IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Invited presentation 1-QU-I-1 given at ISEC, 28 July-1 August 2019, Riverside, USA.

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High Coherence Quantum Annealing and Fast, High-Fidelity Flux Qubit Readout

ISEC July 31, 2019

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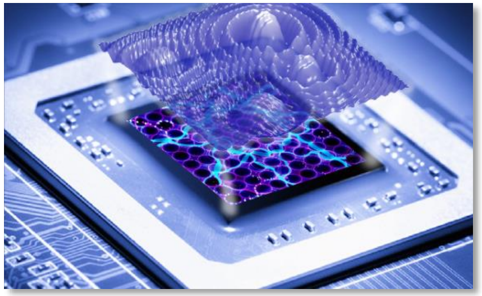
- This material is based upon work supported by the Intelligence Advanced Research Projects Activity (IARPA) through the Army Research Office (ARO) under Contract No. W911NF-17-C-0050. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Intelligence Advanced Research Projects Activity (IARPA) and the Army Research Office (ARO).

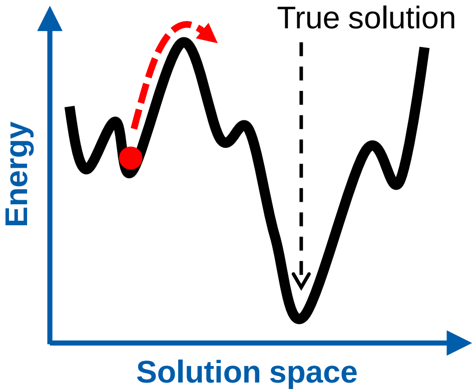
Quantum Enhanced Optimization

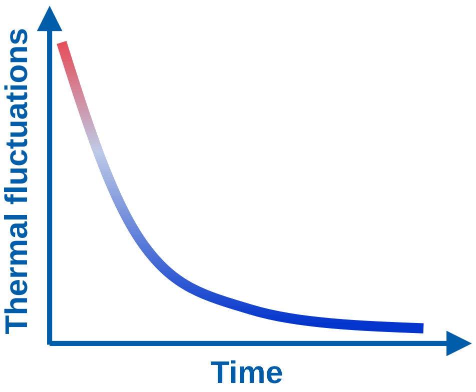
- What is Quantum Enhanced Optimization (QEO)?
  - IARPA-funded program to get to the heart of quantum annealing
  - Large collaboration combining industry and academic institutions; performer team led by USC
  - Builds upon key groundwork and capabilities from MIT LL, NASA, Texas A&M, ETH
  - Qubit technology: superconducting qubits fabricated at MIT LL
- Goal: Understand the physics and the viability of quantum annealing as a computing resource
  - Build advanced testbeds enabling innovative experiments
  - Determine basis of design for application-scale QA systems achieving quantum enhancement



Annealing Uses Slowly Decreasing Fluctuations to Find Low-Energy States

- In metallurgy: heat treatment to reduce dislocations
  - Heat up to high temperature, then cool slowly
  - Dates back to ancient times (5000 BCE)
- Simulated annealing using classical algorithms
  - Nature-inspired heuristic to solve optimization problems[1]
  - Simulated thermal fluctuations allow escape from local minima





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[1] Science 220 (4598): 671–680

Quantum Annealing Relies on Quantum Mechanical Effects

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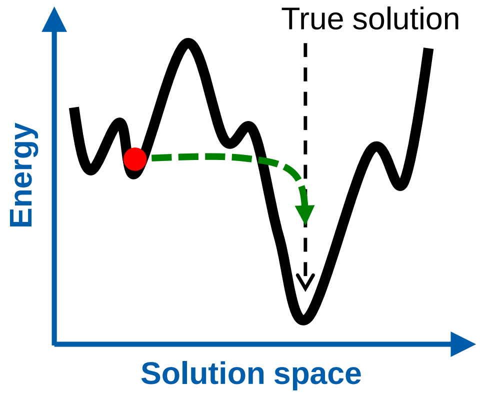
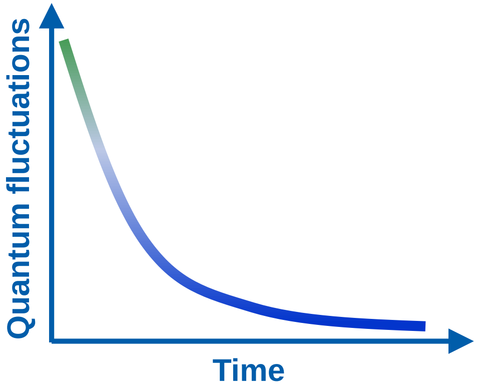
Quantum fluctuations help tunnel out of local energy minima:





Phys. Rev. E 58, 5355 (1998)
Chem. Phys. Lett. 219, 343 (1994)

Quantum Annealing Relies on Quantum Mechanical Effects

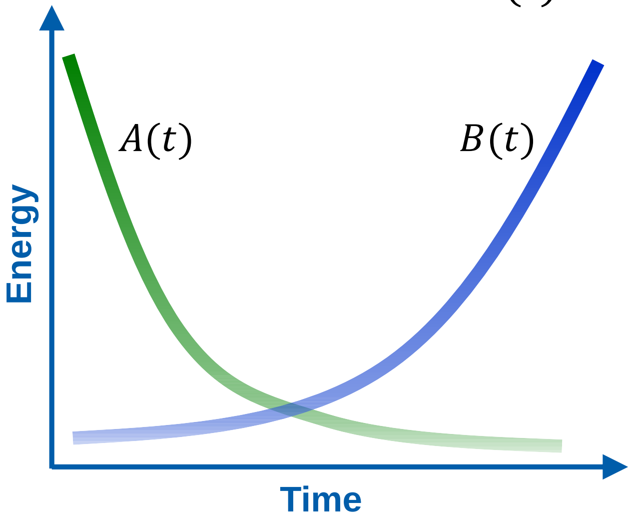
Problem of interest can be encoded in the total energy of the system, i.e. the Hamiltonian H

Typical protocol:

1. Start with large quantum fluctuations
2. Reduce fluctuation part of H while increasing part of H representing problem on interest
3. Read out the solution bit string

problem variables

$$H(t) = -A(t)\underbrace{\sum_i \sigma_x^i}_{\text{Driver Hamiltonian (fluctuations)}} + B(t)\underbrace{\left(\sum_i h_i\sigma_z^i + \sum_{i<j} J_{ij}\sigma_z^i\sigma_z^j\right)}_{\text{Problem Hamiltonian}}$$



