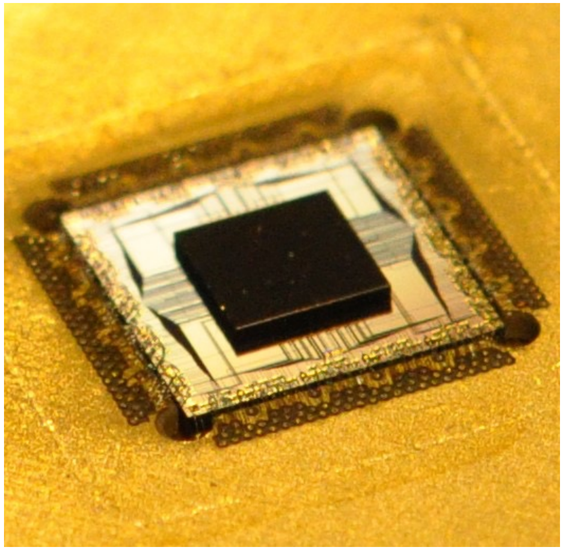
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), May 2022.
Invited presentation ED7-1-INV given at The International Symposium on Superconductivity, Virtual, December 2, 2021.

Quantum Flux Parametron Enabled Readout of High-Coherence Superconducting Qubits



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December 2, 2021

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Outline

- Conflict between High-Coherence and Fast Readout
- Quantum Flux Parametron (QFP) as the solution
  - Provides Amplification of the Qubit Signal
  - Provides Isolation from the Lossy Readout Circuit
- Reading Excited State Populations with QFP Readout

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*Grover, et al., PRX Quantum **1**, 020314 (2020)

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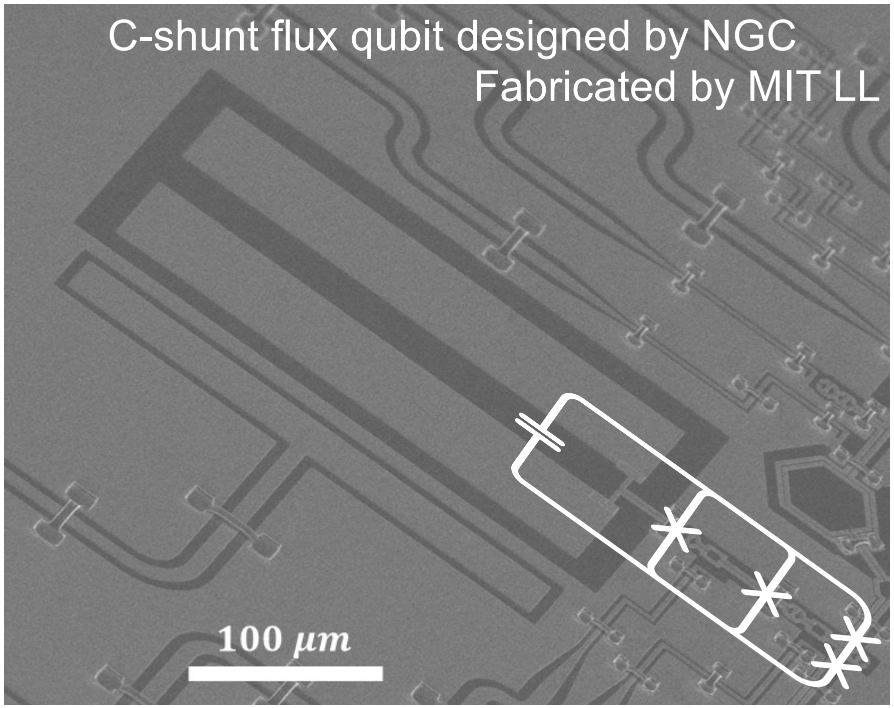
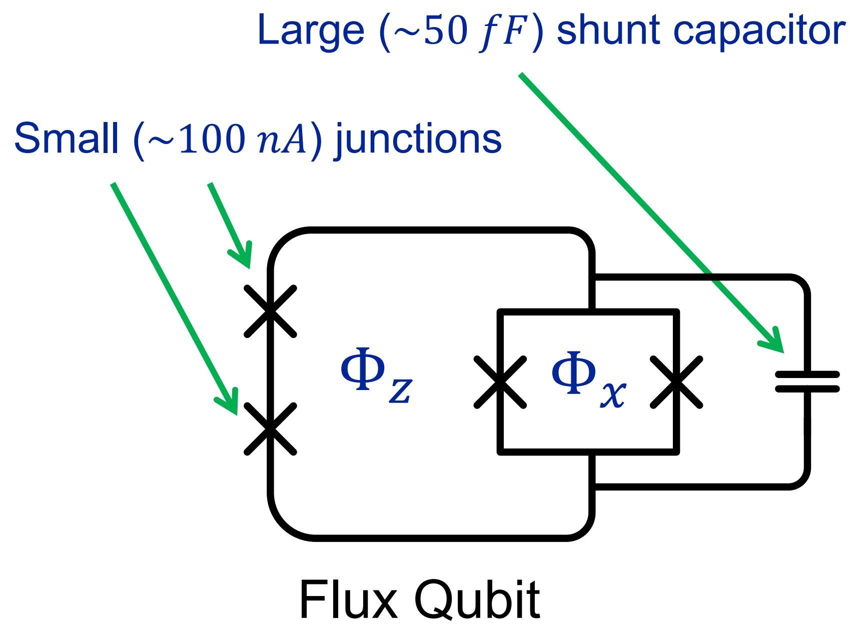
Superconducting Qubits Achieve High-Coherence By Keeping Electrical Signals Small





- Small persistent current reduces magnetic dipole moment
- Large shunt capacitor reduces electric field density
- High-quality hybrid MBE/shadow evaporated aluminum process
- $T_1, T_2 \sim 10$s of μs demonstrated in isolated 3-junction qubits[1z]

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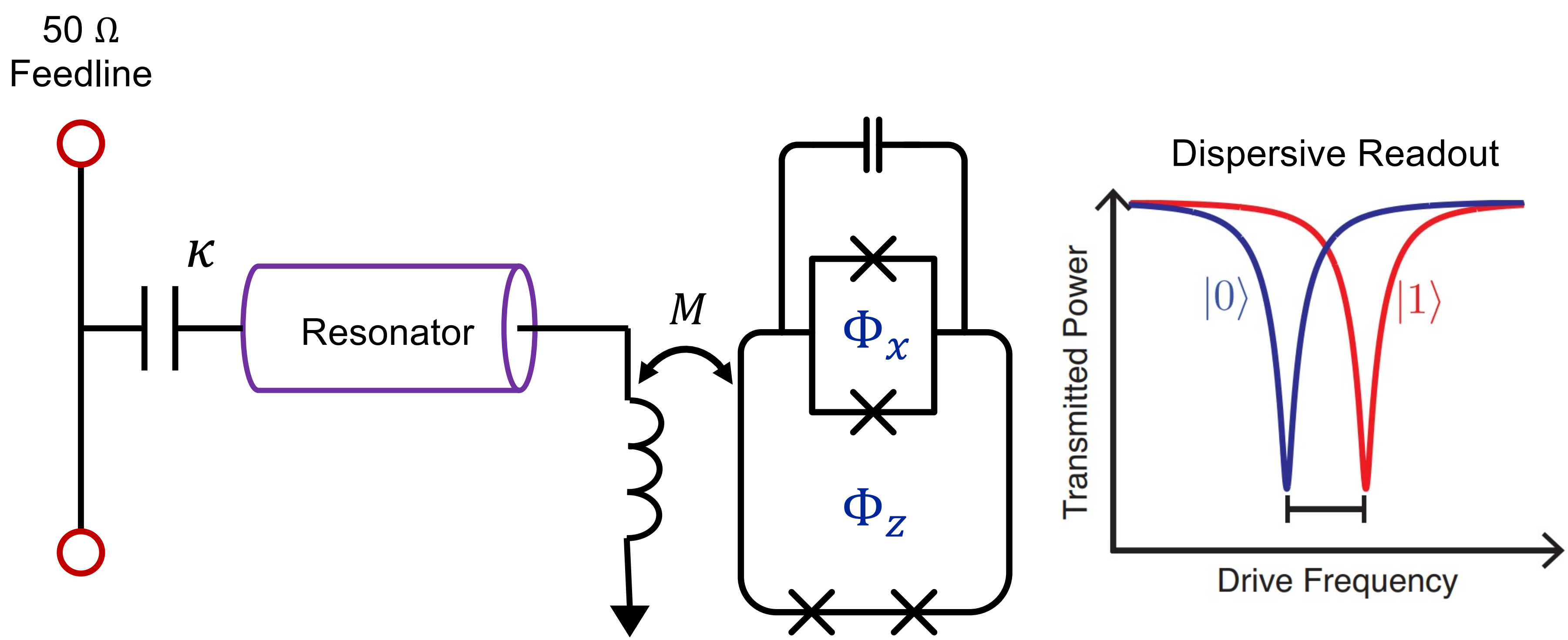
Strong Coupling to the Readout Circuitry is Necessary for Fast-Readout, but Leads to Decoherence



