Superconducting qubit experiments with the QICK

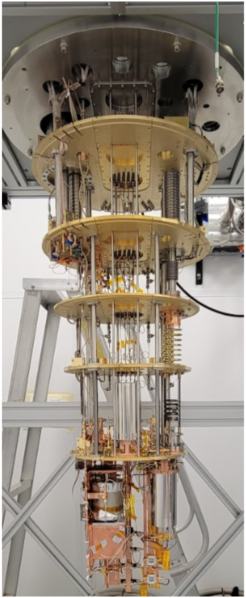
Sara Sussman, Leandro Stefanazzi

September 17, 2023

Presentation Outline

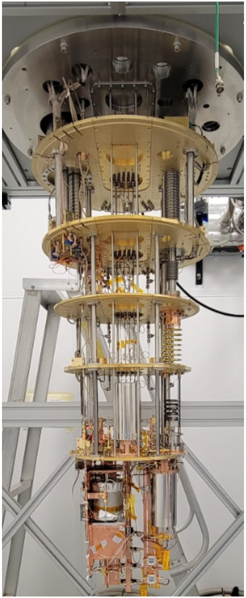
Outline

Superconducting Qubit System



Superconducting Qubit System

Readout and Control System



Superconducting Qubit System

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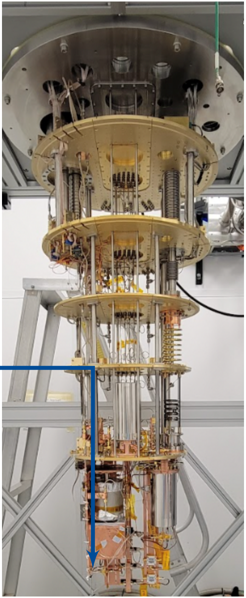
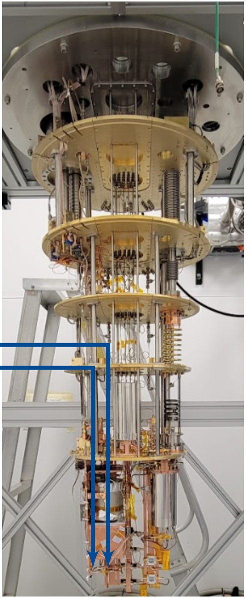
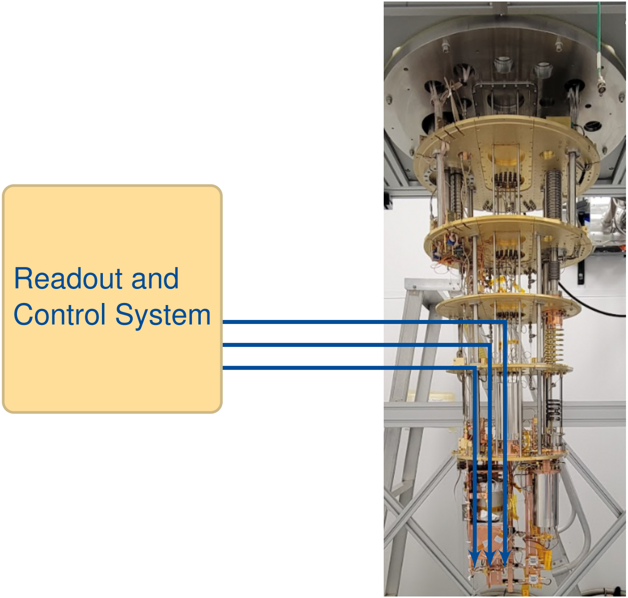