Phys. Rev. E 58, 5355 (1998)
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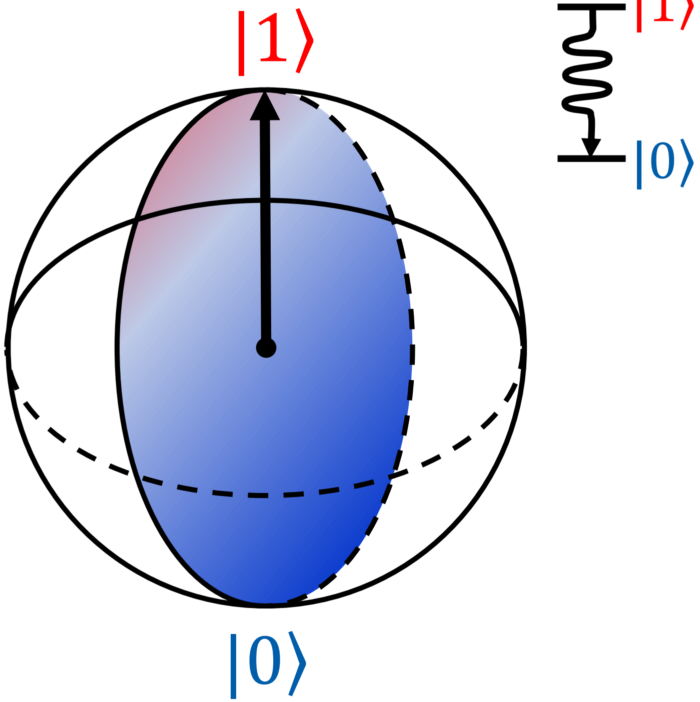
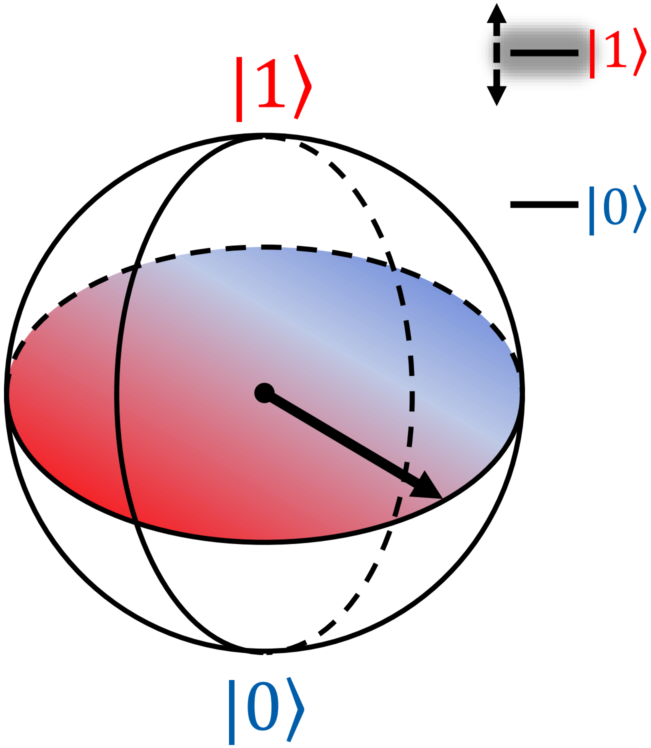
Coherence is the Time Scale on Which the System's Evolution is Primarily Dictated by Quantum Mechanics

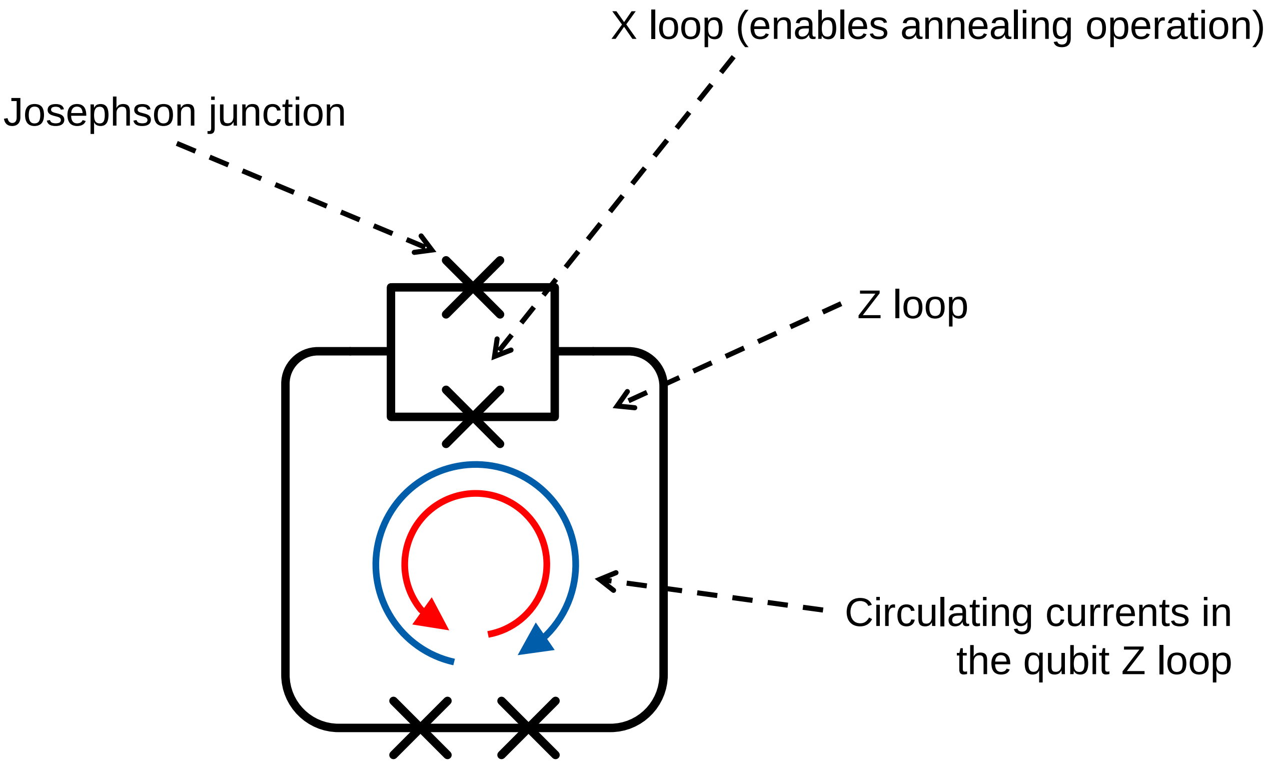
T_1 energy relaxation time



T_2 dephasing time



Flux Qubits Work as Spins in Superconducting Quantum Annealing



X loop (enables annealing operation)

