



Superconducting qubit experiments with the QICK

Sara Sussman, Leandro Stefanazzi
September 17, 2023



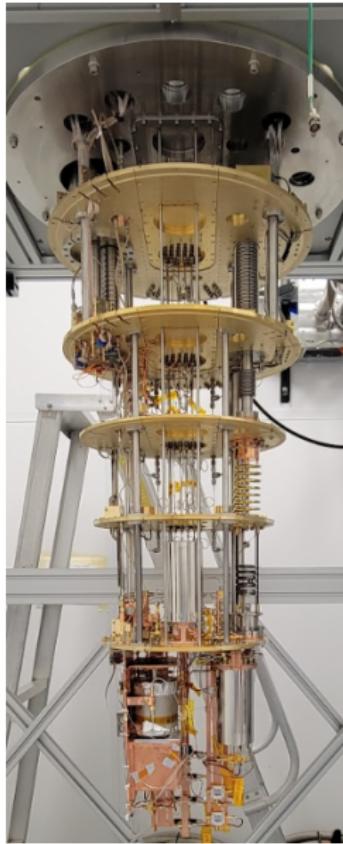
Presentation Outline

- 1 Review from this morning: Readout and Control
- 2 What has been demonstrated so far? Highlights
- 3 Loopback basics
- 4 Mixer-free readout
- 5 Pulse sequences
- 6 Using the resonator and qubit emulator
- 7 Questions and Links

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Superconducting Qubit System



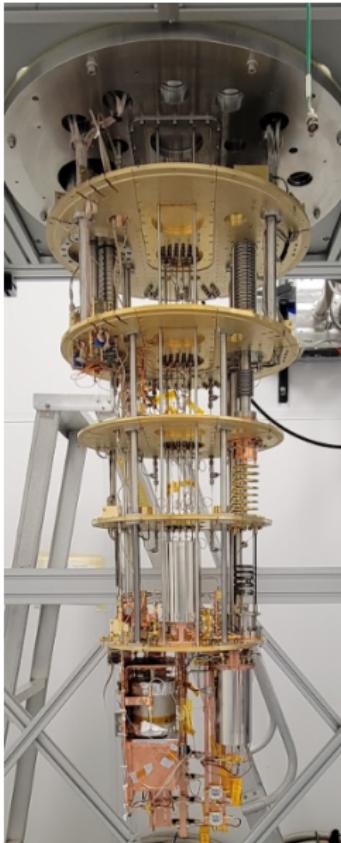
LOUD fridge at Fermilab



Superconducting Qubit System

Readout and
Control System

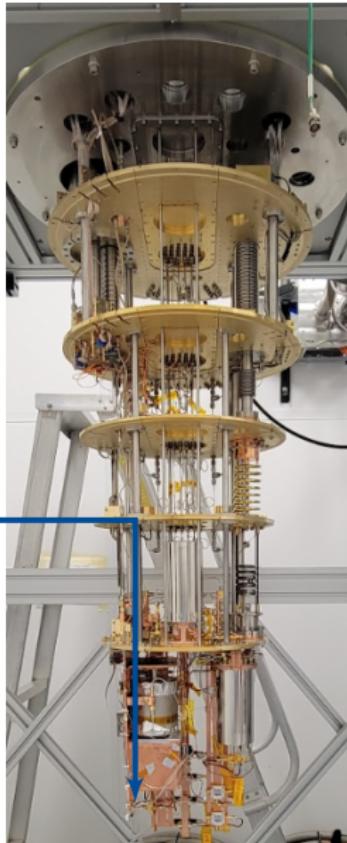
LOUD fridge at Fermilab



Fermilab

Superconducting Qubit System

Readout and
Control System

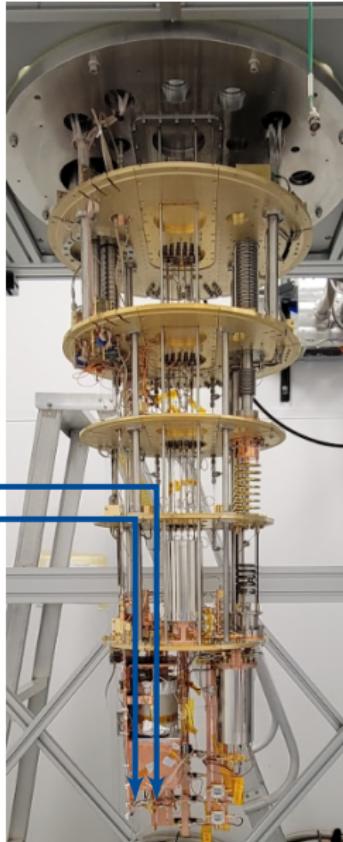


LOUD fridge at Fermilab

Superconducting Qubit System

Readout and
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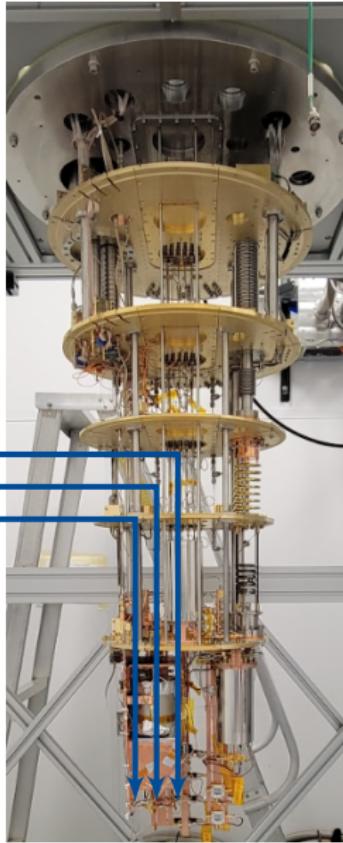
LOUD fridge at Fermilab