Superconducting Qubit System

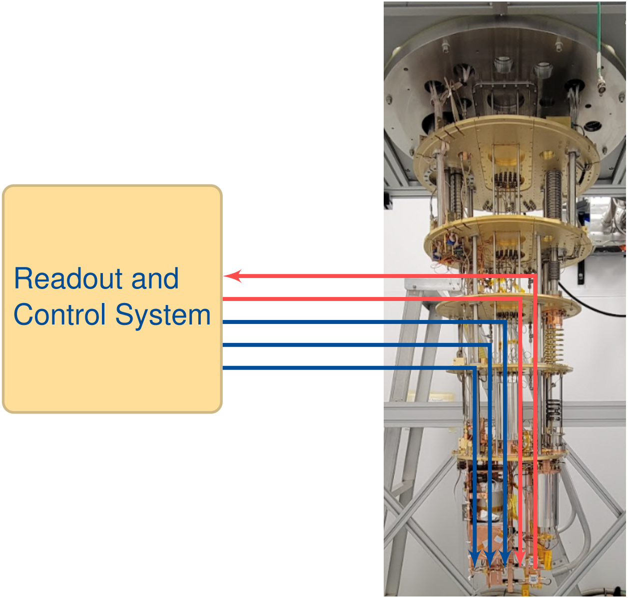
Readout and Control System



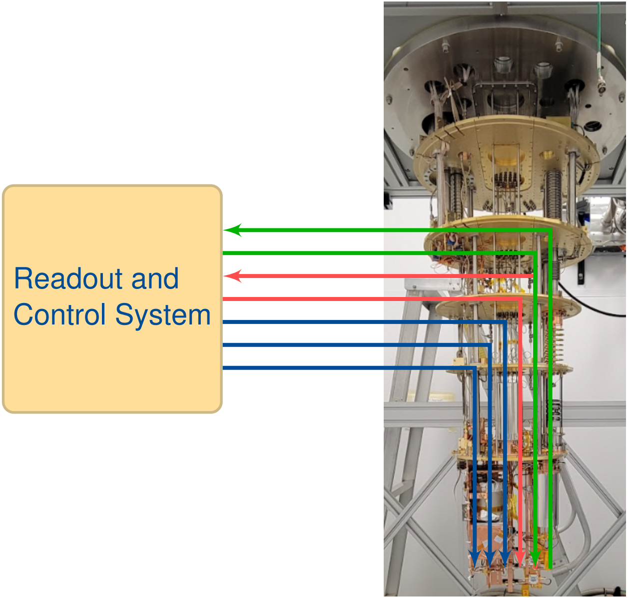
Superconducting Qubit System



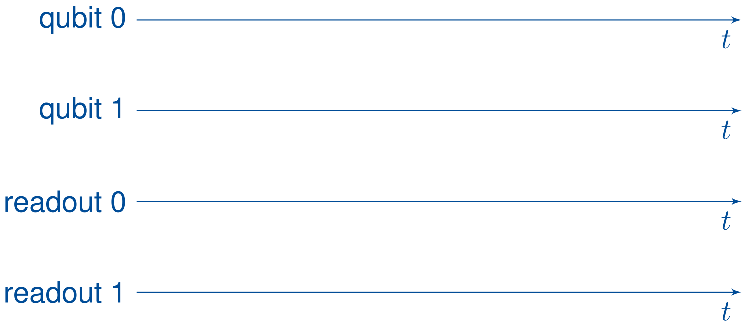
Superconducting Qubit System



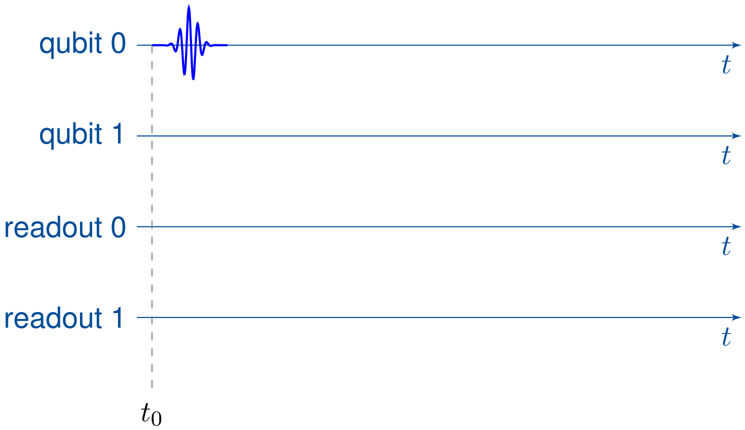
Superconducting Qubit System



Controlling and Reading Qubits

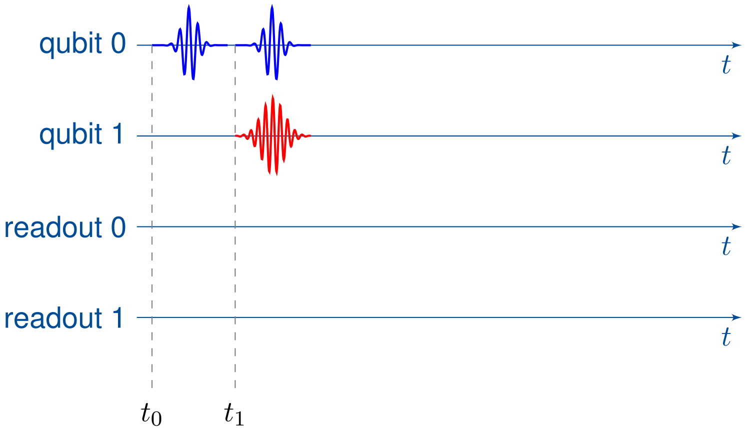


Controlling and Reading Qubits



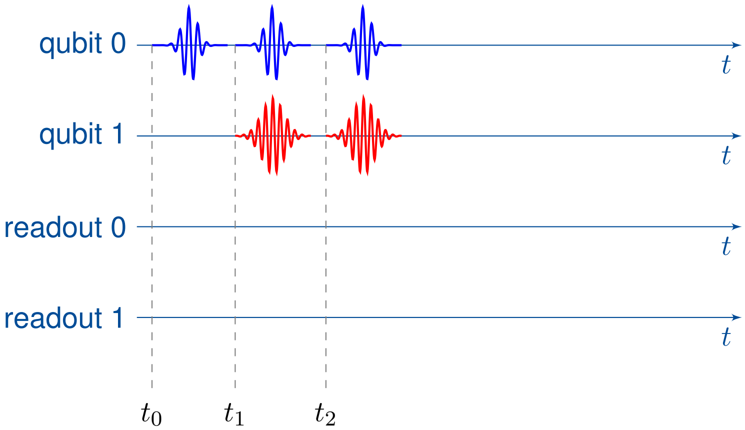