Josephson junction

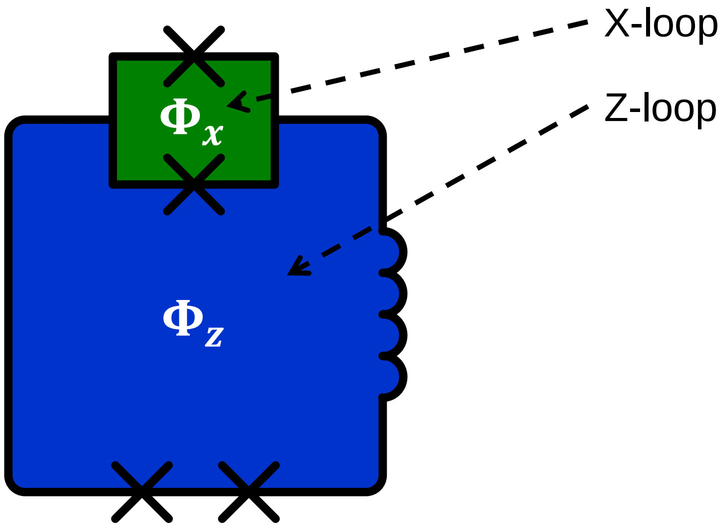
Z loop

Circulating currents in the qubit Z loop

Quantum annealing spin variable corresponds to circulating current state

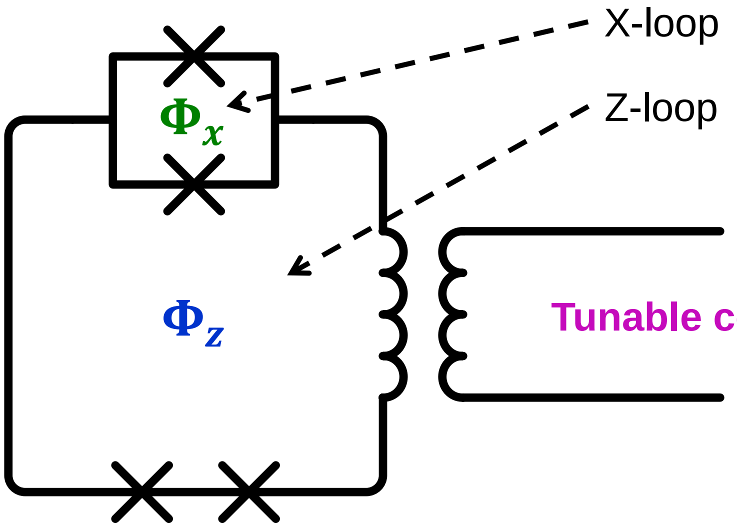
$$|\downarrow\rangle \quad |\uparrow\rangle \quad \longleftrightarrow \quad |\circlearrowright\rangle \quad |\circlearrowleft\rangle$$

Fluctuations and Problem Hamiltonian are Controlled via Applied Magnetic Flux



$$H(t) = \underbrace{-A(t)\sum_i \sigma_x^i}_{\text{Driver Hamiltonian}} + \underbrace{B(t)\left(\sum_i h_i\sigma_z^i + \sum_{i<j} J_{ij}\sigma_z^i\sigma_z^j\right)}_{\text{Problem Hamiltonian}}$$

Magnetic Flux Coupling to Other Qubits Encodes Pairwise Interactions



X-loop

Z-loop

Tunable coupling to other qubits

$$H(t) = -A(t)\underbrace{\sum_i \sigma_x^i}_{\text{Driver Hamiltonian}} + B(t)\underbrace{\left(\sum_i h_i\sigma_z^i + \sum_{i<j} J_{ij}\sigma_z^i\sigma_z^j\right)}_{\text{Problem Hamiltonian}}$$

The Answer to the Computation Must be Read Out with High Fidelity

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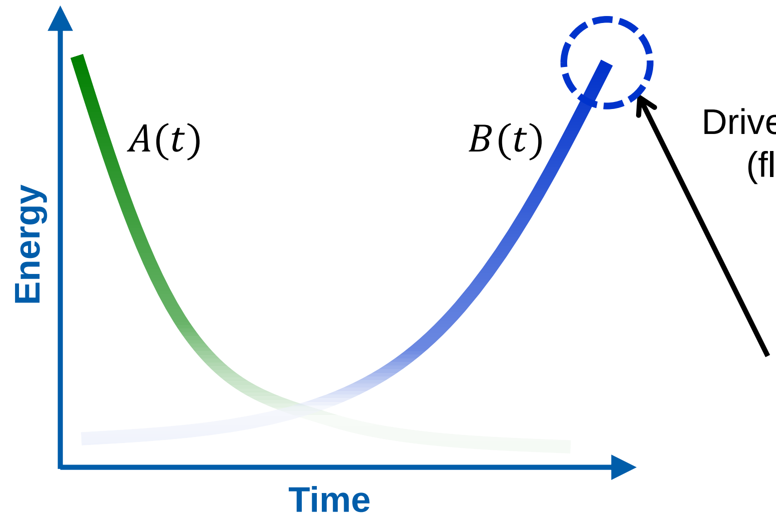
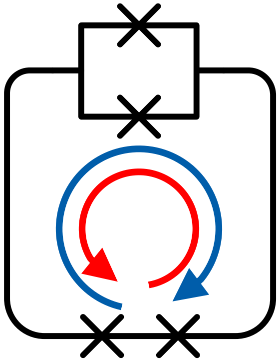
problem variables

$$H(t) = -A(t)\underbrace{\sum_i \sigma_x^i}_{\text{Driver Hamiltonian (fluctuations)}} + B(t)\underbrace{\left(\sum_i h_i\sigma_z^i + \sum_{i<j} J_{ij}\sigma_z^i\sigma_z^j\right)}_{\text{Problem Hamiltonian}}$$



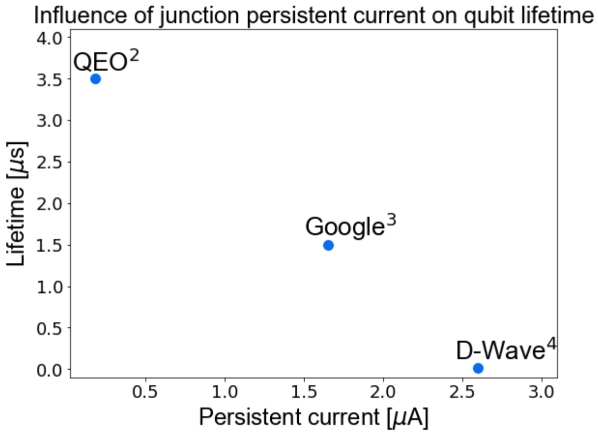
Qubit states at the end of the anneal encode the answer (bit configuration for the solution)