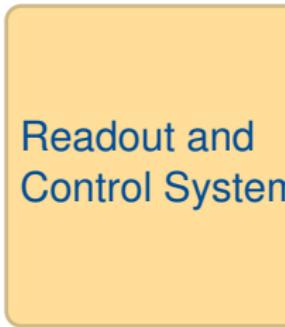
Superconducting Qubit System

Readout and Control System

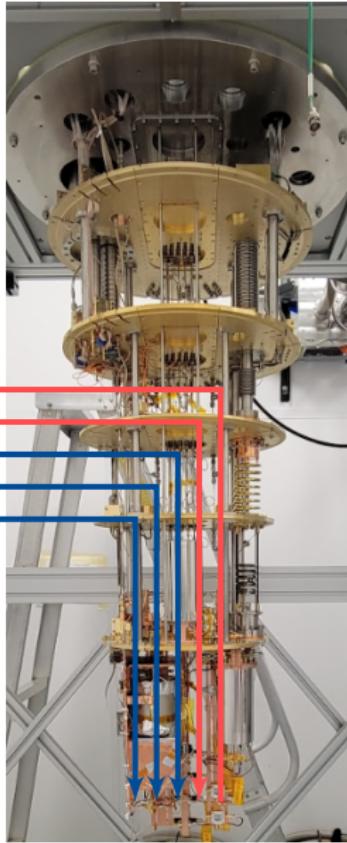
LOUD fridge at Fermilab



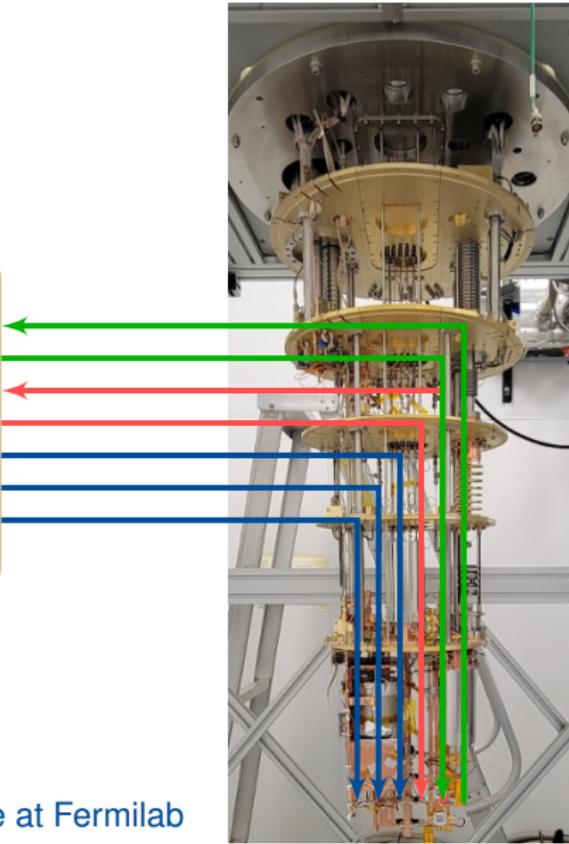
Superconducting Qubit System



LOUD fridge at Fermilab



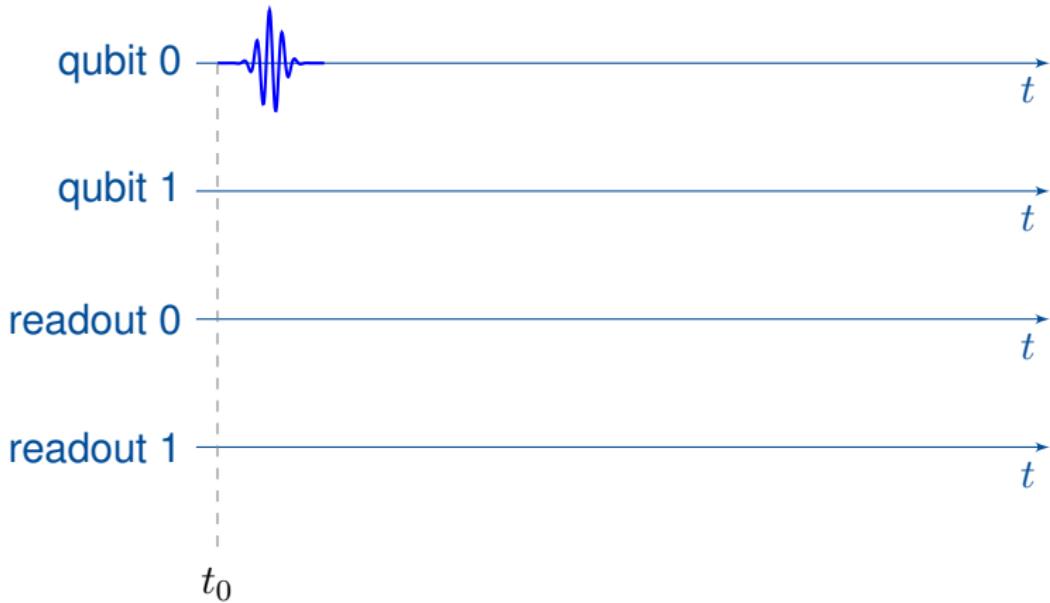
Superconducting Qubit System



Controlling and Reading Qubits

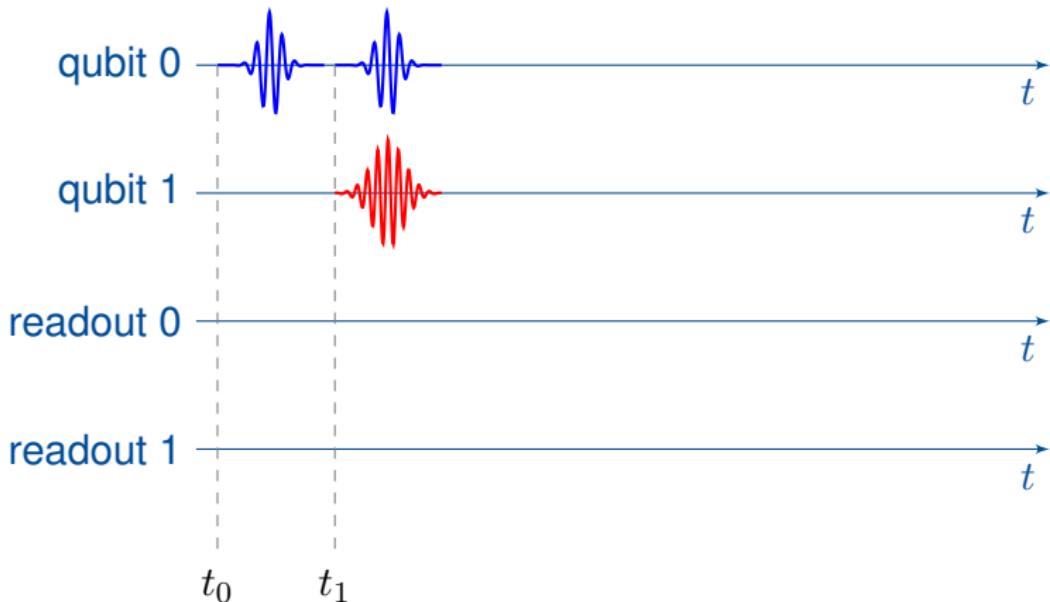