A control pulse is applied to qubit 0 at $t = t_0$.

Controlling and Reading Qubits



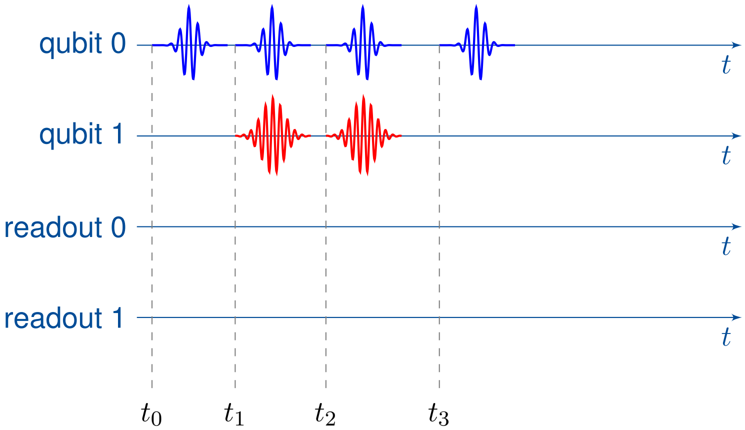
Both qubits are excited at $t = t_1$.

Controlling and Reading Qubits



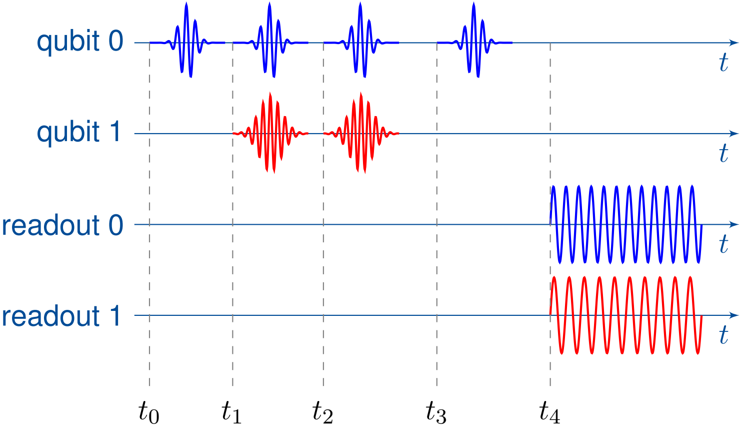
Yet another control pulse for both qubits at $t = t_2$.

Controlling and Reading Qubits



One last touch at $t = t_3$ on qubit 0.

Controlling and Reading Qubits



Readout pulses are sent together at $t = t_4$.