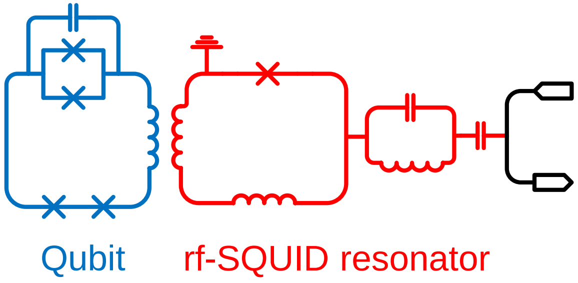
- Flux qubit states are circulating currents
- Small-junction C-shunt flux qubits have tiny circulating currents (~ 100 nA) – must be measured with high fidelity



Low Persistent Current Flux Qubits Present Unique Challenge For Readout

- There is a strong correlation between the size of persistent currents and flux noise
- QEO C-shunt flux qubits rely on low persistent currents to achieve high coherence but produce small readout signal[1]
- Previously demonstrated persistent current readout couples rf-SQUID tunable resonator directly to qubit[2]
  - Capable of high-fidelity readout but is slow
  - Fast readout requires low-Q resonator which needs to be isolated from qubit to maximize coherence





[1]Yan *et al.*, Nat. Comm. 7, 12964 (2016)
[2]Novikov *et al.*, arXiv:1809.04485
[3]Quintana *et al.*, PRL 118, 057702 (2017); AQC 2018
[4]R Harris *et al.* New J. Phys. **11** 123022 (2009)
-No published T_1 data available; https://www.youtube.com/watch?v=CrPQvDt8MlU

Readout Solution: Quantum Flux Parametron (QFP) Amplifies Small Qubit Signal and Provides Isolation

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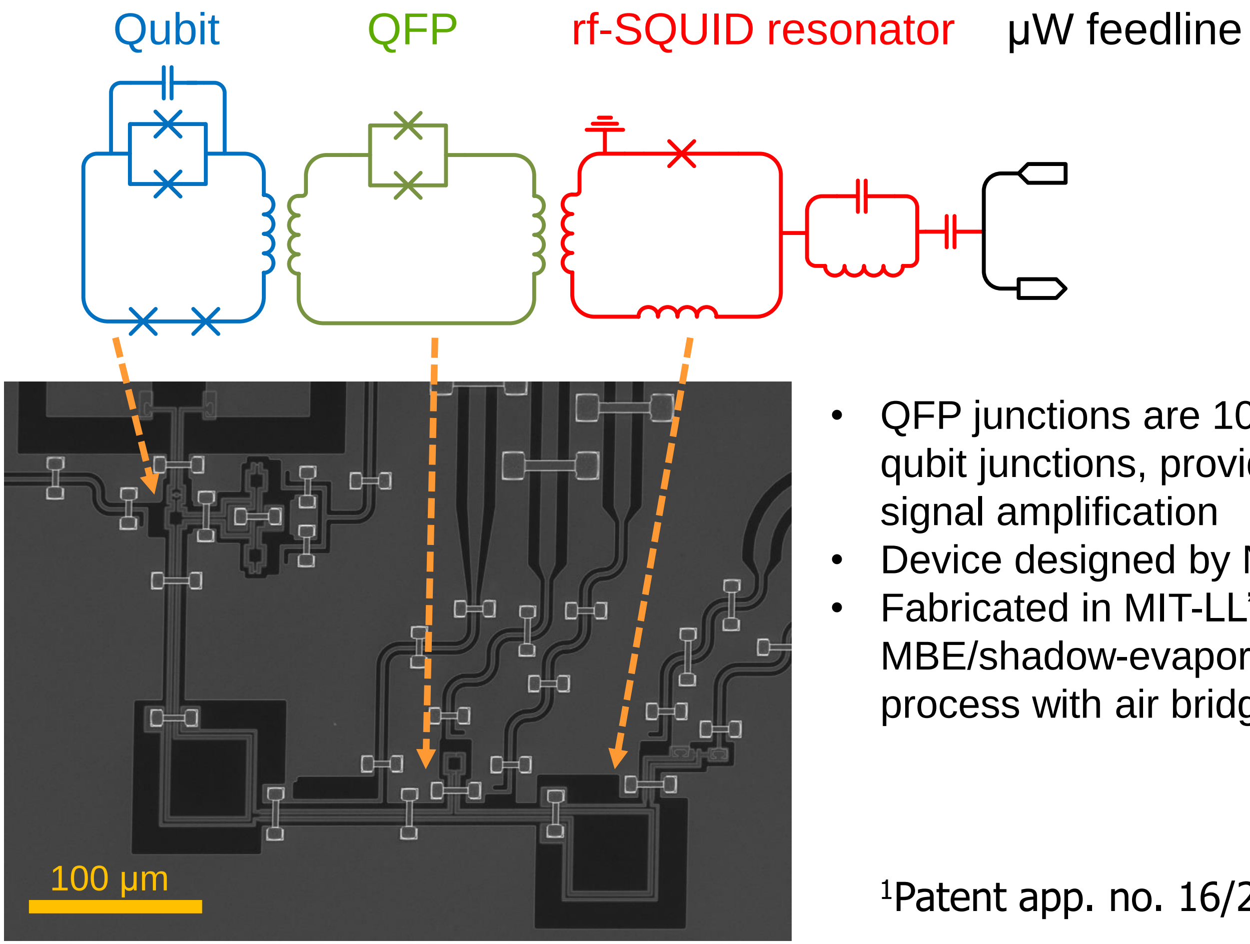
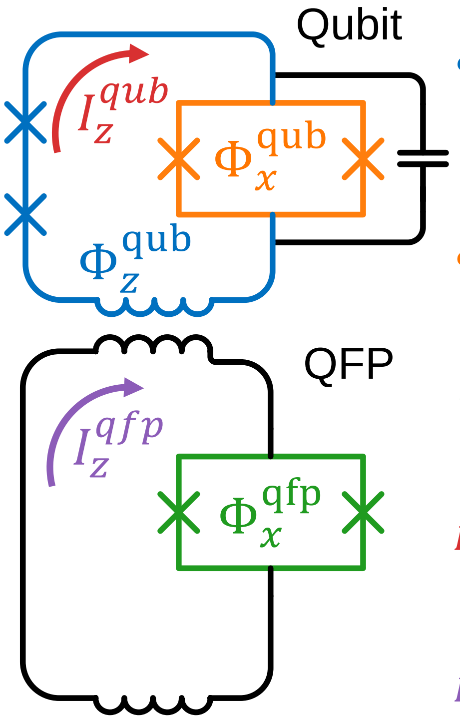