Controlling and Reading Qubits



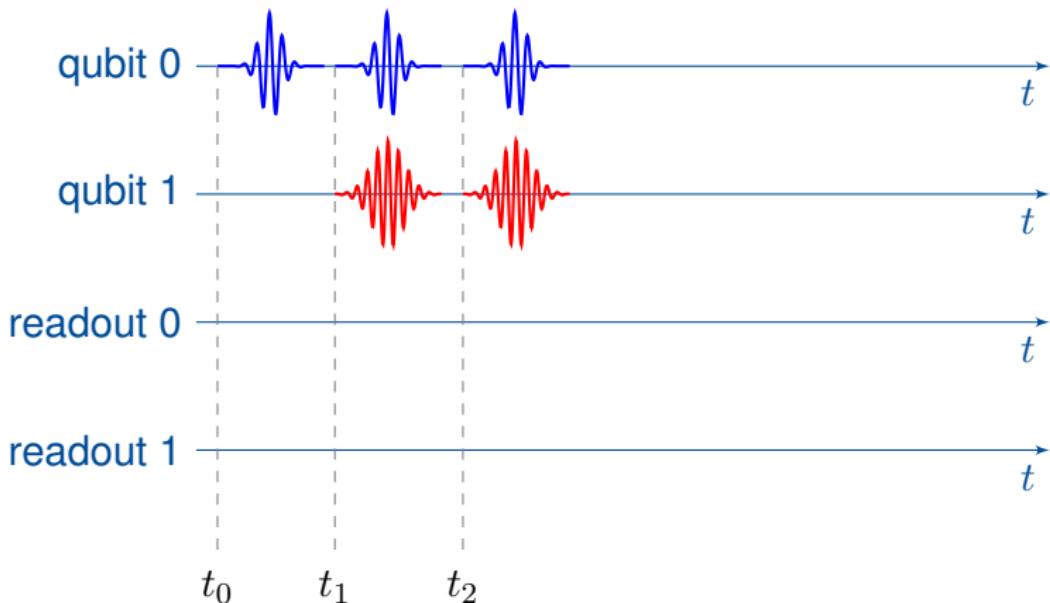
A control pulse is applied to qubit 0 at $t = t_0$.

Controlling and Reading Qubits



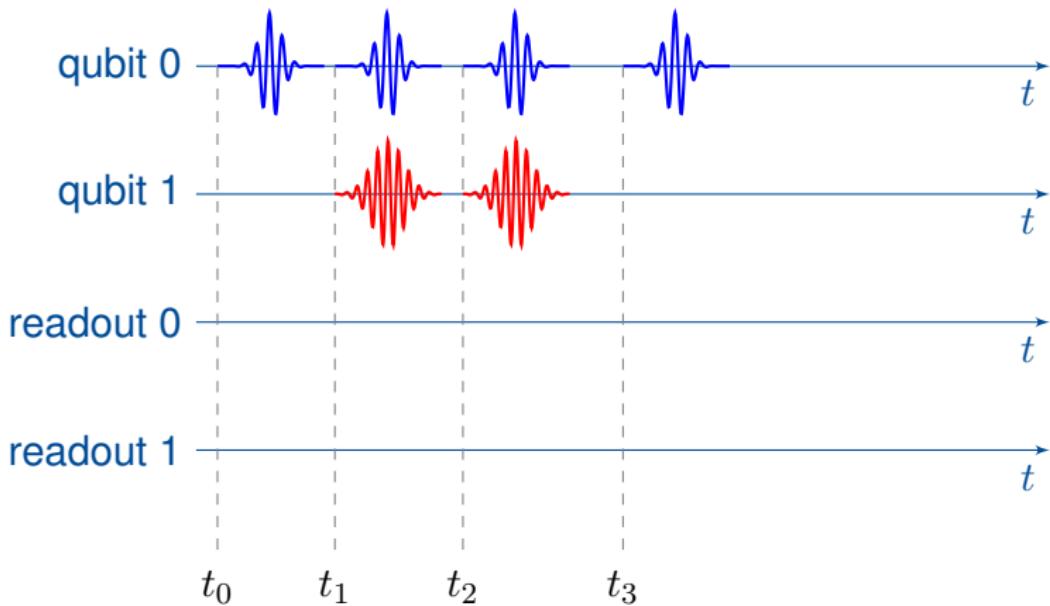
Both qubits are excited at $t = t_1$.

Controlling and Reading Qubits



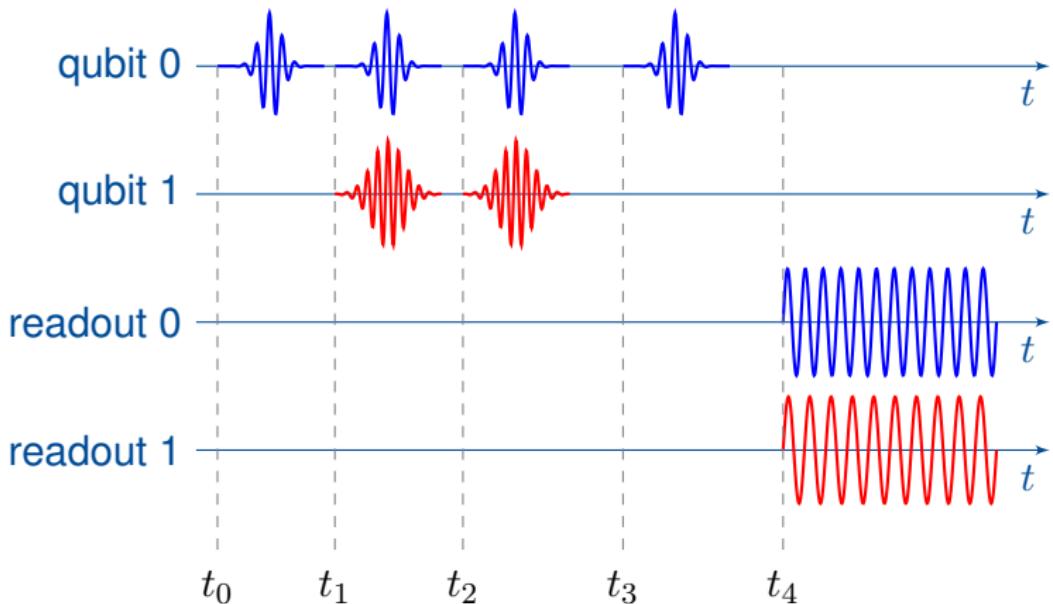
Yet another control pulse for both qubits at $t = t_2$.