Let's gather some specs

- Frequency range: ~~few GHz~~ DC up to ~~10 GHz~~ over 12 GHz....
- Phase coherence
- Frequency *jumping* capability.
- Pulse duration: from ns to μs.
- Phase sync across channels.
- Real or complex envelope.
- Pulse sequence: could be anything.
- The cheaper the better.
- Need to adapt to experiments.

Outline

High-fidelity parametric entangling gates

Tunable inductive coupler for high fidelity gates between fluxonium qubits

Helin Zhang,[1,2,*] Chunyang Ding,[1,2,3,*] D. K. Weiss,[4,5] Ziwen Huang,[4,†] Yuwei Ma,[1,2] Charles Guinn,[6] Sara Sussman,[6] Sai Pavan Chitta,[4] Danyang Chen,[4] Andrew A. Houck,[6] Jens Koch,[4] and David I. Schuster[1,2,3,7,‡]

[1] *James Franck Institute, University of Chicago, Chicago, Illinois 60637, USA*
[2] *Department of Physics, University of Chicago, Chicago, Illinois 60637, USA*
[3] *Department of Physics and Applied Physics, Stanford University, Stanford, California 94305*
[4] *Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA*
[5] *Yale Quantum Institute, Yale University, New Haven, CT 06511, USA*
[6] *Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
[7] *Pritzker School of Molecular Engineering, University of Chicago, Chicago, Illinois 60637, USA*

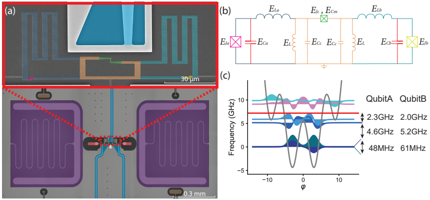
The fluxonium qubit is a promising candidate for quantum computation due to its long coherence times and large anharmonicity. We present a tunable coupler that realizes strong inductive coupling between two heavy-fluxonium qubits, each with $\sim$ 50MHz frequencies and $\sim$ 5 GHz anharmonicities. The coupler enables the qubits to have a large tuning range of XX coupling strengths (-35 to 75 MHz). The ZZ coupling strength is $<$ 3kHz across the entire coupler bias range, and $<$ 100Hz at the coupler off-position. These qualities lead to fast, high-fidelity single- and two-qubit gates. By driving at the difference frequency of the two qubits, we realize a $\sqrt{i\mathrm{SWAP}}$ gate in 258ns with fidelity 99.72%, and by driving at the sum frequency of the two qubits, we achieve a $\sqrt{b\mathrm{SWAP}}$ gate in 102ns with fidelity 99.91%. This latter gate is only 5 qubit Larmor periods in length. We run cross-entropy benchmarking for over 20 consecutive hours and measure stable gate fidelities, with $\sqrt{b\mathrm{SWAP}}$ drift (2σ) $<$ 0.02% and $\sqrt{i\mathrm{SWAP}}$ drift $<$ 0.08%.

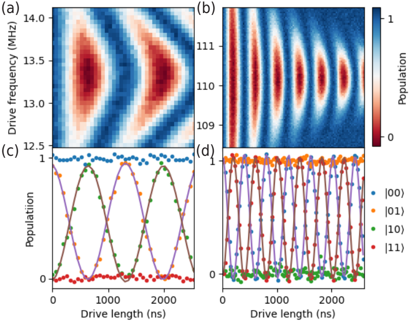
I. INTRODUCTION

Superconducting circuits are a promising platform for the development of scalable, error-corrected quantum computation, heralded by many recent advances towards large scale quantum processors [1, 2] and continued improvements on performances of qubits and gate operations [3–5]. These advances have relied on the transmon qubit [6], and through collective effort, these qubits have achieved excellent coherence times [5, 7] and gate fideli- ties approaching the quantum error correction thresh-

have demonstrated high-fidelity two-qubit fluxonium gates using either fixed capacitive coupling [18–21] or a tunable capacitive coupler [15, 22]. While these two-qubit gate schemes are promising, they either populate states outside of the computational subspace or use high-frequency fluxonium qubits. In this work, we realize a tunable *inductive* coupler, and perform (> 99.9%) fidelity two-qubit gates. Our inductive coupler, similar to the g-mon coupler [23, 24], realizes a large interaction strength even for low-frequency qubits, without involving any higher energy levels. This enables the gate to take