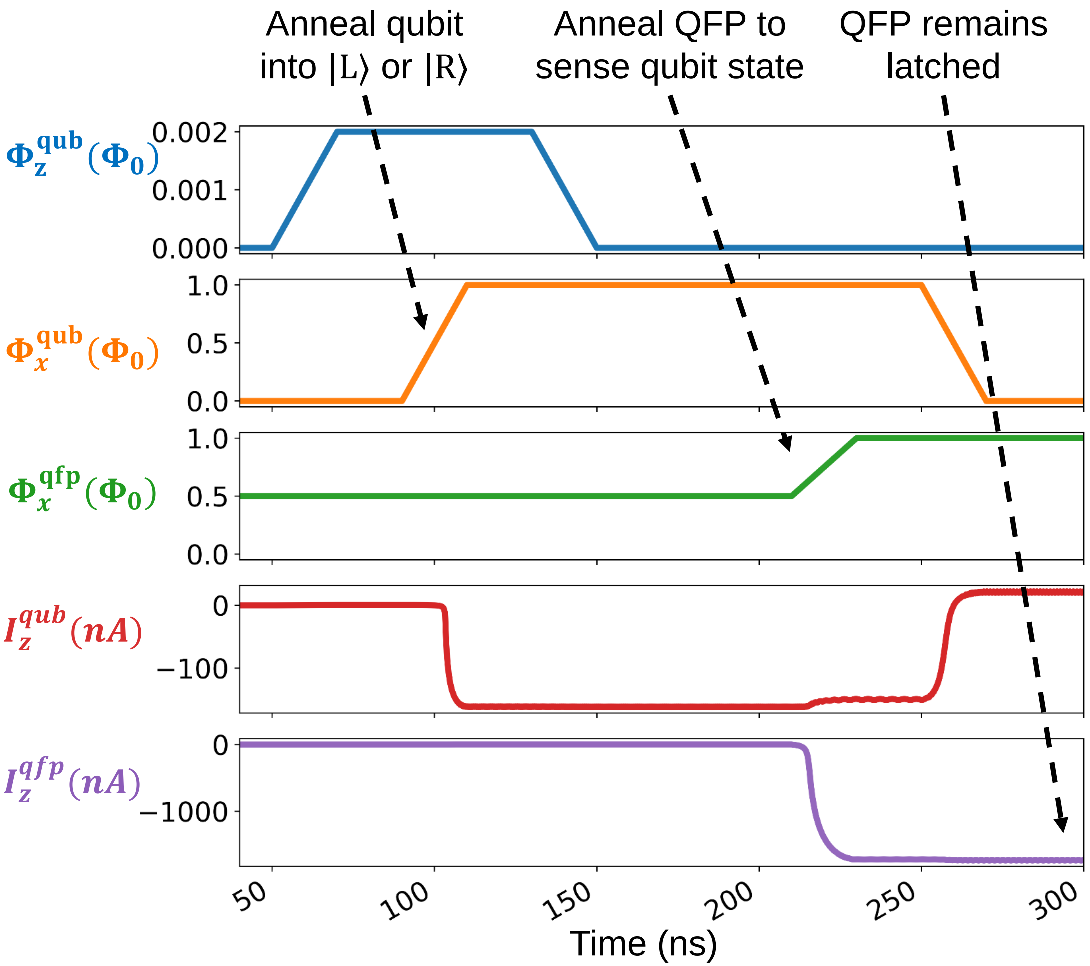
Image provided by MIT-LL

- QFP junctions are 10x larger than qubit junctions, providing small-signal amplification
- Device designed by NGC[1]
- Fabricated in MIT-LL's hybrid MBE/shadow-evaporated Al process with air bridges

[1] Patent app. no. 16/277,560

WRspice Simulations Confirm QFP Latching




Anneal qubit into |L⟩ or |R⟩

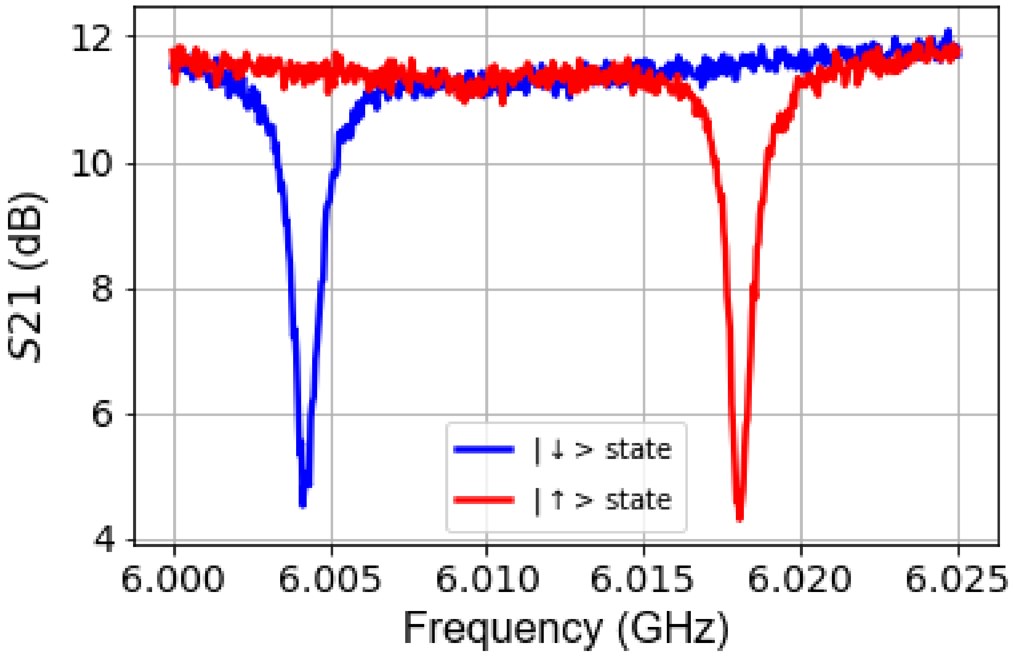
Anneal QFP to sense qubit state

QFP remains latched

Qubit Persistent Current States Produce Large Shifts in QFP Transition

- The latched QFP persistent-current state induces a large flux into the tunable resonator