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 μ s.
- Phase sync across channels.
- Real or complex envelope.
- Pulse sequence: could be anything.
- The cheaper the better.
- Need to adapt to experiments.

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High-fidelity parametric entangling gates

10v1 [quant-ph] 11 Sep 2023

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 Quinn,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*

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⁶*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*

⁷*Pritzker School of Molecular Engineering, University of Chicago, Chicago, Illinois 60637, USA*

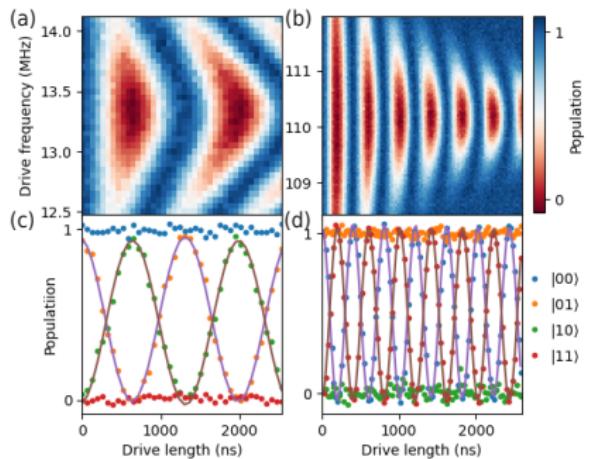
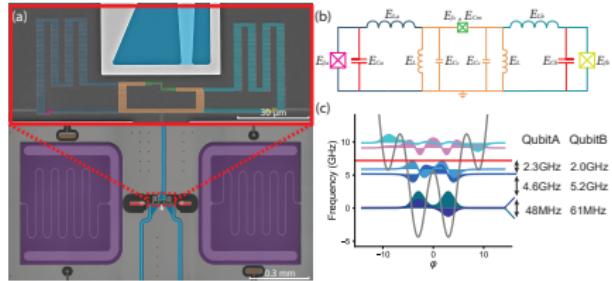
The fluxonium qubit is a promising candidate for quantum computation due to its long coherence times and large anharmonicity. We present a tunable coupler that realizes strong inductive coupling between two heavy-fluxonium qubits, each with $\sim 50\text{MHz}$ frequencies and $\sim 5\text{ GHz}$ anharmonicities. The coupler enables the qubits to have a large tuning range of XX coupling strengths (-35 to 75 MHz). The ZZ coupling strength is $< 3\text{kHz}$ across the entire coupler bias range, and $< 100\text{Hz}$ 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 $\sqrt{i}\text{SWAP}$ gate in 258ns with fidelity 99.72% , and by driving at the sum frequency of the two qubits, we achieve a $\sqrt{b}\text{SWAP}$ 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 $\sqrt{b}\text{SWAP}$ drift (2σ) $< 0.02\%$ and $\sqrt{i}\text{SWAP}$ 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 fidelities 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-mom 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

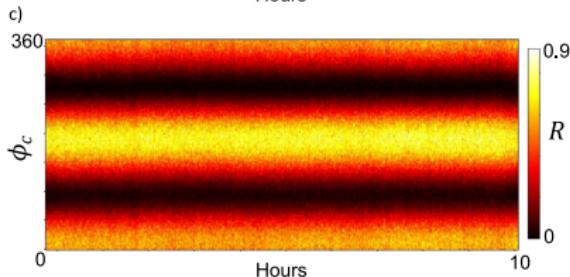
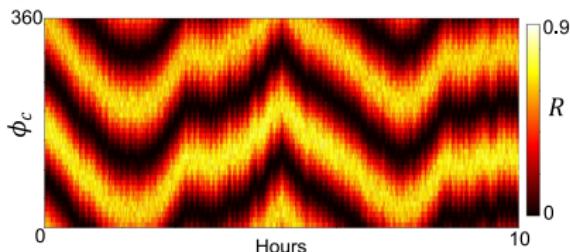
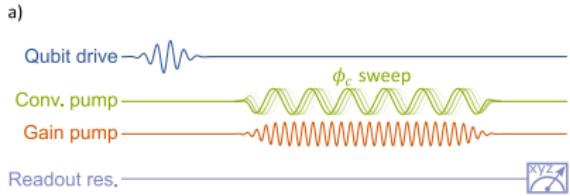
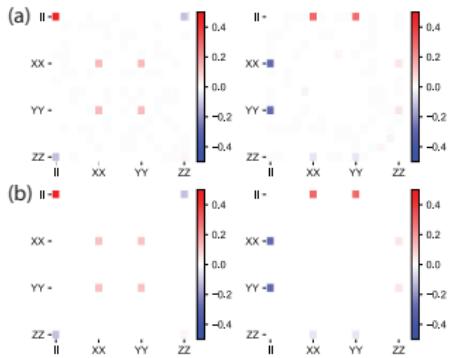
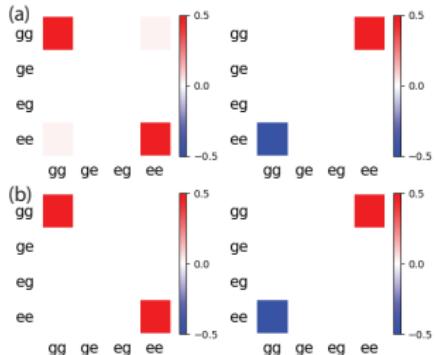
iSWAP and bSWAP between two fluxoniums



Helin Zhang, Chunyang Ding et al. (2023)