- A large mutual inductance, M, is necessary to get a large dispersive shift
- A strong coupling to the feedline, κ, is necessary for high-bandwidth measurement
- Coupling to the 50 Ω feedline leads to energy dissipation in the qubit

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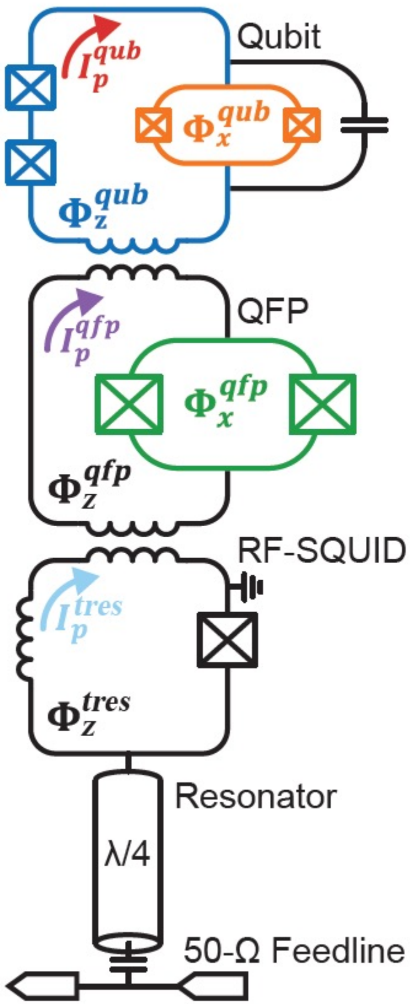
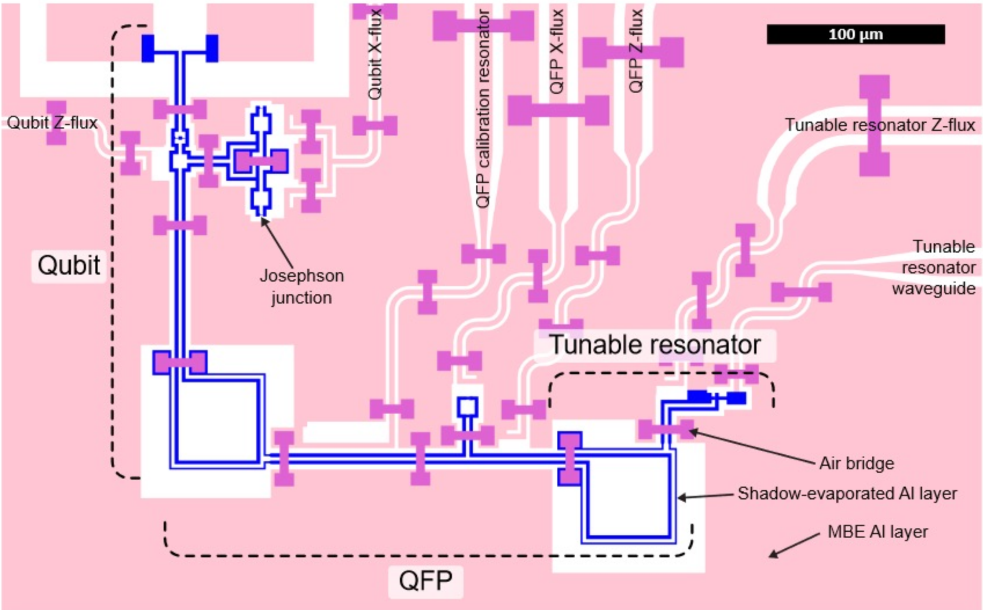
Quantum Flux Parametron (QFP) Can Provide Both Strong Coupling and Isolation from the Environment





- When the QFP is annealed, it assumes a DC circulating current, I_p^{qfp}, that depends on the state of the qubit
- The QFP provides a flux-tunable mutual inductance between the flux qubit and the readout resonator
- When $\Phi_x^{qfp} = 0.5\Phi_0$ it presents zero effective mutual inductance to the readout

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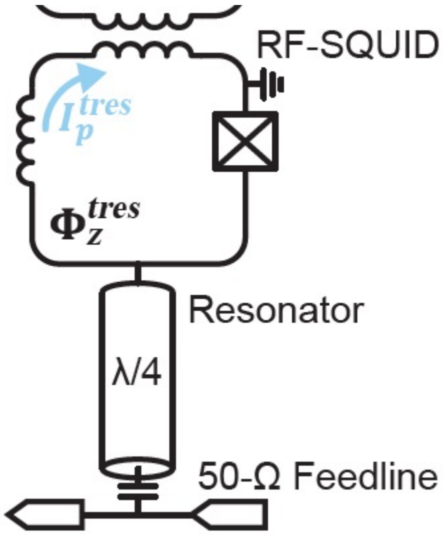
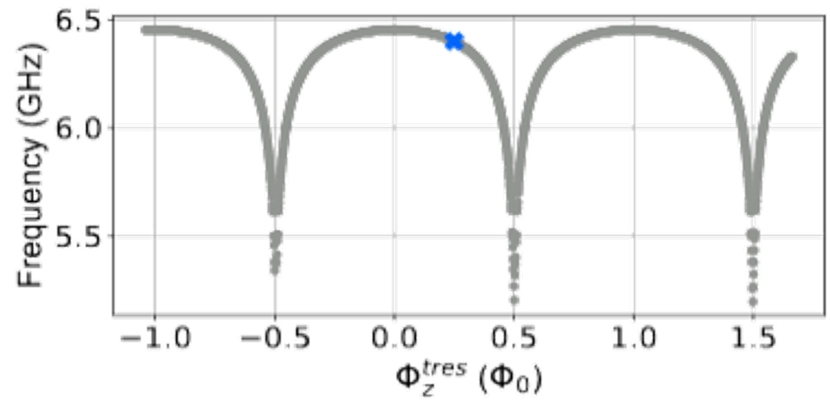
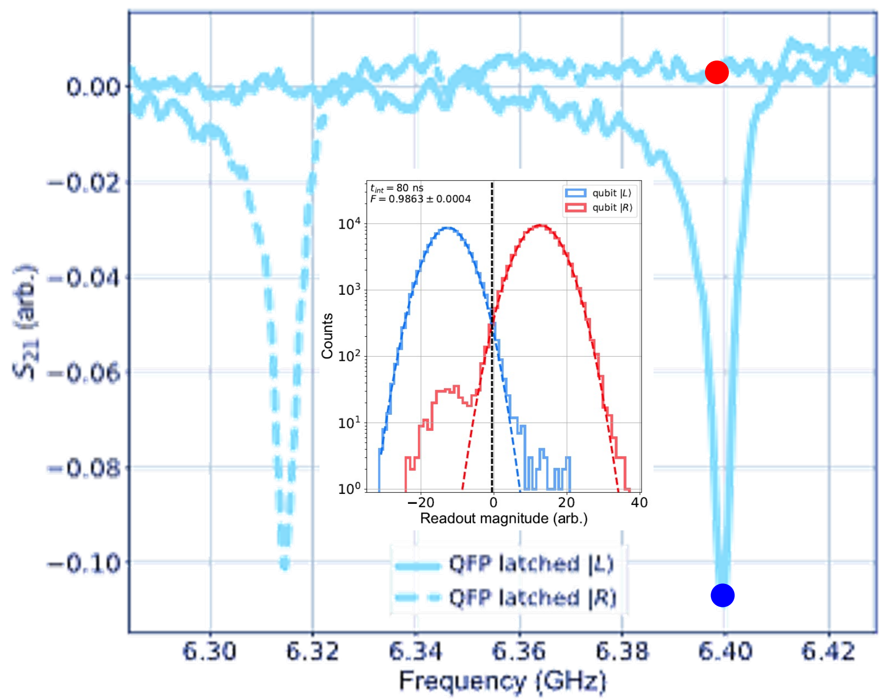
Flux-Tunable Resonator Used as Final Stage of Readout Chain