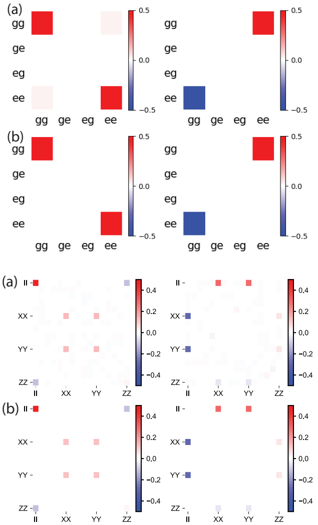
iSWAP and bSWAP between two fluxoniums

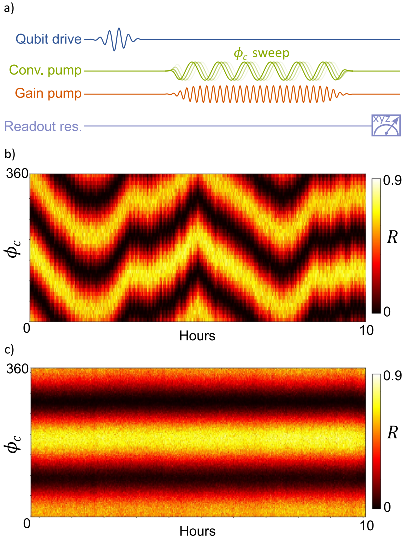




Helin Zhang, Chunyang Ding et al. (2023)

Phase-locked parametric drives

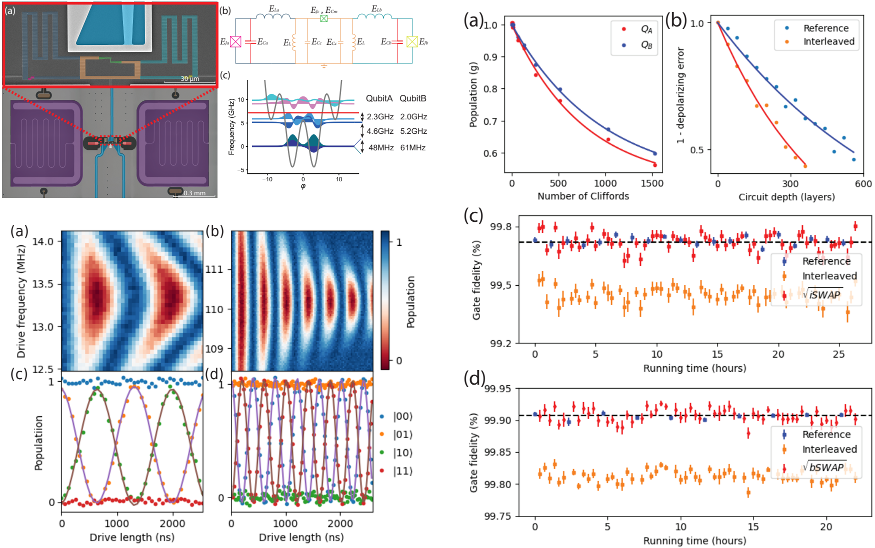




Helin Zhang, Chunyang Ding et al. (2023)

Chao Zhou APS MM (2023)

High-fidelity parametric entangling gates



Helin Zhang, Chunyang Ding et al. (2023)

Pre-distorted fast flux pulses, MUX readout

Flat-band localization and interaction-induced delocalization of photons

Jeronimo G.C. Martinez*, Christie S. Chiu*, Basil M. Smitham, and Andrew A. Houck
Princeton University, Department of Electrical and Computer Engineering

Advances in quantum engineering have enabled the design, measurement, and precise control of synthetic condensed matter systems [1]. The platform of superconducting circuits offers two particular capabilities [2, 3]: flexible connectivity of circuit elements that enables a variety of lattice geometries, and circuit nonlinearity that provides access to strongly interacting physics. Separately, these features have allowed for the creation of curved-space lattices [4] and the realization of strongly correlated phases [5–7] and dynamics [8–10] in one-dimensional chains and square lattices. Missing in this suite of simulations is the simultaneous integration of interacting particles into lattices with unique band dispersions, such as dispersionless flat bands. An ideal building block for flat-band physics is the Aharonov-Bohm cage [11]: a single plaquette of a lattice whose band structure consists entirely of flat bands. Here, we experimentally construct an Aharonov-Bohm cage and observe the localization of a single photon, the hallmark of all-bands-flat physics. Upon placing an interaction-bound photon pair into the cage, we see a delocalized walk indicating an escape from Aharonov-Bohm caging [12]. We further find that a variation of caging persists for two particles initialized on opposite sites of the cage. These results mark the first experimental observation of a quantum walk that becomes delocalized due to interactions and establish superconducting circuits for studies of flat-band-lattice dynamics with strong interactions.

