demonstration in [8]: the parametric iSWAP entangling gate utilized in the router requires extremely stable and time-critical phase reset for the various drive DDSes. This will eliminate the 'history' of phase which shows up in other control hardware. It is important that DDS implementation not inherit flaws from hardware previous runs.

- For another experiment involving reading out a transmon using a SNAIL [9], QICK was shown to outperform other control hardware (see Figure 3) when it came to this stable phase reset for the various drive DDSes. The Hatridge lab can now do long experiments and collect detailed data with no recalibration (as long as the quantum device itself is stable)!

3. SQMS, Fermilab

- Focus Area 1: Materials. Goal: Understand and mitigate the key mechanisms of decoherence in superconducting qubits and SRF cavities. 2D test resonators and qubits to characterize improved performance with each fabrication and material stack! 3D cavity characterization.

- Focus Area 2: Devices. Goal: Device performance test, integration and quantum controls development towards high coherence 2D and 3D SC architectures. Round robin experiment. 3D SRF qubit experiments.

- Focus Area 3: Physics and Sensing. Goal: Exploit the center technological advancements for fundamental physics to develop and deploy search schemes with detection sensitivity orders of magnitude compared to state-of-the-art. Dark photon experiments (double SRF cavities). Axion search (cavity + qubit).

- Focus Area 4: Science. Goal: Investigate and develop quantum algorithms and simulations enabled by the groundbreaking SQMS 3D and 2D prototypes through co-design principles. Multi-qubit 2D QPU devices from Rigetti and FNAL to run algorithms.

- SQMS planned use and development related to QICK: Acquired 12 QICK boards (11 ZCU216 and 1 ZCU111) and expect to get more later. Intended use for standard 2D qubit char. experiments (among others e.g. KS Gen2 and QM). Potential use for 16+ qubit QPUs (assuming sync. and data over SFP28). Develop deeper memory depth per channel (perhaps DDR). Develop integration into testbed-wide acquisition software (Labber/QCoDeS/Acquirius). Characterizing synced DAC/ADC firmware for down-converted readout.

- QICK complexities and challenges. Fragmentation of firmware existing in the wild (number of gens, multiplexing, etc). Lack of documentation of new features and IPs. No existing integration with lab acquisition frameworks. Limited memory depth (mostly for DAC). Synchronization beyond two boards.

4. David Schuster, Stanford

- Digital vs Analog signal synthesis: Used to think about local oscillators and mixing of specific frequencies in limited bandwidths combined for control. Now can think in V(t) or for efficiency digital versions of the analog processes that behave ideally. Even for things we could do before QICK has changed the way we think! See Figure 4.
- Real time readout: Better readout design results in high fidelity readout. Qubit prepared by measurement w/ feedback. Statistical infidelity $\approx 2\%$. Infidelity of prepared states $\approx 8\%$. See Figure 5.
- QICK preserves device coherence. Relaxation time $\approx$ 100-400us. Qubit effective temperature $\approx$ 100mK. T2* $\approx$ 90-500us. See Figure 6.
- Inducing a parametric interaction – iSWAP: Drive at 21.13 MHz (ge-eg). Observe iSWAP interaction in $\approx$ 212ns. Rate = 1.175 MHz. Tuneup is a work in progress (process tomography, two-qubit randomized benchmarking, etc.). As discussed by Prof. Hatridge, requires initial phase sync and stability between channels at different frequencies. See Figure 7.
- QICK capabilities to build for future:
  - Firmware: Improved support for optical experiments. FIR filter for fast flux. Multi-board experiments. Interpolated / spline based waveforms. Direct to RAM saving of ADC data. Better trigger engine. Use of realtime processors. Reconfigurable modules. Crosstalk compensation.
  - Hardware / Analog Frontend: Modular quantum control frontend. QICK VNA / Signal Analyzer. Fast real-time scope. Analog noise performance. More ddr/bandwidth. Temperature stabilization.
  - Software: OpenQASM 3 / Qiskit pulse support. Lower latency program switching. Improved remote serving (AWS/direct). Experiment libraries.
- QICK is exemplar of NQI initiatives: Very difficult to develop these systems in universities. Companies keep developments proprietary. Not general enough to be used for experiments. Can't develop custom modules. DOE engineers (QICK team) had decades of experience solving the exact type of problems that arise in quantum control. Were able to make useful system in <1yr that is now our primary measurement system. QICK developments relevant to non-quantum DOE efforts.
- Challenges moving forward: Very important to make sure we can support these efforts sustainably. Need to continue to develop QICK firmware. Need to develop hardware and make it available. Need to continue higher level software. As more people use QICK need to support users without overtaxing developers/engineers. How can we continue to adapt QICK to more use cases while keeping things manageable (fragmentation). Need continued (and expanded) support from DOE. Equally important need to build robust /collaborative community.