- DC Flux detected by the RF SQUID alters the electrical length of the resonator
- Resonator is strongly coupled to the feedline allowing for fast interrogation
  - $Q_e = 760$
  - 98.7% Visibility in 80 ns
  - >99.9% Visibility in 1 μs

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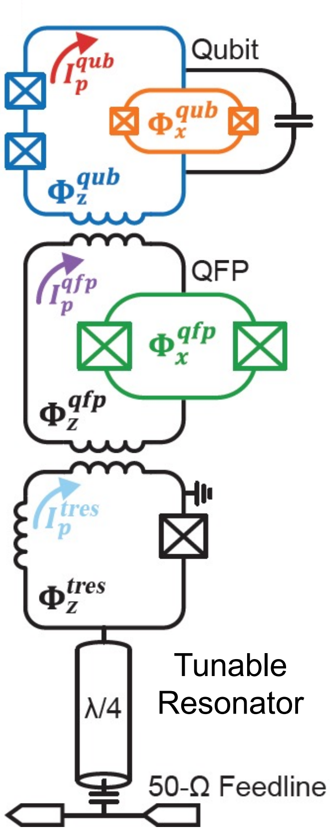
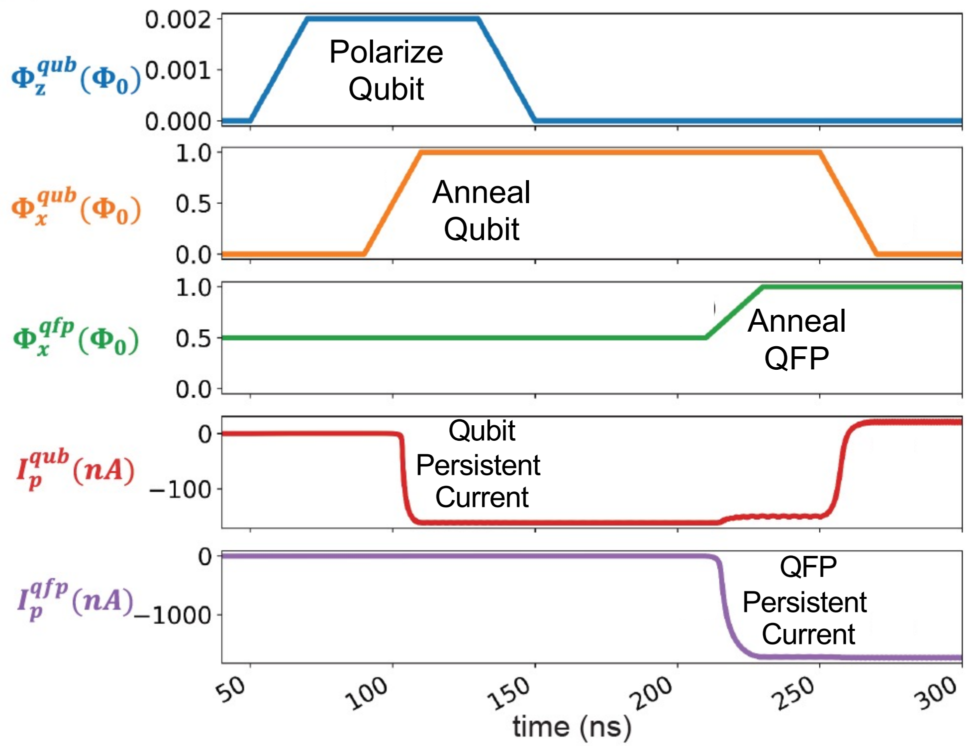
QFP Acts as Amplifier for Qubit Signal





- The QFP idles at $\Phi_x^{qfp} = 0.5\Phi_0$ to provide isolation during qubit operations
- After the flux qubit is annealed, the QFP is annealed
- WRSpice simulation of the circuit shows that the circulating current signal is amplified by an order of magnitude between the flux qubit and QFP

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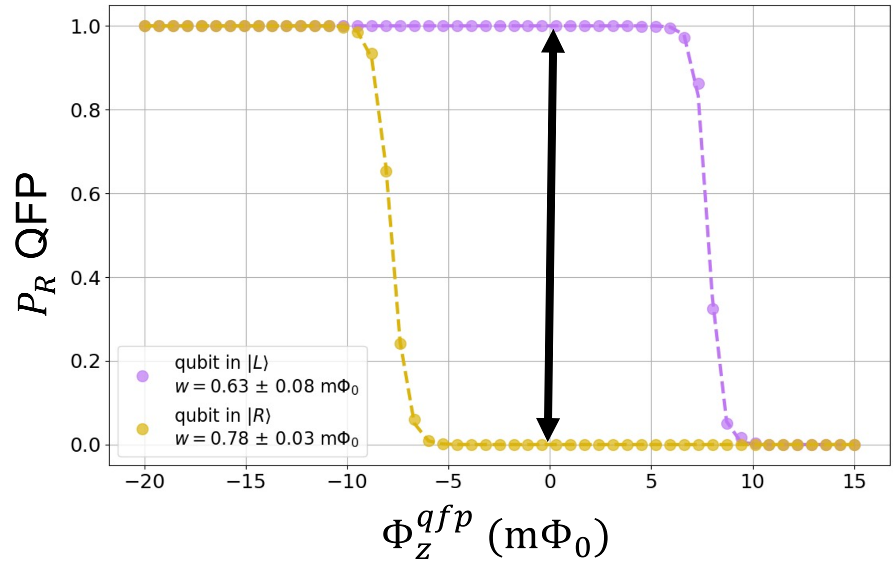
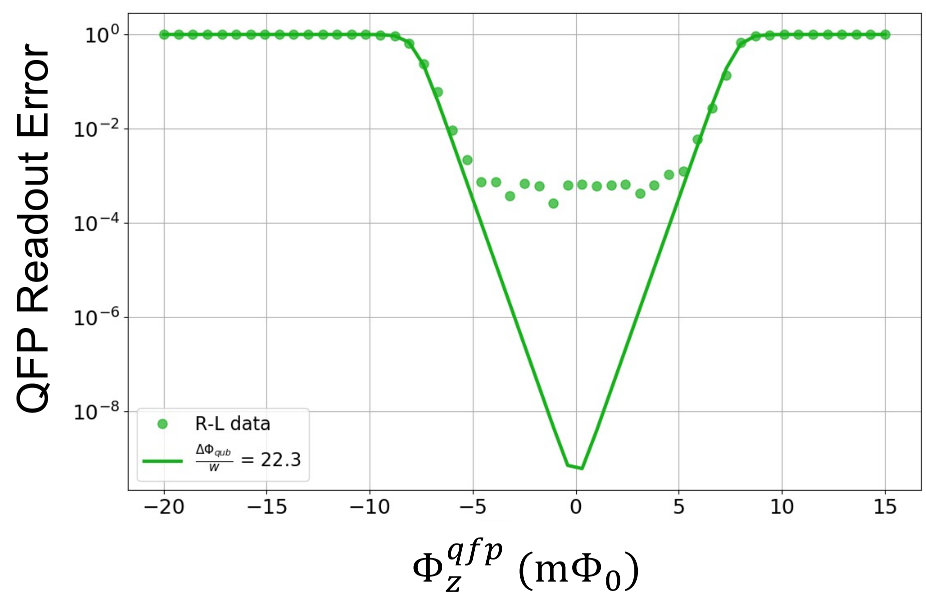
High-Visibility Readout Observed in the Flux Qubit-QFP-Tunable Resonator System

- Readout visibility is assess by comparing the QFP S-curve with respect to Φ_z when the flux qubit has been prepared in $|L\rangle$ and $|R\rangle$ circulating current states.
- Shift in QFP S-curve is 20 times larger than the intrinsic S-curve width.
- Floor in the QFP readout error is related to preparation fidelity of flux qubit $|L\rangle$ and $|R\rangle$

QFP is capable of amplifying the small persistent current for high-fidelity readout.