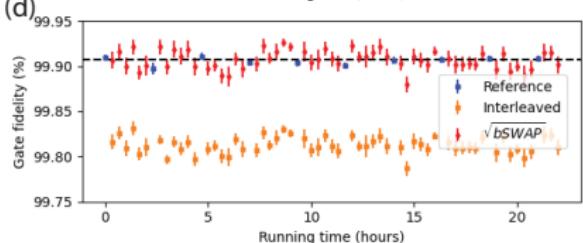
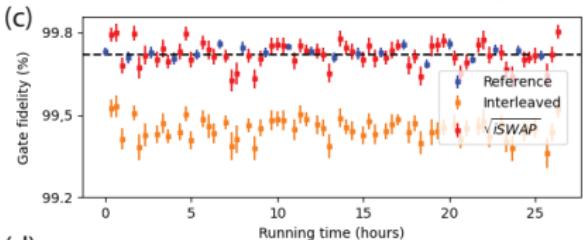
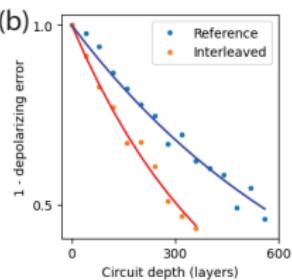
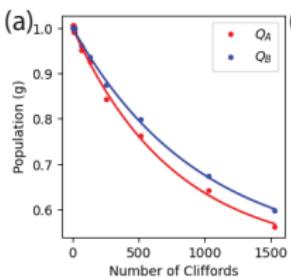
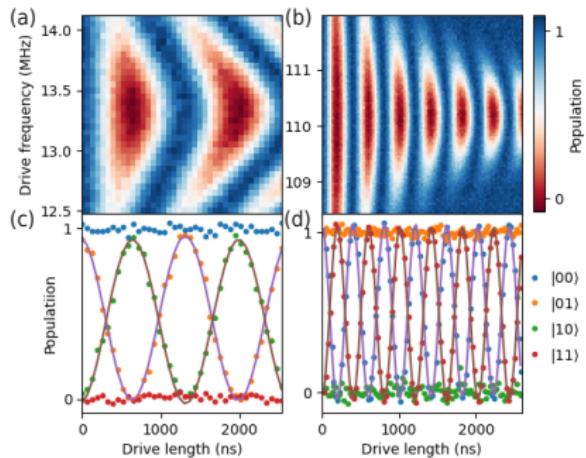
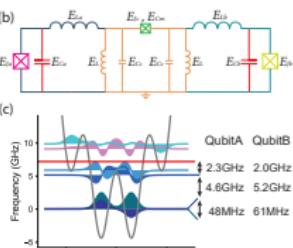
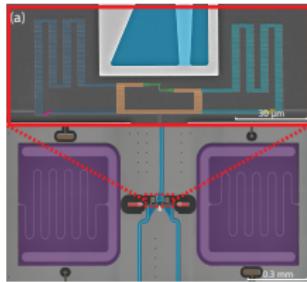
Phase-locked parametric drives



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

70v2 [quant-ph] 13 Jun 2023

Flat-band localization and interaction-induced delocalization of photons

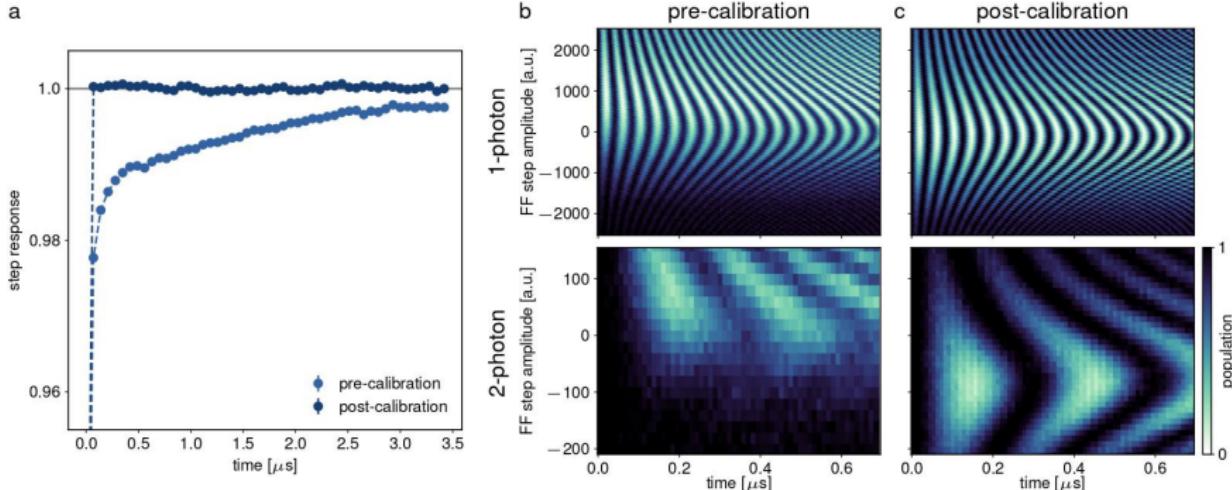
Jeronimo G.C. Martinez*, Christie S. Chiu*, Basil M. Smitham, and Andrew A. Houck
Princeton University, Department of Electrical and Computer Engineering

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.