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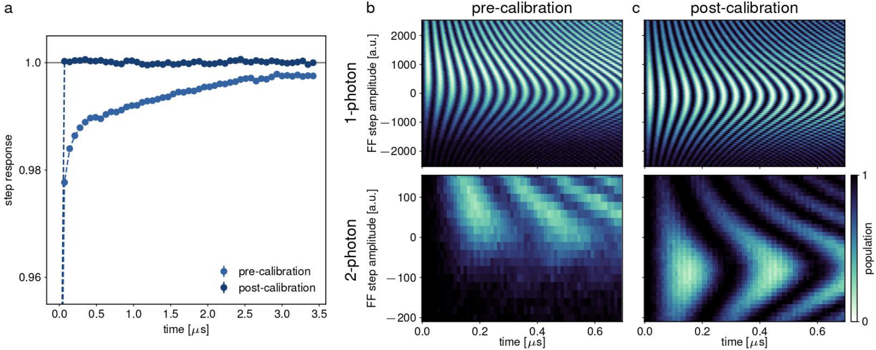
Flat electronic bands quench the kinetic energy of electrons and provide a lattice environment that is uniquely susceptible to interactions, disorder, and particle statistics. As a result, they can host a wide range of phenomena, from itinerant ferromagnetism in spinful systems [13, 14] to the fractional quantum Hall effect [15], fractional Chern insulator states [16–18], and strongly correlated phases observed in magic-angle twisted bilayer graphene [19, 20]. The role of flat bands in high-temperature superconductivity [21, 22] and quantum thermalization [23–25], as well as searches for novel flat-band materials [26], are also active areas

understood through the Aharonov-Bohm effect. More specifically, the tight-binding electron accumulates an Aharonov-Bohm phase as it hops around a closed loop of the lattice, or plaquette. Additionally, the lattice plaquettes are arranged in such a way that causes complete destructive wavefunction interference beyond some region of the lattice and localizes the electron to a finite number of sites. This phenomenon is known as Aharonov-Bohm "caging" [11]. In the rhombus lattice, Aharonov-Bohm caging occurs at a magnetic field of half a flux quantum through each plaquette, corresponding to a geometric phase of π. All three bands

Pre-distorted fast flux pulses



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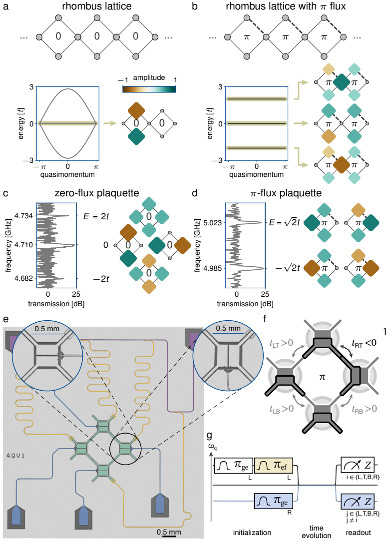
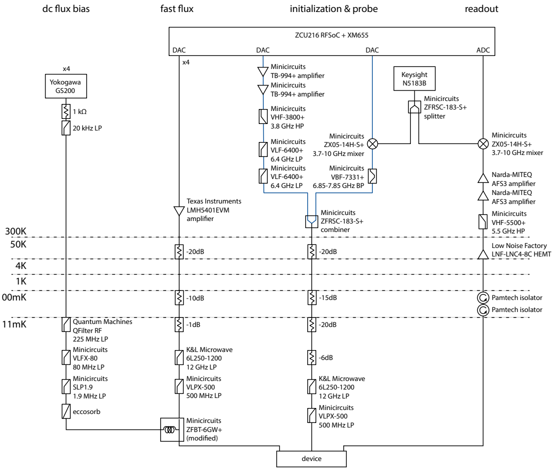
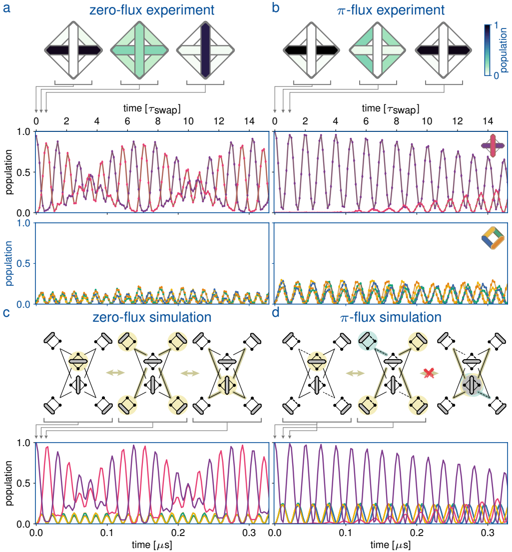
Multiplexed readout (x2 for this experiment)