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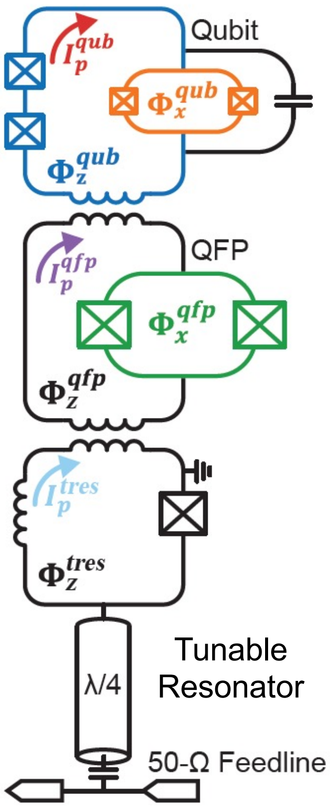
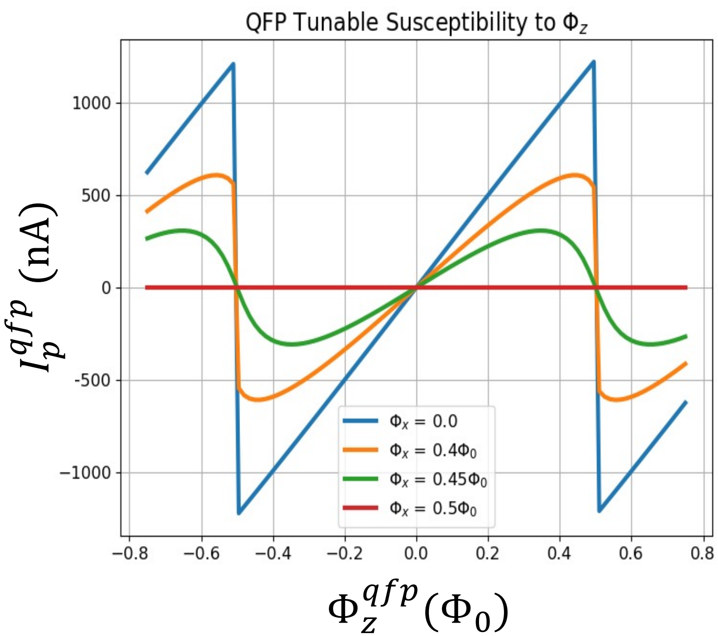
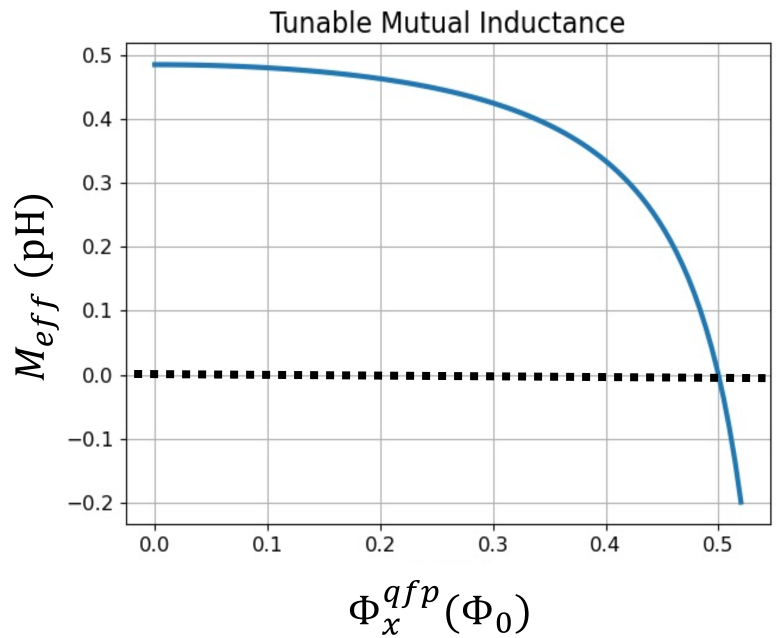
QFP Provides Isolation by Acting as a Tunable Effective Mutual Inductance to the Qubit



$$M_{eff} = M_{qub} M_{tres} \chi$$

$$\chi = dI_p / d\Phi_z$$





- The magnetic susceptibility, χ, of the QFP can be tuned with applied flux, Φ_x^{qfp}
- Tuning the effective mutual inductance, M_{eff}, to zero isolates the qubit from the lossy readout resonator.

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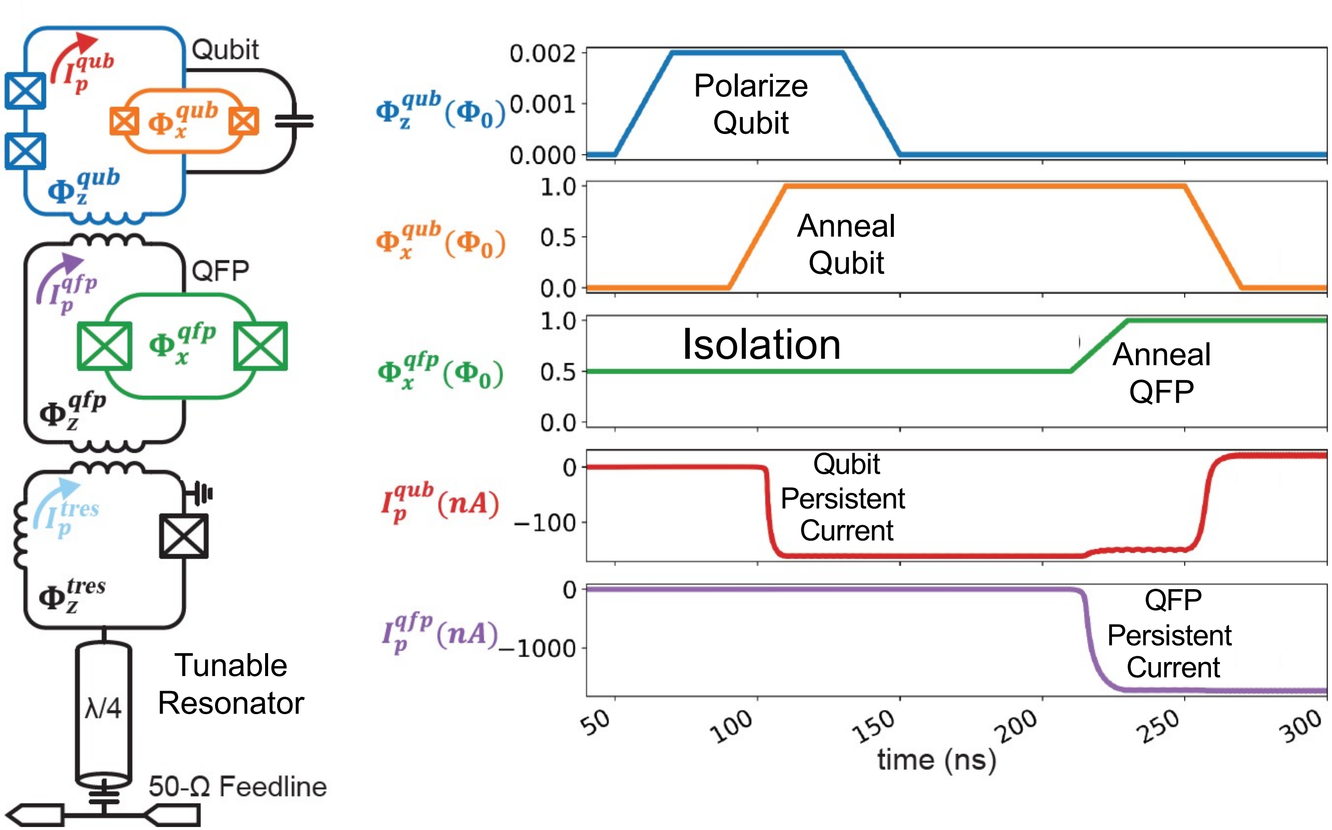
QFP Provides Isolation While Operations are Performed on the Qubit