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

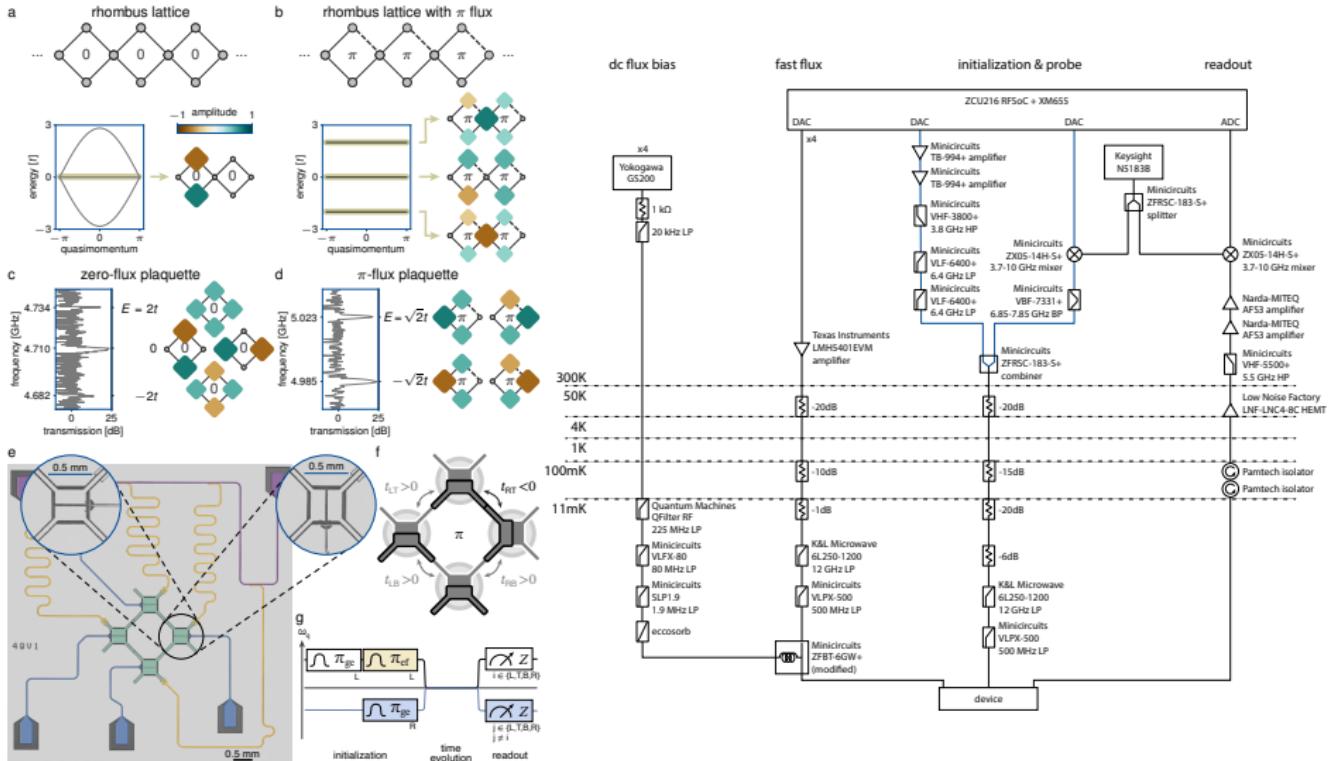
understood through the Aharonov-Bohm effect. More specifically, the tight-binding electron accumulates an Aharonov-Bohm phase as it hops around a closed loop of the lattice, or plaquette. Additionally, the lattice plaquettes are arranged in such a way that causes complete destructive wavefunction interference 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



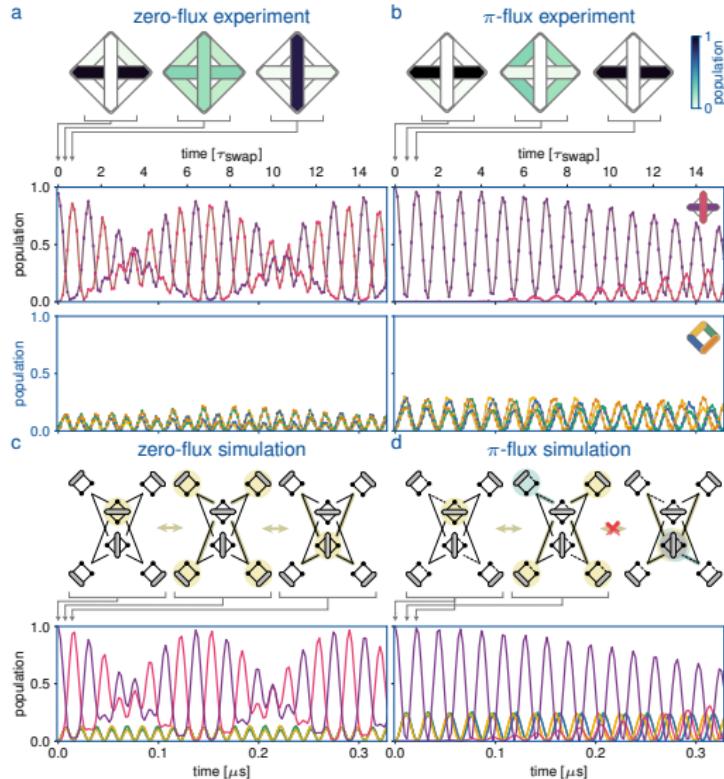
Jeronimo Martinez, Christie Chiu et al. (2023)

Multiplexed readout (x2 for this experiment)



Jeronimo Martinez, Christie Chiu et al. (2023)

Example: measure time-evolved particle pair

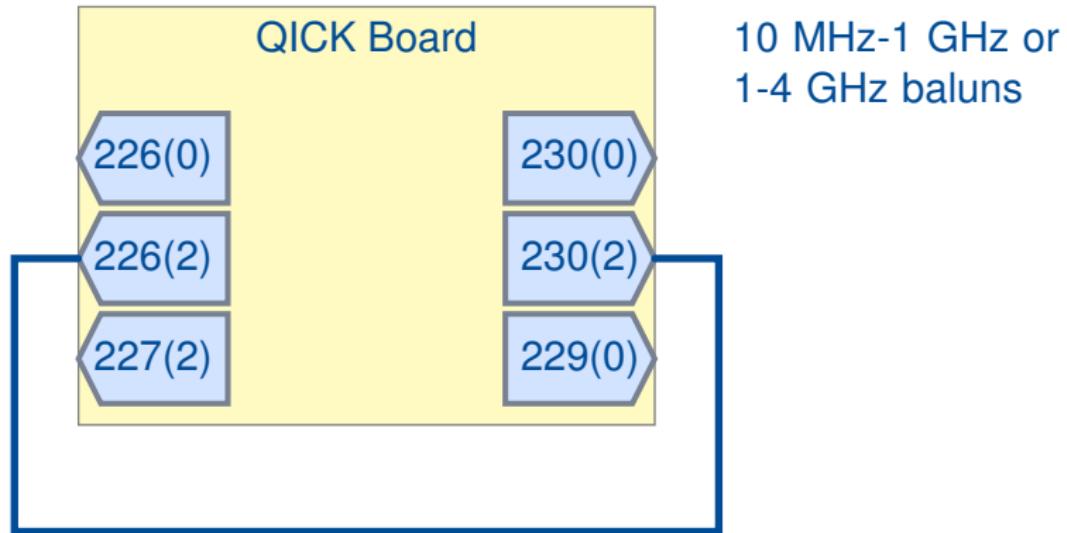


Jeronimo Martinez, Christie Chiu et al. (2023)