5. Quantum Control Platforms for Gravitational Physics in GQuEST, Lee McCuller, Caltech

How strongly can we probe mirror displacement for gravitational physics? Is squeezed light the best we can do?
GQuEST: Gravity from Quantum Entanglement of Space-Time.

- Achieving quantum-noise limited sensitivity is tough. Acoustic isolation takes a lot of engineering.
- High Frequency signals are ideal when the physics supports them. Many efforts are centered on low-mass dark matter.
- The best experiments test a model, a theory. Ideally, either test result is significant.
- New theory predicting observable signatures of quantum gravity checks the boxes.
- The GQuEST realization
  - Metric fluctuation signal modulates Stokes, anti-Stokes photon side-bands.
  - Use a series of optical filters to select photon sidebands.
  - Requires extreme sideband/carrier contrast $\approx$ 240dB.
  - New interferometer for Raman/Brillouin spectroscopy of spacetime.
- Sensing and control needs
  - Good active and tons of passive isolation of laser noise.

  - Feedback control of interferometer and cavities.
  - Many VCO sources and demodulators.

- The LIGO servo board:
  - The LIGO "Common Mode" board is a generic 2-channel in, 2-channel out servo in analog.
  - Implements 8 custom, toggle-able Sallen-Key filters. Equiv, digital biquad filter (i.e. SoS). Much more aggressive loop shapes than PID. They are conditionally stable!
  - Offsets added at appropriate points
  - Along with testpoint/excitation for loop measurements.
  - Demodulation, mixing done externally with low noise demod boards.
  - Requires $\approx$ 40 binary controls and many analog readbacks (expensive for univ. labs)
- Table-top frequency stabilization servo.
  - Actuates with laser temp, laser PZT, EOM.
  - EOM path is in a short 10ns round-trip for highest bandwidth.
  - Locks two lasers to shot noise of the beatnote to 100kHz or so. Ends up limited by fiber or acoustic pickup between the lasers. Basically makes a secondary laser equivalent to a primary.
  - The VCO on the secondary allows one to then modulate the secondary substantially faster than an AOM for single-sideband modulation.
  - This is a principle of operation for the LIGO in-vacuum squeezed light source and its coherent control system.
- Cross Correlating Spectrum Analyzer
  - Also equipped with a "standard Michelson" readout.
  - Like Holometer, needs multi channel $\approx$ 100MHz time-averaged cross correlations to dig in to noise. Gives resolution that photon counting doesn't.

6. Jeff Thompson, Princeton

- AMO control is a rapidly growing field: 40+ tweezer arrays started in last 2 years around the world. Qubits encoded in atoms in optical tweezers. Dynamically reconfigurable geometry. Gates controlled by light. Interactions using Rydberg states. 16 Acousto-Optic modulators (50-350 MHz).
  - 1/4 are VCOs, 1/4 are AWGs, 1/2 are DDS.
  - 5 Electro-optic modulators (0.1-5 GHz).
  - 4 intensity feedback loops.
  - 8 frequency feedback loops.
- Challenges:
  - Programming, synchronizing many heterogeneous devices
  - Lots of PID loops, challenging to monitor, re-lock, operate on transient signals (ie, sample-and-hold for short pulses)
  - Hard to do conditional program flow: waveform update is slow.
  - Long-term: need for higher-bandwidth image processing and control of many-pixel displays
- Progress has been made setting up a laser pulse stabilization demo with the QICK in the Thompson lab (see Figure 8).