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- WRSpice simulation of the circuit shows that the circulating current signal is amplified by an order of magnitude between the flux qubit and QFP

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Pause to Acknowledge Our Forefathers

- D-Wave has been using QFPs to amplify and lock in the state of their qubits since before the D-Wave One (2009).
- Using a tunable RF SQUID as an intermediary between the qubit and the readout circuit goes back to John Clarke's group and the INSQUID (2001).
- The question remained for us whether it would work for qubits with ~μs coherence times.

Superconducting device to isolate, entangle, and read out quantum flux states

T.L. Robertson,[1] B.L.T. Plourde,[1] Antonio García-Martínez,[1] P.A. Reichardt,[1] B. Chesca,[2] R. Kleiner,[2] Yuriy Makhlin,[3] Gerd Schön,[3] A. Shnirman,[3] F.K. Wilhelm,[4] D.J. Van Harlingen,[1,*] and John Clarke[1]

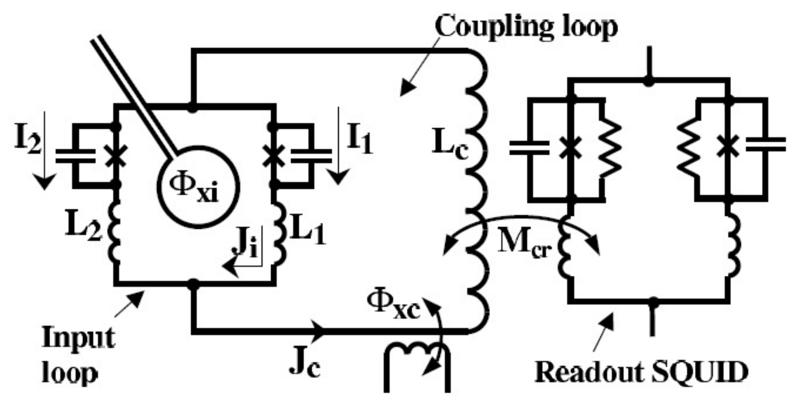

FIG. 1: Schematic of INSQUID with two flux bias lines coupled to readout dc SQUID with resistive shunts.

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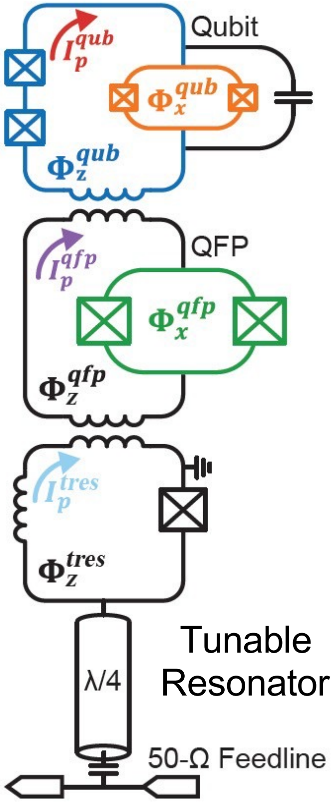
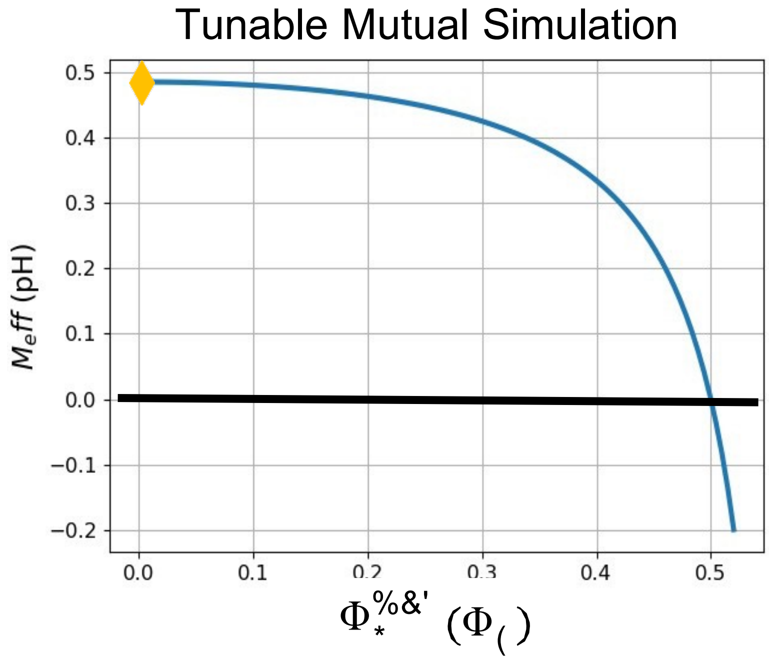
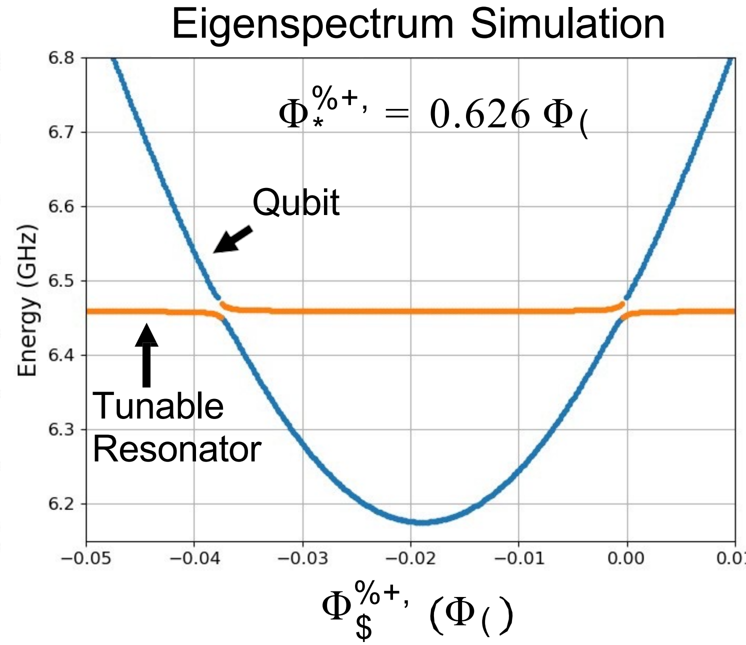
Coupling Between the Qubit and Tunable Resonator Creates an Avoided Crossing







- When $\Phi_{\$}^{"\#!} = 0$, the qubit is coupled to tunable resonator level and there should be an avoided crossing in the spectrum
- When $\Phi_{\$}^{"\#!} \approx 0.5\ \Phi_{\%}$, the levels should form a direct crossing with no gap
- The avoided and direct crossings were observed by probing the tunable resonator