Jeronimo Martinez, Christie Chiu et al. (2023)

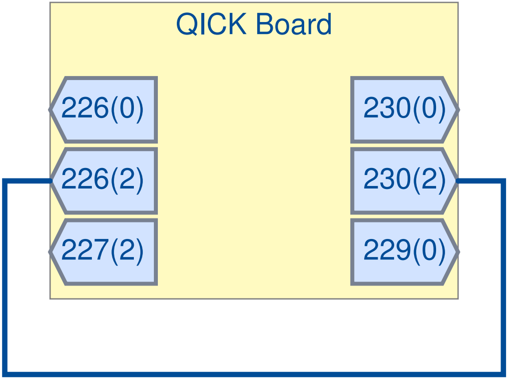
Example: measure time-evolved particle pair



Jeronimo Martinez, Christie Chiu et al. (2023)

Outline

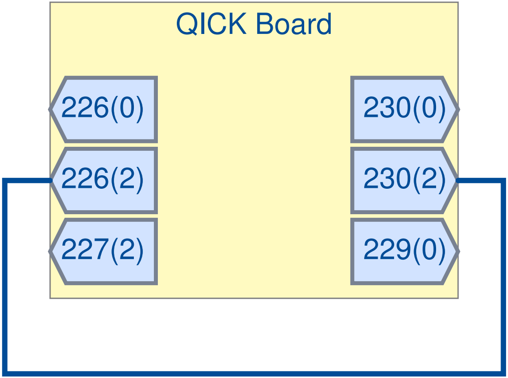
Connections for `00_Send_receive_pulse`



10 MHz-1 GHz or
1-4 GHz baluns

Outline

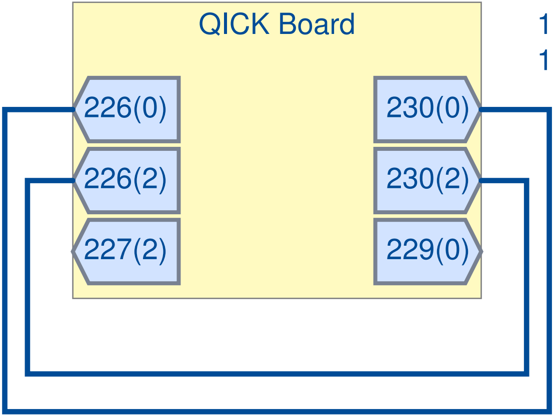
Connections for `Mixer_free_readout`



5-6 GHz baluns

Outline

Connections for `Pulse_sequence`

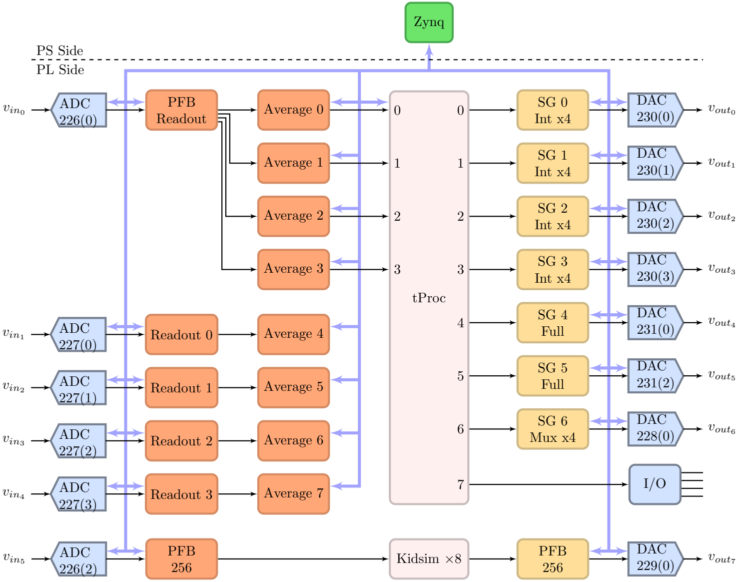


10 MHz-1 GHz or
1-4 GHz baluns

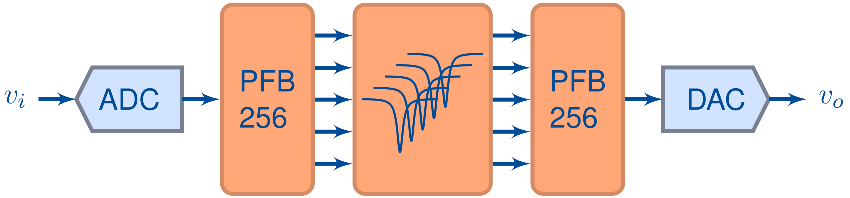
DACs must be on the same tile (e.g. 230) to ensure correct pulse timing.

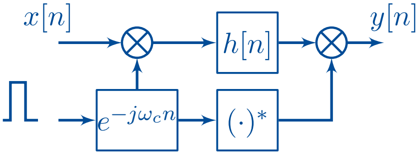
Outline

QICK Training Firmware

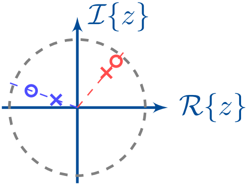


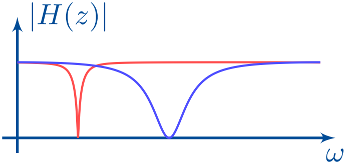
Resonator and Qubit Emulator





Resonator frequency and Q factor can be adjusted.