7. Cristián Peña, Fermilab

- Entanglement-based Protocol: Quantum Teleportation.
  - Qubit preparation and stability control
  - Entanglement generation and stability control
  - Time synchronization
  - Bell State measurement
  - Timestamping and Correlation
  - Polarization control
  - Laser and IM control
- Photon arrival time is critical for quantum indistinguishability. Determines the teleportation and swapping fidelities.
- Electronics requirements $\omega \approx$ [10-100] ps; $\delta \approx$ [50-1000] ps; $\Delta \approx$ [100-2000] ps.
- Fast IM (EOM) require: $A \approx$ [1-10] V (coarse). Fine adj. $\approx$ 5-10% of A. 4 channels with adjustable phases (ps jitter)
- Requirements: Clock distribution through optical fiber with <3ps jitter. Produce RF and optical clock signals in 1300-1600nm range. Ability to lock to reference RF and optical clocks on fibers coexisting with quantum signals at 1536nm. Minimizing background rates on quantum channels are of paramount importance, and have identified as important control parameters: Optical clock duty cycle. Amplitude and wavelength of clock signal. Automated time synchronization monitoring and feedback control for time drift.
- Future needs for more advanced Q-Network protocols: Control framework is needed to "operate" the future networks: Teleportation/Swapping control: BSM logic, feed forward logic, etc. Control for Q-repeater functionality: BSM logic, Q-memory control, etc. Feedback controls on various system components : Intensity Modulators, Polarization controllers, HOM logic and time delay controllers, etc. Automated Q-link diagnostics : testing standard protocols across network links, measure standard fidelities, and initiate automatic warnings or corrections

8. Conor Bradley, Bernien lab

- Current Master clock: Adwin Pro II Microprocessor.
  - Generates slow (us-timescale) pulses for trapping, cooling, etc.
  - Generates trigger TTL signals for other hardware.
- Current Single-qubit and two-qubit gates:
  - Modulation waveforms generated by pre-programmed 1 GS/s AWG, triggered by Adwin.
  - 1Q gates: IQ modulate independent MW sources at 6.8/9.2 GHz.
  - 2Q gates (in development): Amplitude/phase/frequency profile applied to AOMs.
- Feedback Operations (re-arrangement and gates): EMCCD image processed on PC, outcome used to re-program 1 GS/s AWG (Spectrum), triggered by Adwin.
- Laser Stabilisation: Independent CW intensity locking circuits based on tap-off photo-diodes, not synced to experiment.
- Key additional requirement:
  - Fast pulses.
  - Cavity-enhanced spontaneous emission timescale $\approx$ ns.
  - Require optical pulse shaping with features on $\approx$ 100 ps timescale.
  - For example using a standalone 4 GS/s AWG driving an EOM.
  - Integrating with the rest of the experiment would be a challenge!.
- Longer term requirement: multi-node experiments will require synchronization. Board jitter should not limit this, e.g. need $\approx$ <10s of ps jitter.

9. Quantum Sensing, Aaron Chou (Fermilab)

96% of the energy budget in the universe has so far been undetectable other than via its gravitational effects. This is the prime experimental target for QUANTUM SENSING! The current understanding of the dark matter landscape. A diverse variety of experimental techniques are proposed to cover every decade of possible dark matter mass. Dark matter of some sort is probably flying through your lab. Does it have interactions stronger than gravity? Sensitive single-quantum devices are operated in a cryostat and/or vacuum system and well-shielded from external disturbances (heat, light, sound) in order to maximize their coherence time.

One detection setup would be a transmon qubit in a 6 GHz aluminum cavity: dark matter waves scatter on walls of cavity, depositing the occasional single photon. Measure quantized AC Stark shift of qubit frequency to ascertain presence of the signal photon.