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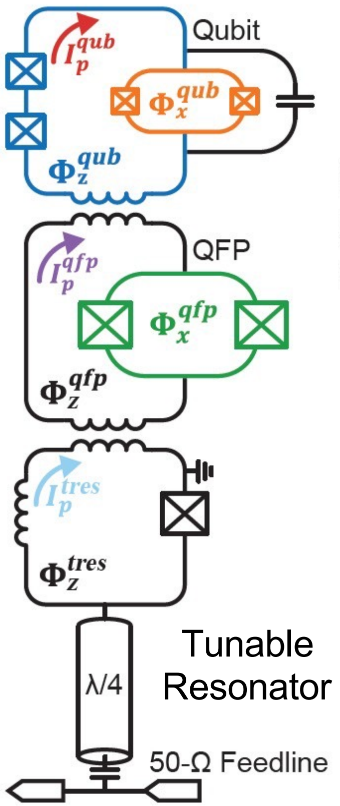
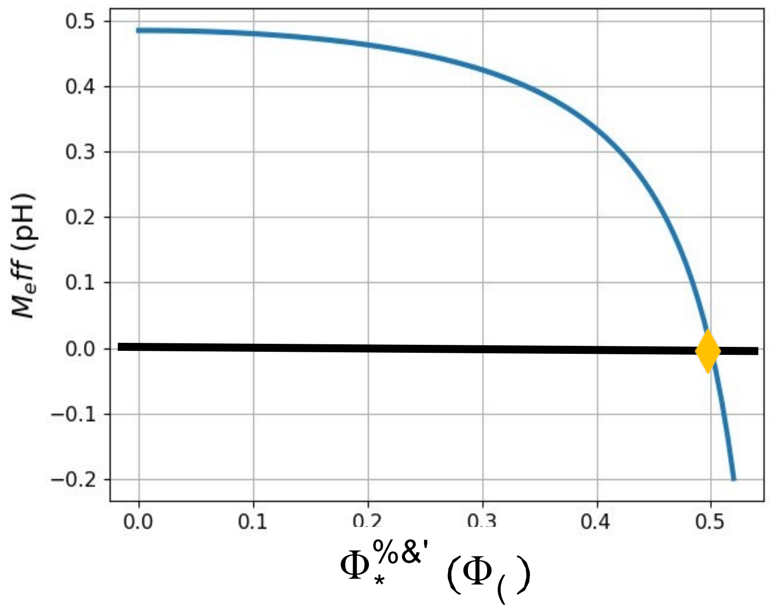
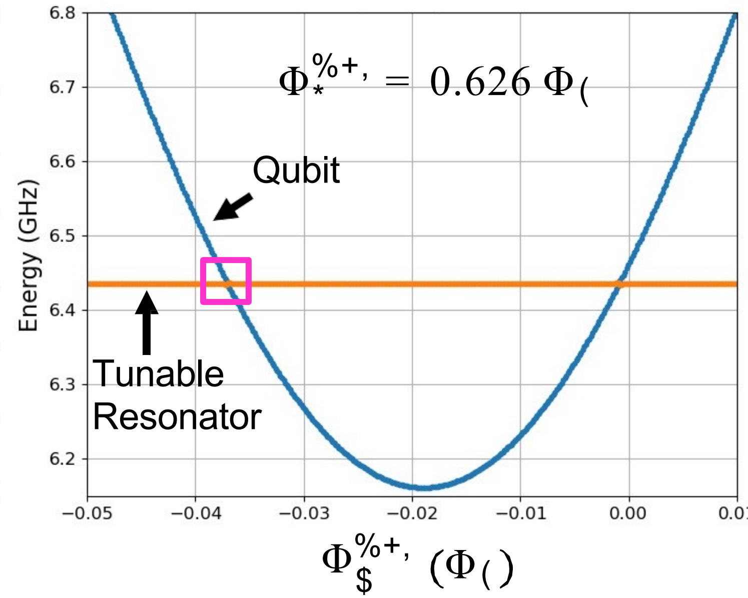


Tunable Mutual Simulation



Eigenspectrum Simulation



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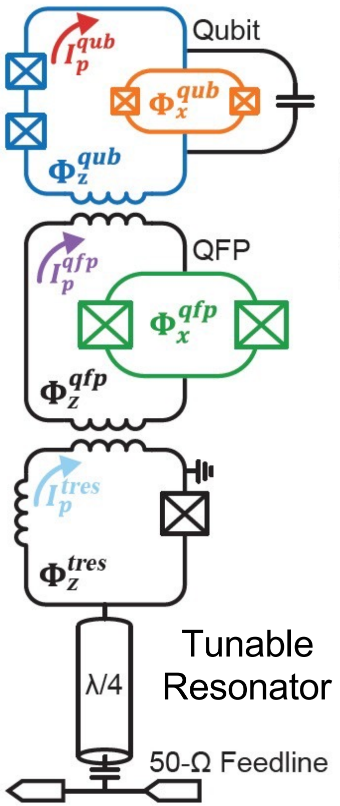

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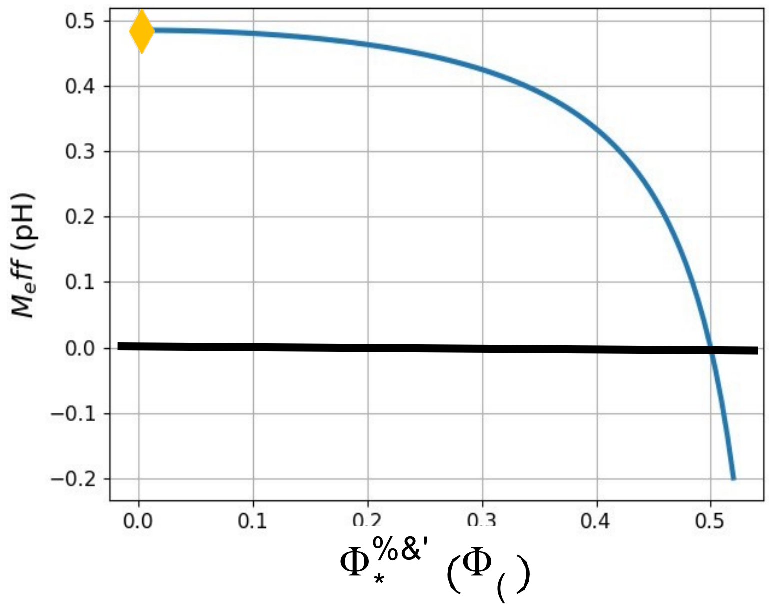
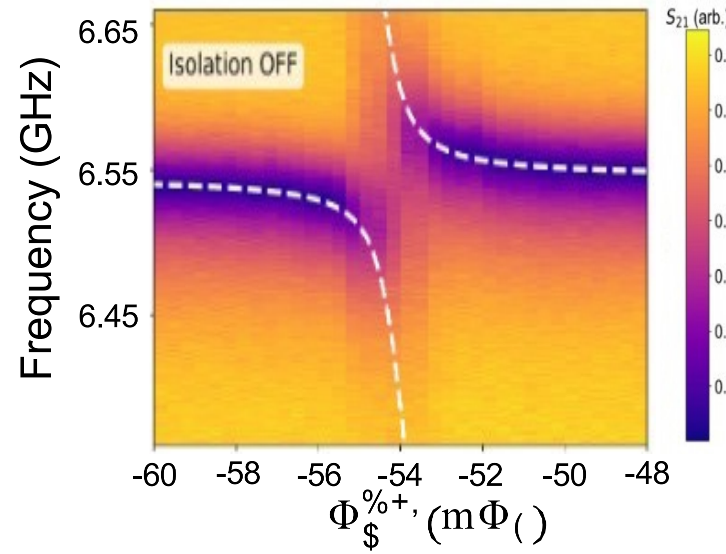