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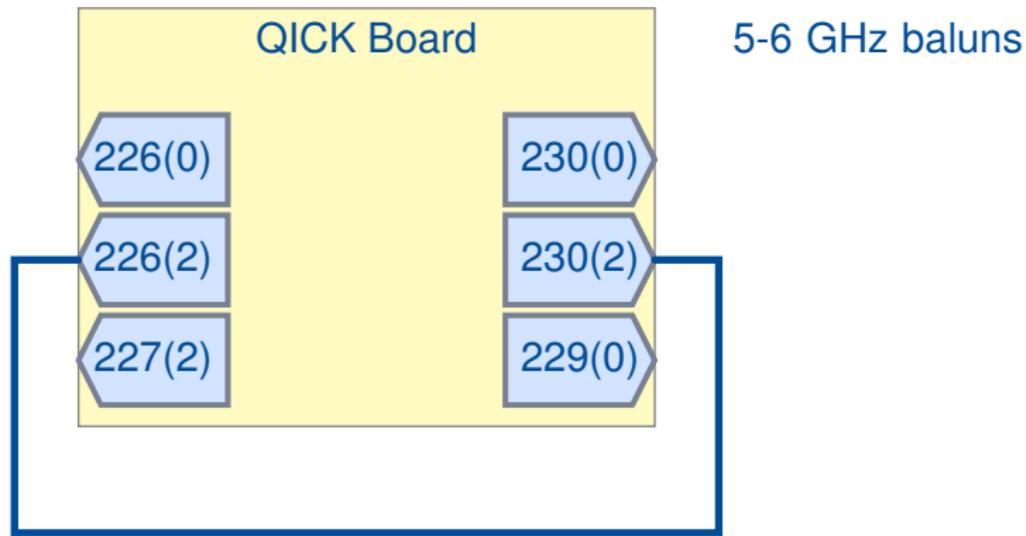
Connections for 00_Send_receive_pulse



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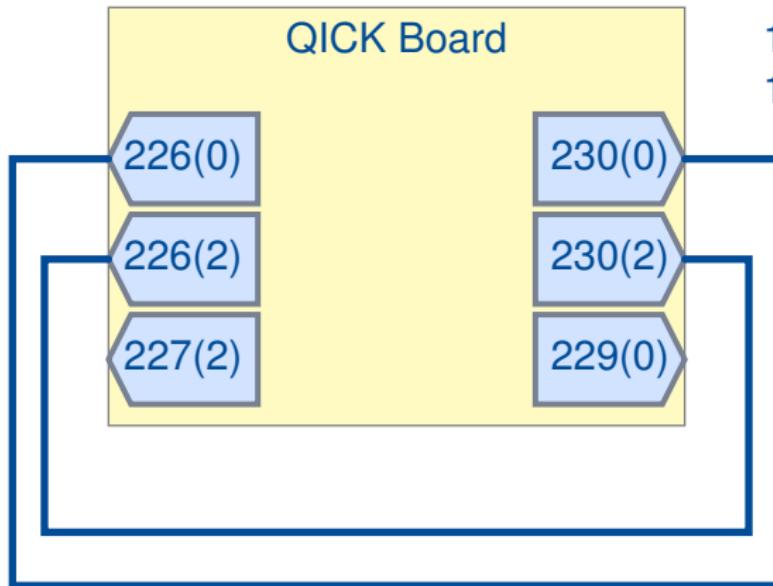
Connections for Mixer_free_readout



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Connections for Pulse_sequence

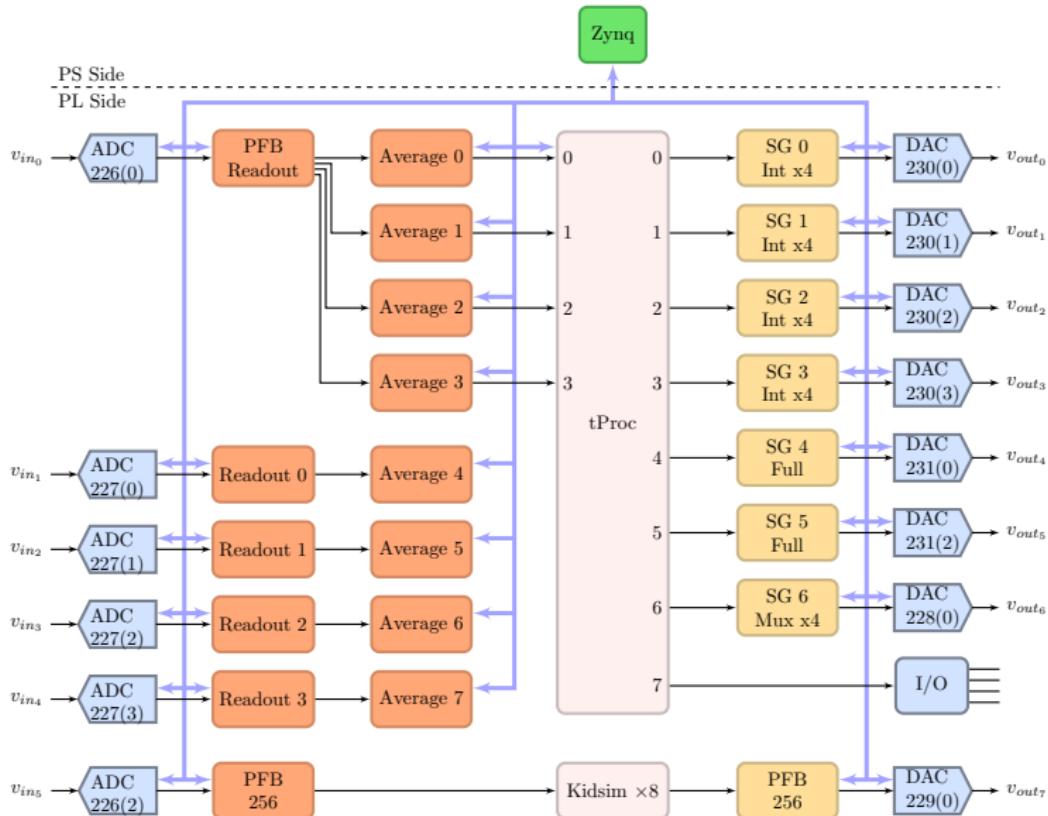


DACs must be on the same tile (e.g. 230) to ensure correct pulse timing.