- Metrology gain vs Standard Quantum Limit for various single photon detectors.
  - Superconducting nanowire single photon detectors
  - Dark Rate R = 10-5 Hz
  - Bandwidth B = 1015 Hz (or smaller if narrow band filtered)
  - Number of modes Nmodes= Area/(wavelength)2 = 102
  - Effective occupation number n = (R / B) / Nmodes = 10-22
  - Effective noise squeezing factor = 1/sqrt(n) = 110 dB
- Quantum capacitance detector (charge qubits)
  - Dark Rate R = 1 Hz
  - Bandwidth B = 1 THz
  - Effective occupation number n = R / B = 10-12
  - Effective noise squeezing factor = 1/sqrt(n) = 60 dB
- Transmon qubits (artificial atomic clock)
  - Effective occupation number n=10-3
  - Effective noise squeezing factor = 1/sqrt(n) = 16 dB

Superconducting devices all suffer from mysterious non-equilibrium quasiparticle population » Boltzmann suppressed $n = e^{\frac{-1.2K}{0.01K}} = 10^{-52}$. These now appear to be created in discrete, time-resolved events with much higher rate than cosmic rays. Low gap materials experience noise due to coupling to background phonons from substrate microfracture events. Non-equilibrium particles are probably not due to dark matter but rather due to mechanical disturbances.

- Next generation qubit-based microcalorimeters will reduce thresholds to milli-eV, provide first look at sub-eV spectrum. Need large numbers of qubit control channels to instrument this microcalorimeter.
- Windchime concept: Accelerometers to sense force from passing dark matter.
  - Larger mass accelerometers needed for detecting gravitational (spin-2) force from DM. Cubic meter array of 109 accelerometers with millimeter spacing to detect force from passing dark matter.
  - Need to control large numbers of sensor/qubit channels for such multi-sensor arrays

10. Matt Shaw, NASA-JPL

- Superconducting Nanowire Single Photon Detectors (SNSPDs) with Low Energy Thresholds:
  - Time-resolved single photon counting from UV to mid-IR. This is a world-leading detector performance.
  - Operating temperature: 1-4 K in most cases.
  - High Efficiency 98% SDE @ 1550 nm (NIST).
  - Low Dark Counts $6e^{-6}$ cps (MIT/NIST).
  - UV–Mid-IR Operation Photon counting from 0.1-18 µm (JPL/MIT/NIST).

  - Kilopixel Array Formats 32x32 “row-column” with thermally coupled imager (NIST/JPL).
  - High Time Resolution 2.6 ps FWHM (MIT/JPL/NIST).
  - High Event Rate 1.4 Gcps in 32-element array (JPL).
- SNSPD Applications related to QIS: Space-to-Ground Quantum Communication. Quantum Communication. Trapped Ion Quantum Computing. Linear Optical Quantum Computing.
- SNSPD Applications related to Fundamental Physics and Astronomy: Dark Matter searches. Tabletop tests of quantum gravity. Exoplanet science. Ultrafast optical transients.
- Next Steps for Longwave SNSPD Development:
  - Move to co-sputtered films with higher Si content to further reduce Tc.
  - Expect Tc $\approx$ 0.5 – 0.7 K is possible with WSi, for 100 – 200 mK operating temperature.
  - Demonstrate saturated efficiency at 30 μm wavelengths.
  - Work on optimized coupling efficiency at long wavelengths using optical stacks and antennas.
  - Develop calibrated efficiency measurements at long wavelengths.
  - Scale up frequency-domain readout to large number of pixels.

11. Glenn Jones, Rigetti

Current control system:

- 10+ control lines per rack unit to keep rack space reasonable.
- All control lines need to share a common clock.
- clock distribution and time transfer become more complex $\rightarrow$ leverage.
- solutions like White Rabbit.
- Need scalable solutions for low latency message passing. Needs to leverage technology.
- Time Sensitive Networking. For instance at https://en.wikipedia.org/wiki/Time-Sensitive Networking
- Manufacturability, testability, reliability become increasingly important.