Measured Avoided Crossing



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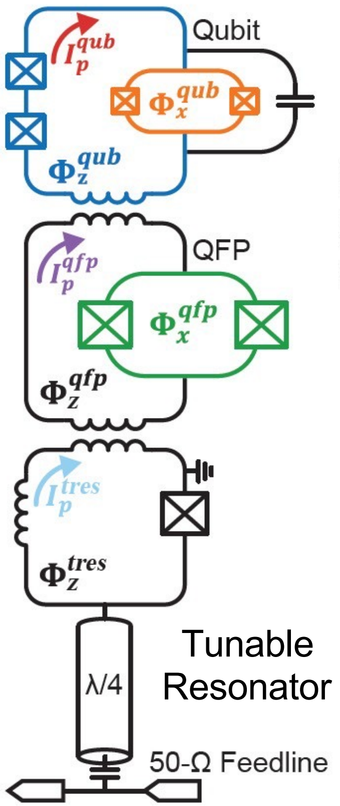

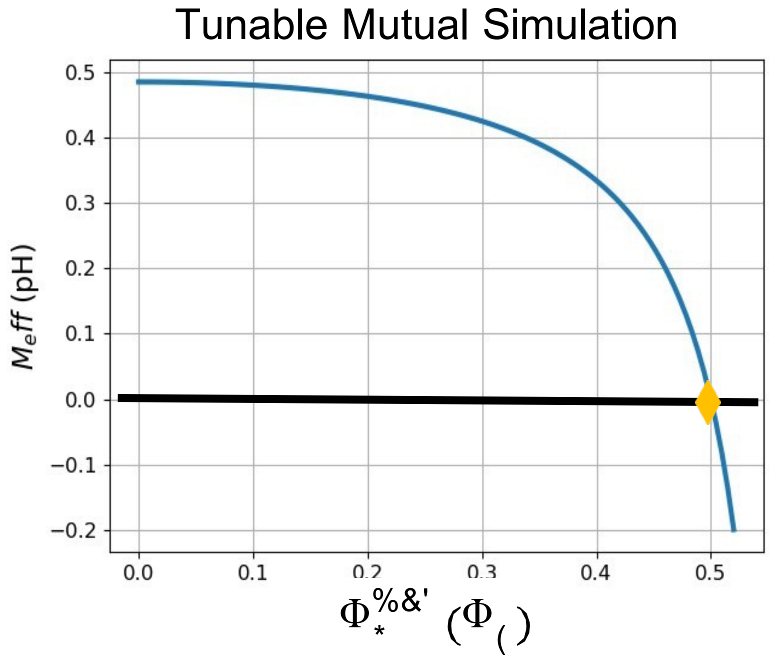

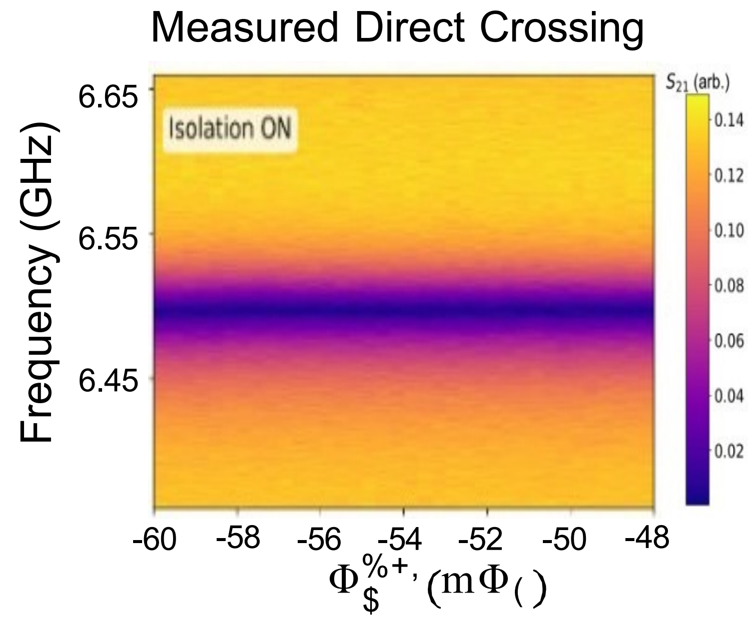

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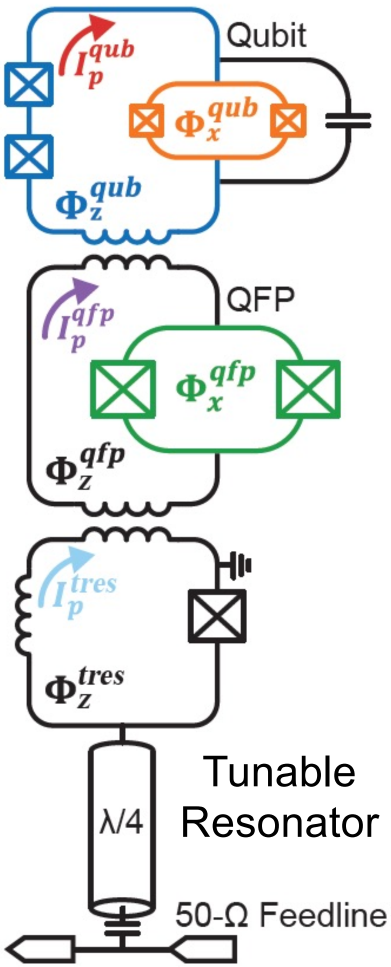
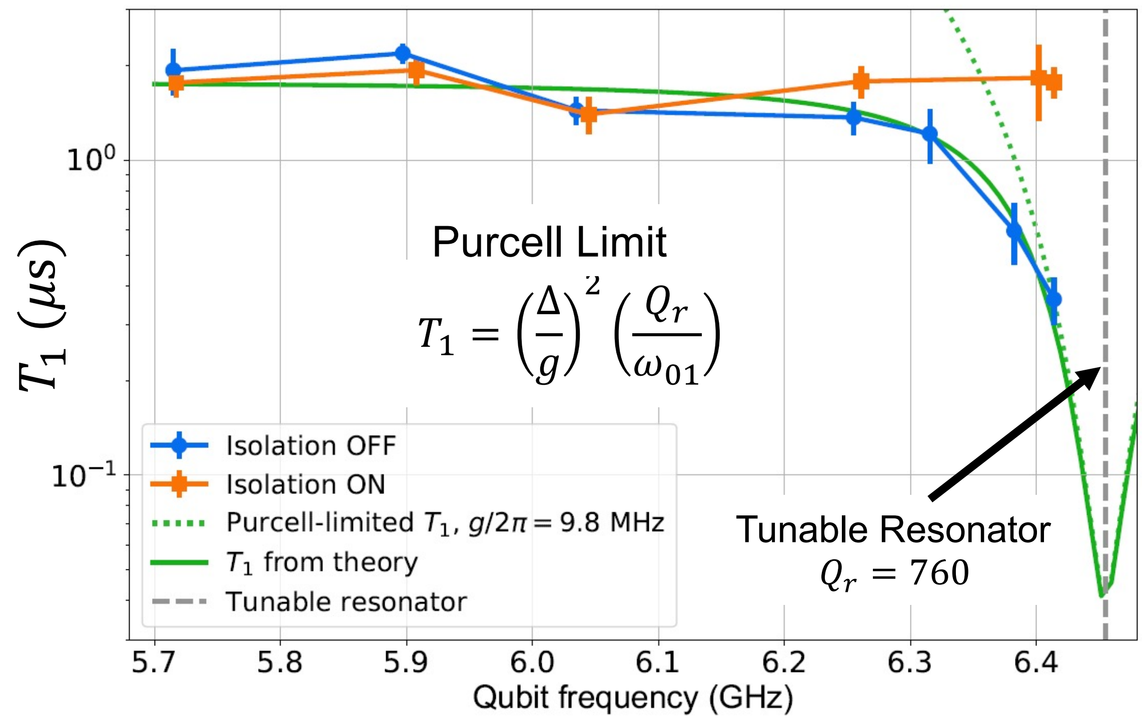
QFP Isolation Protects the Qubit from Purcell Loss into Tunable Resonator Readout



Flux Qubit Lifetime Measurements



- These measurements of T_1 performed with conventional dispersive readout
- Without QFP isolation, qubit lifetime decreased due to Purcell loss into readout resonator
- With QFP isolation, the qubit's lifetime was maintained at ~2 μs despite $\Delta = 200$ MHz of detuning.