- The state-dependent shift in the resonator allows us to discriminate the qubit state with high fidelity



Single-Shot Measurements are Thresholded to Obtain Fidelity and Qubit Transition Width

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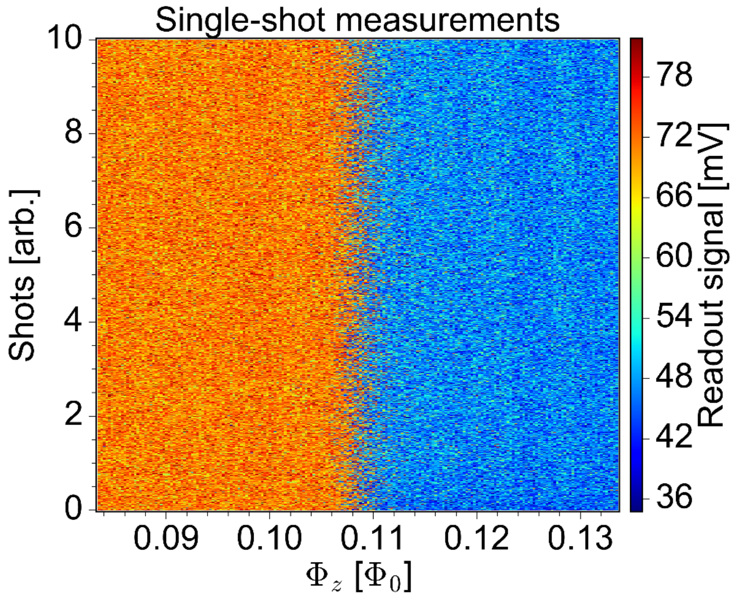
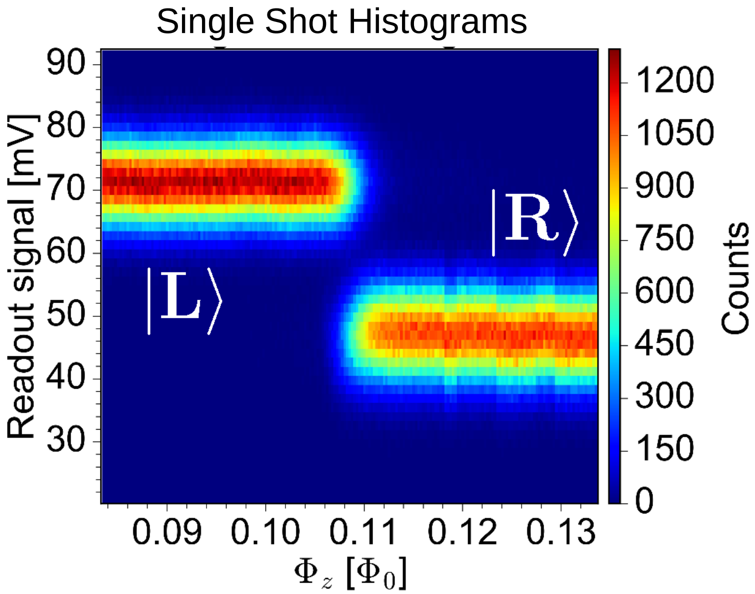


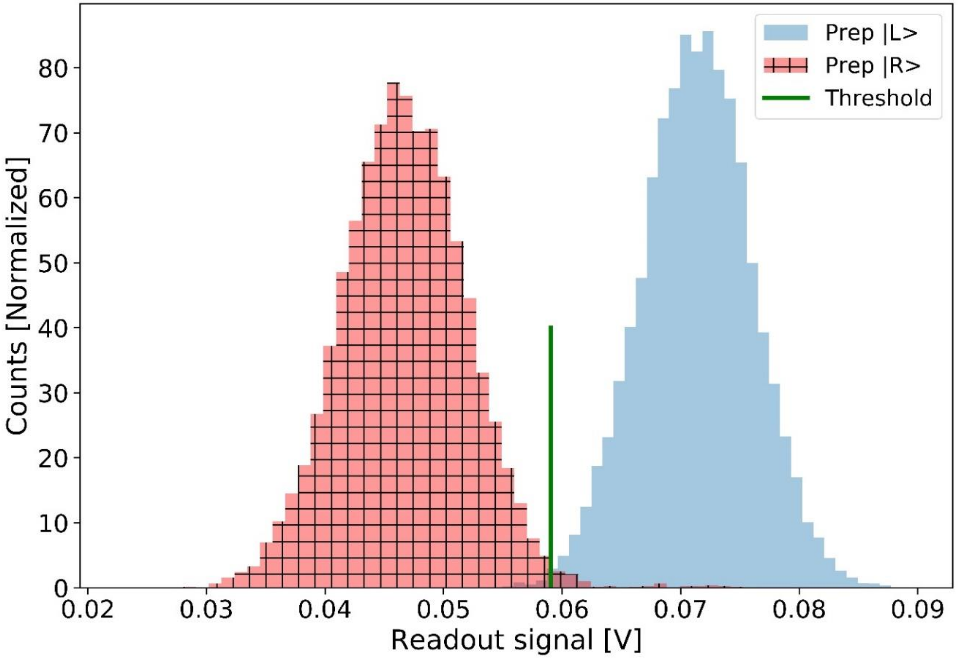


- The readout tone sits at a frequency to provide good contrast between left and right states

- We collect many repetitions of single-shot measurements, which are then histogrammed

- For this data, the qubit was annealed in 1 us, the QFP in 10 ns, and the signal was integrated for 80 ns

Readout Fidelity of >99% Demonstrated



- We threshold the data to convert to persistent-current-state probabilities
- Fit to simple model to extract width, which scales inversely with critical current
- Achieved 99% fidelity in 90 ns (10 ns anneal & 80 ns integration)
- Highest observed fidelity: 99.9 % in 1 us