12. Jeff Heckey, Amazon AWS

- The AWS SideQICK project: Simple Cloud Batching for QICK
  - 1. Deploy to Cloud.
  - 2. Download code from GitHub
  - 3. Run install script
  - 4. Add a new QICK device
  - 5. Add a user
  - 6. Run a Workload
- SideQICK Benefits:
  - Workloads are completely encapsulated.
  - Cloud connected.
  - Device scaling.
  - Transparent operation.
  - Simple permissions.
  - Improved security.
  - Low cost.

13. Patrick Lysaght, Xilinx-AMD

- QICK, RFSoC and RFSoC-PYNQ: AMD facilitates RFSoC development through PYNQ, Jupiter notebooks. See Figure 9.
- RFSoC 4x2 Kit low cost, available for university research. Zynq UltraScale+ RFSoC Gen 3 ZU48DR. 4 x 5 GSPS ADC and 2 x 9.85 GSPS DAC 14-bit ports. 6 GHz RF input bandwidth. QSFP28 interface for 4x25, 2x50 or 1x100 Gbps Ethernet. 4 GB PS and PL DRAM. ZCU208 compatible clocking subsystem. OLED display and battery-backed real-time clock Extensive tutorials and overlays including spectrum analyzer. $2,149 for academic use. See Figure 10.
- RFSoC Book free for academia, pdf version.
- Additional Resources: RFSoC overlays as Python libraries.

14. Ryan Jones, ColdQuanta

RF Control system:

- Laser intensity servos. They are gated and offloaded from the processor for better bandwidth.
- Useful DDS features have been ported to RFSoC.
- Working in RAM-mode.
- Requires Fast amplitude, frequency, phase shift-keying control.
- Requires scalable multitone synthesis.

Some thoughts on QICK software approach:

- We love open-source!
- The tProcessor assembly approach is simple and powerful.
- Please avoid the temptation to roll out a DSL in the future.
- It would be fantastic to see efforts to synchronize, distribute control and memory across multiple boards.
- Flexible interfaces to other (non-QICK) peripherals.
- Please consider an API to run a real-time kernel. That could include an ABI (C/Rust/LLVM) to the tProcessor from the ARM R5 processor. Also more sophisticated control flows than are reasonable from tProcessor assembly without Python overhead.

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[1] L. Stefanazzi, K. Treptow, N. Wilcer, C. Stoughton, C. Bradford, S. Uemura, S. Zorzetti, S. Montella, G. Cancelo, S. Sussman, A. Houck, S. Saxena, H. Arnaldi, A. Agrawal, H. Zhang, C. Ding, and D. I. Schuster, Rev. Sci. Instrum **93**, 044709 (2022).
[2] "QICK Workshop Indico page," `https://indico.fnal.gov/event/57557/contributions/` (2023).
[3] S. Uemura, L. Stefanazzi, K. Treptow, N. Wilcer, C. Stoughton, M. Di Federico, S. Sussman, D. Schuster, A. Agrawal, H. Zhang, C. Ding, K. Nowrouzi, N. Fruitwala, G. Huang, A. Butko, Y. Xu, C. Guinn, and A. Houck, Bulletin of the American Physical Society (2023).
[4] "QICK Github repository," `https://github.com/openquantumhardware/qick` (2023).
[5] "QICK ReadTheDocs," `https://qick-docs.readthedocs.io/en/latest/` (2023).
[6] J. Bryon, D. K. Weiss, X. You, S. Sussman, X. Croot, Z. Huang, J. Koch, and A. Houck, arXiv preprint arXiv:2208.03738 (2022).
[7] J. Martinez, C. Chiu, B. Smitham, S. Sussman, and A. Houck, Bulletin of the American Physical Society (2023).
[8] C. Zhou, P. Lu, M. Praquin, T.-C. Chien, R. Kaufman, X. Cao, M. Xia, R. Mong, W. Pfaff, D. Pekker, and M. Hatridge, "A modular quantum computer based on a quantum state router," (2021).
[9] C. Zhou, J. J. Repicky, M. Xia, M. M. Mucci, R. Mong, and M. J. Hatridge, Bulletin of the American Physical Society (2023).