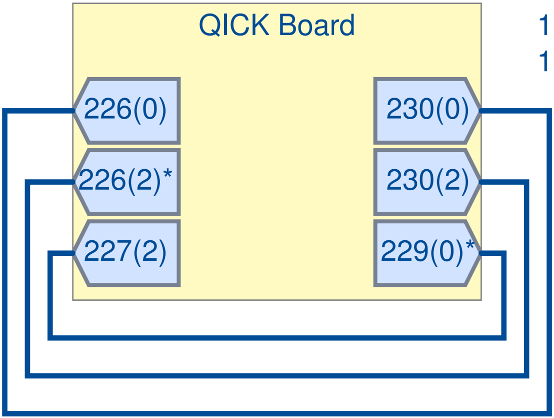




First uses for resonator and qubit emulator

- Teach new people about the basics of quantum measurement
- Model how various types of readout infidelity and parameters such as resonator quality factor impact quantum measurements
- Test amplifier chains e.g. at very low drive power
- Test FPGA filters designed to improve readout fidelity
- These are just a few ideas...users will come up with more

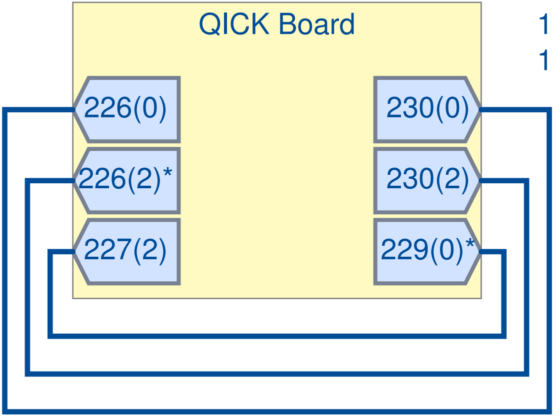
Connections for `Resonator_emulator_phase`



10 MHz-1 GHz or
1-4 GHz baluns

* Connected
via the emulator

Connections for `Qubit_emulator`



10 MHz-1 GHz or
1-4 GHz baluns

* Connected
via the emulator

Outline

Thanks for your attention!

Questions?

Project files and examples:

https://github.com/openquantumhardware/qick.git

https://github.com/openquantumhardware/QCE2023_public.git

https://qick-docs.readthedocs.io/en/latest/papers.html