Flux Qubit Transition Width Measured

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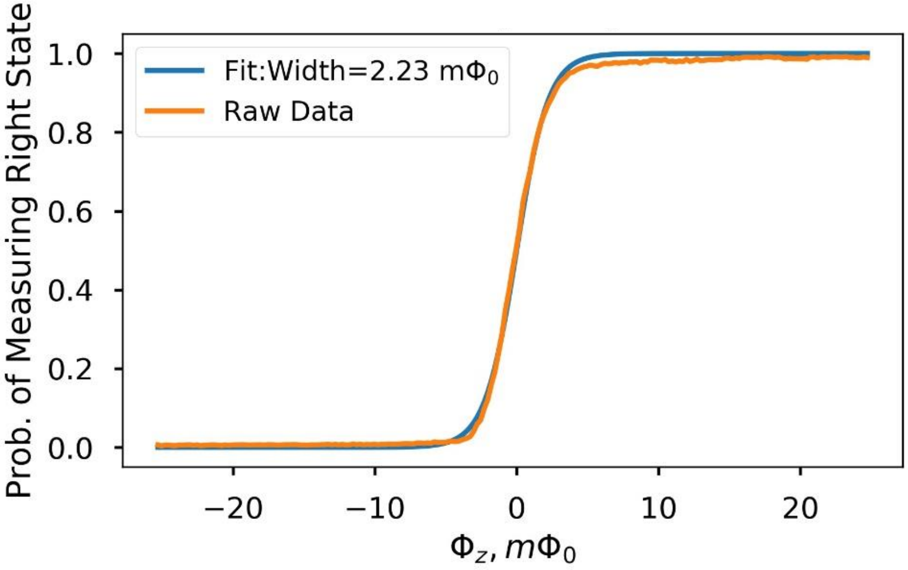


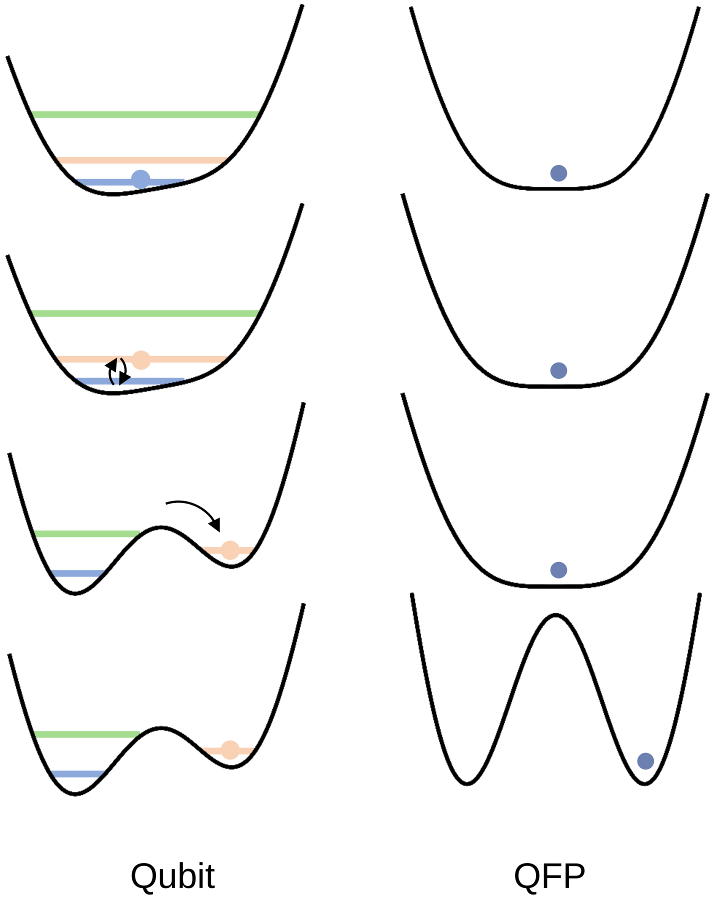
$$P_{|R>} = \frac{1}{2}\left[1 + \tanh\left(\frac{\Phi_z^{ex} - \Phi_z^{o}}{W}\right)\right]$$

- Threshold data to convert to persistent-current-state probabilities
- Fit to simple model to extract width, which scales inversely with critical current

R. Harris et al., Phys. Rev. B **81**, 134510 (2010)

Preparing and reading out an excited state without a dispersive resonator

1. Apply initial tilt bias to qubit z-flux, within one macroscopic resonant tunneling (MRT) spacing
2. Microwave drive resonantly excites the qubit
3. Qubit is annealed; ground/excited states map to left/right wells. QFP persistent current is suppressed.
4. QFP is annealed from a flux sensitive point and enters a latched state.
5. Tunable resonator is probed by transmission of microwave tone.



Experimental demonstration of excited-state readout

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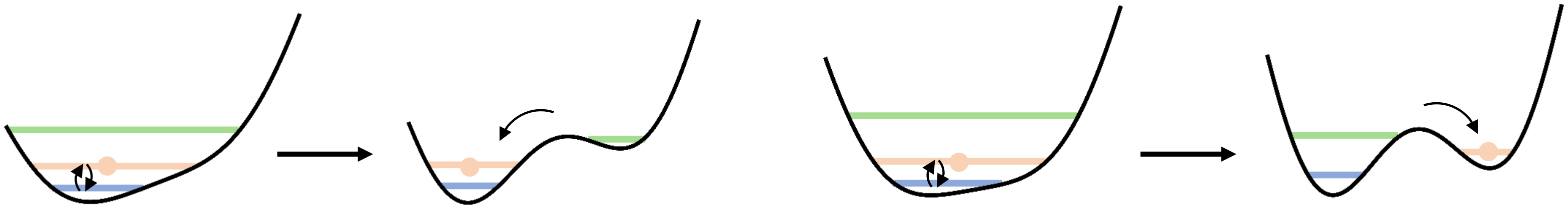
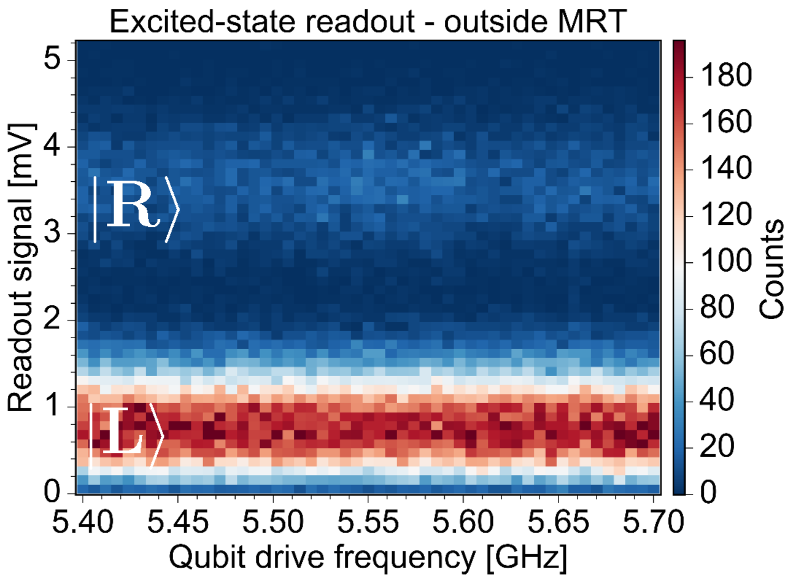
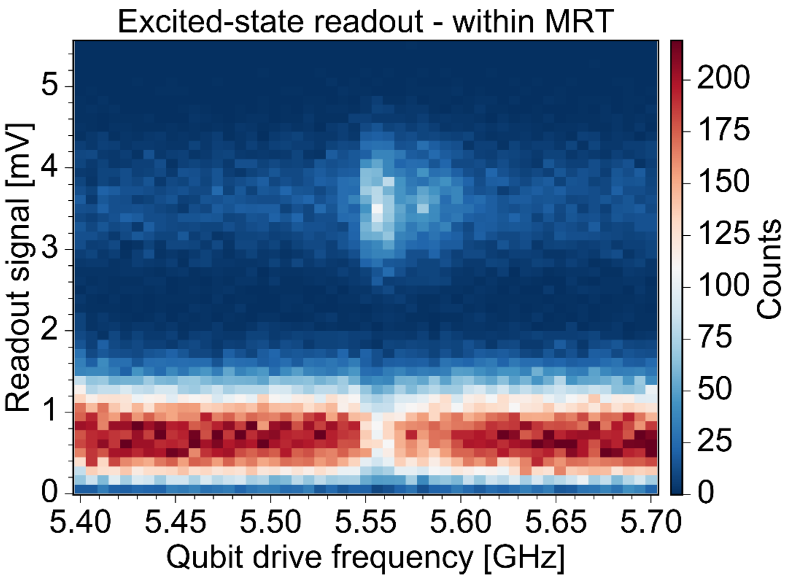