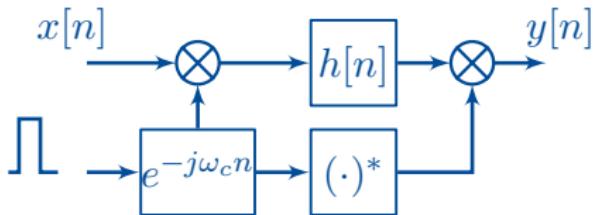
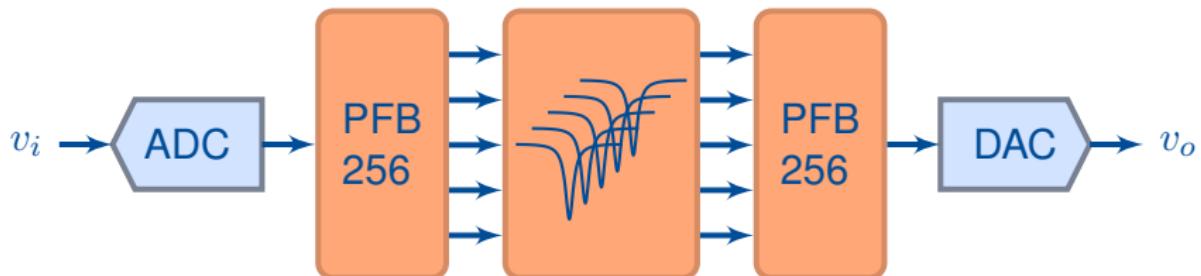
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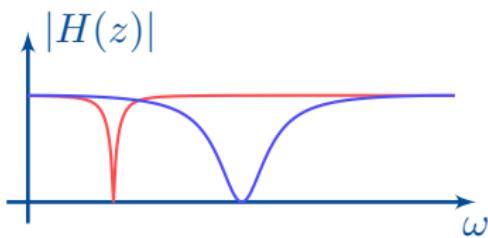
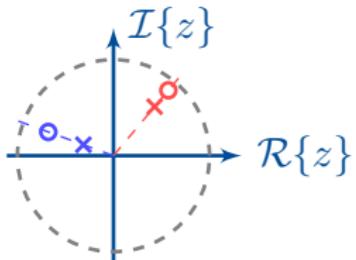
QICK Training Firmware



Resonator and Qubit Emulator



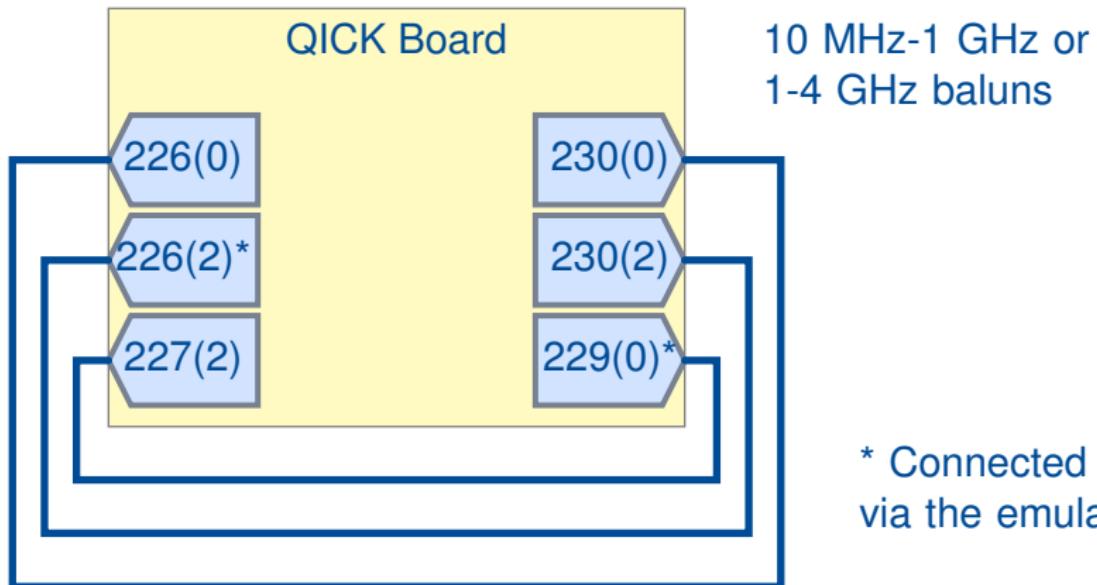
Resonator frequency and Q factor can be adjusted.



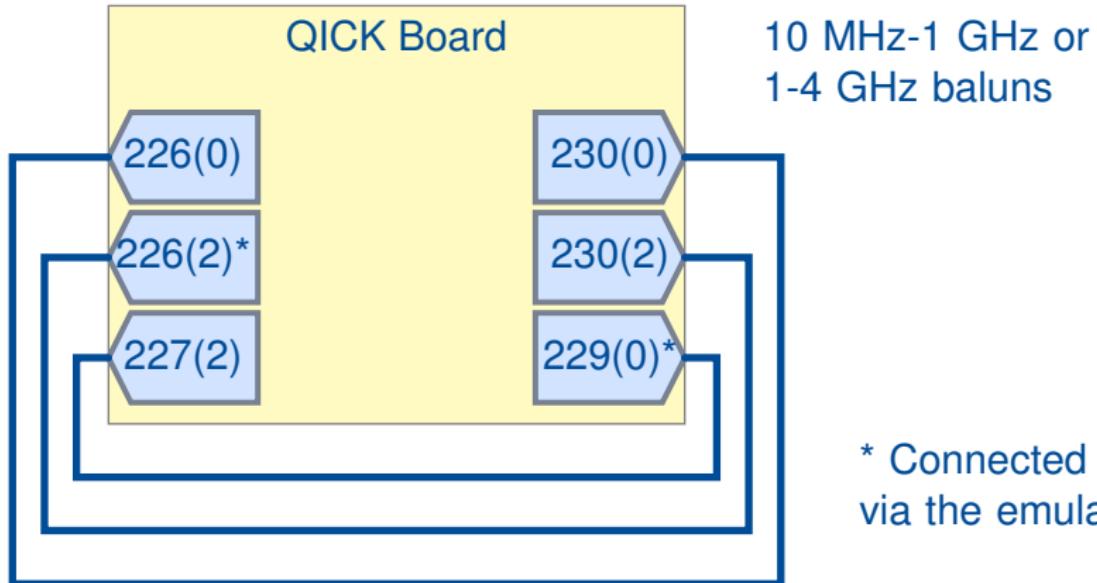
First uses for resonator and qubit emulator

- 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



Connections for Qubit_emulator



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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>