Excited-state readout - outside MRT


Excited-state readout - within MRT

Measuring qubit lifetimes with excited-state readout

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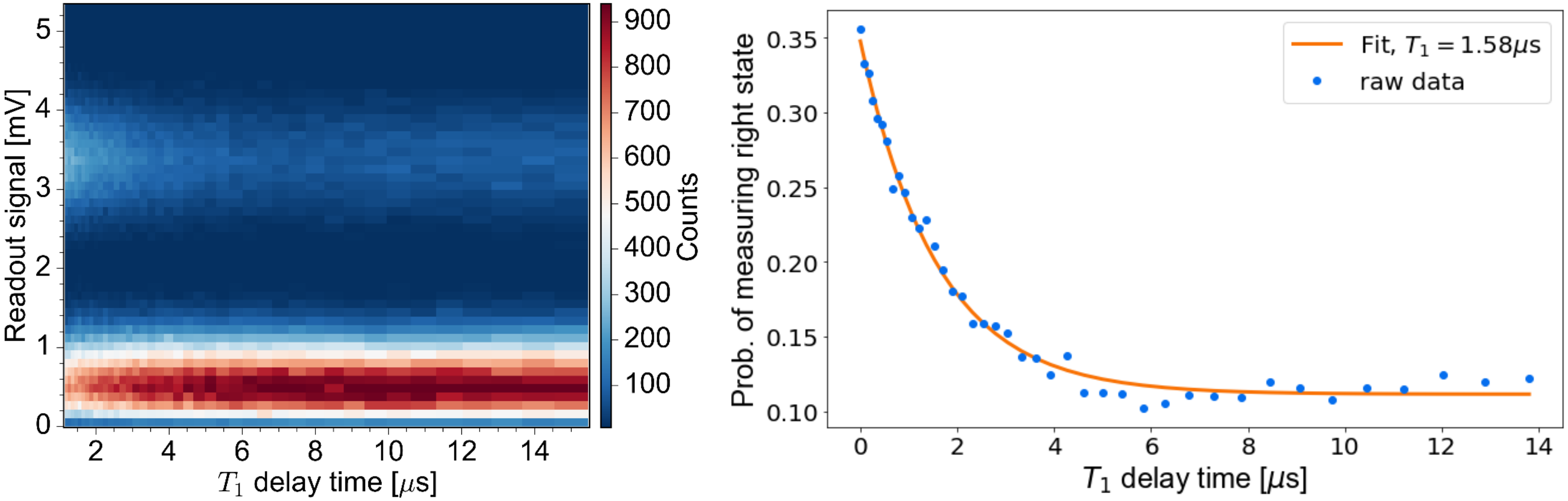

- Performed saturation pulse to prepare 50/50 ground/excited population
- Varied delay between state preparation and readout to measure lifetime
- Data taken for a qubit frequency of ~4.7 GHz

Fast, High-Fidelity Readout of a High-Coherence Flux Qubit For Quantum Annealing Demonstrated

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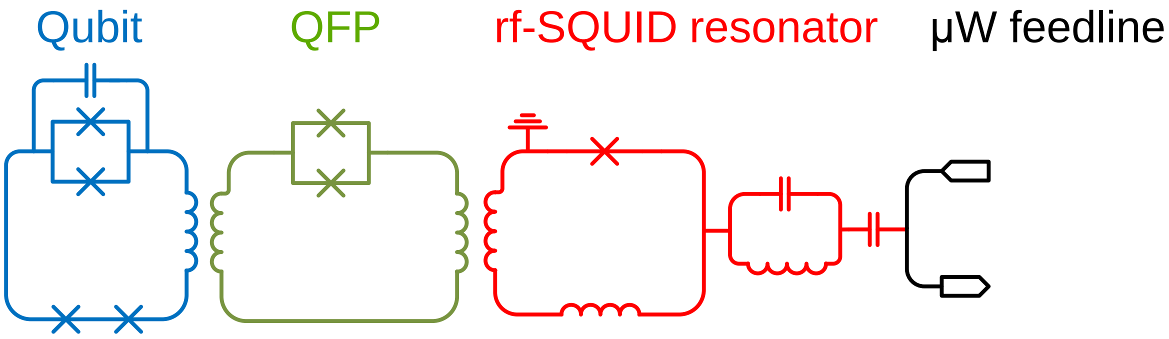
- Quantum flux parametron (QFP) provides a latched amplification of the qubit state while isolating the qubit from the low-Q readout resonator
- 10 ns latching and 80 ns integration results in > 99% readout fidelity (other measurements demonstrate that fidelity can be improved up to at least 99.9% with longer integration of 1 μs)



Acknowledgments

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