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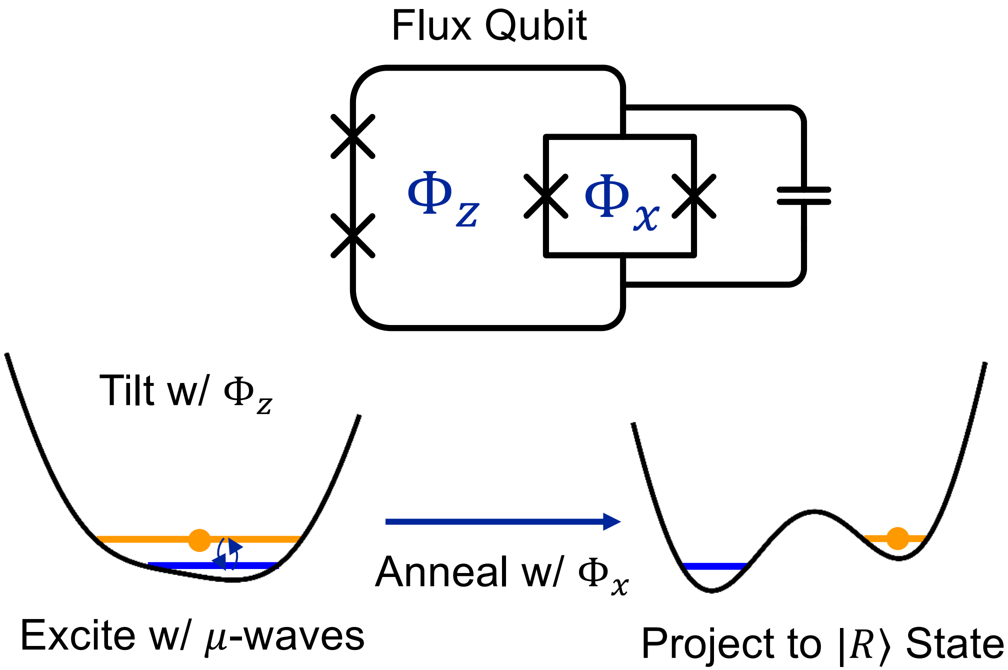
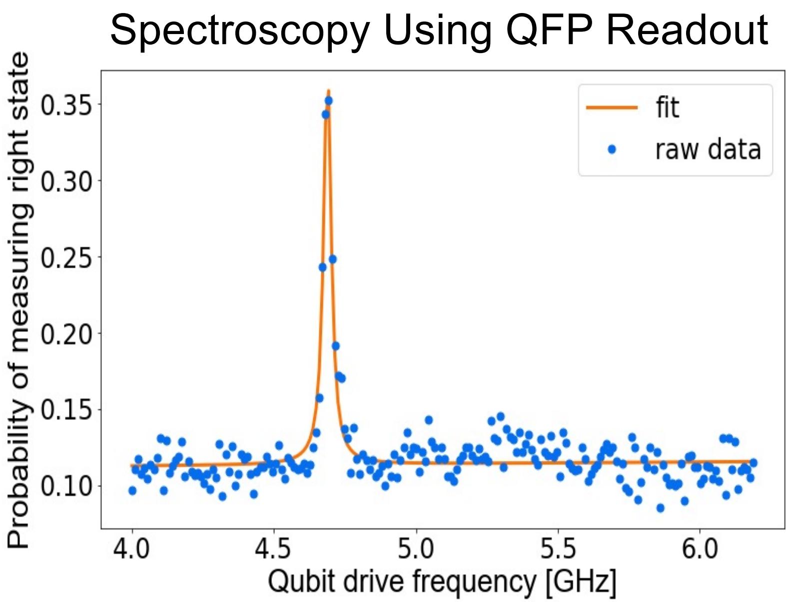
QFP Readout Can Sense an Excitation of the Flux Qubit $|1\rangle$ State



*Quintana, et al., PRL (2017)



- Initial measurements of T_1 were performed using conventional dispersive readout
- However, it should be possible to read an excitation of the flux qubit using the QFP and tunable resonator
- Spectroscopy shows an enhancement in $|R\rangle$ probability when μ-wave drive is resonant with flux qubit

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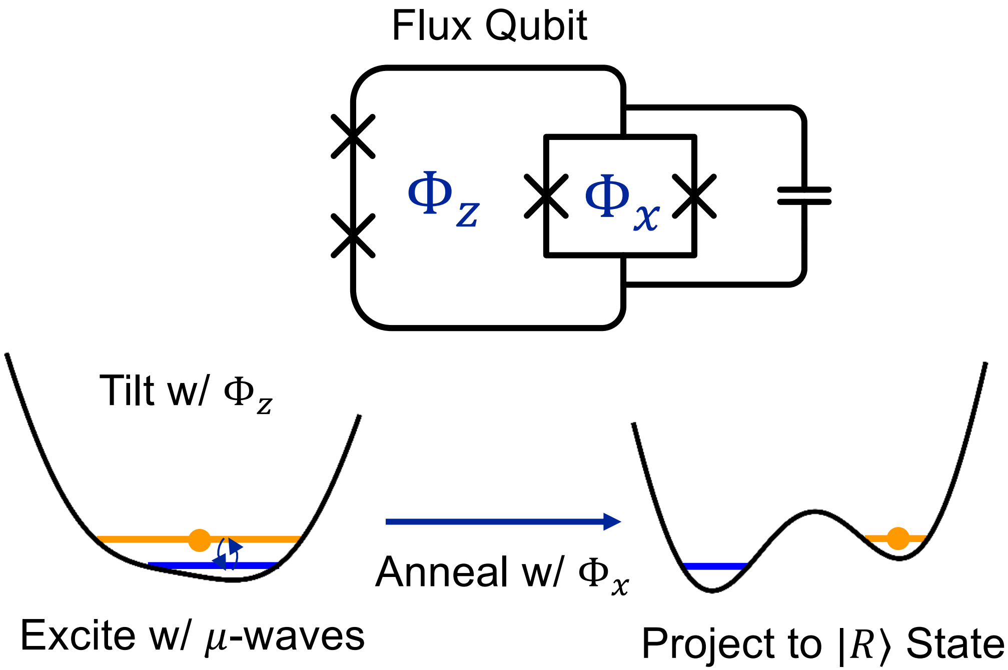

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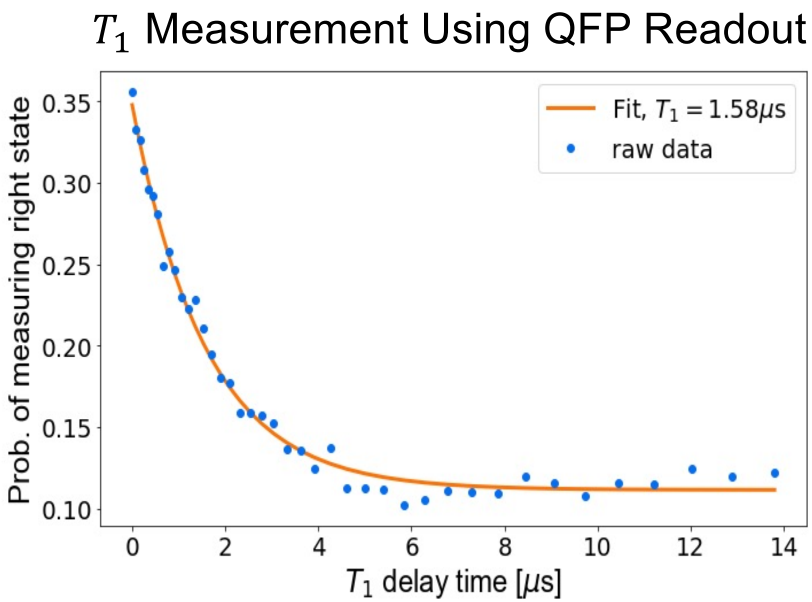
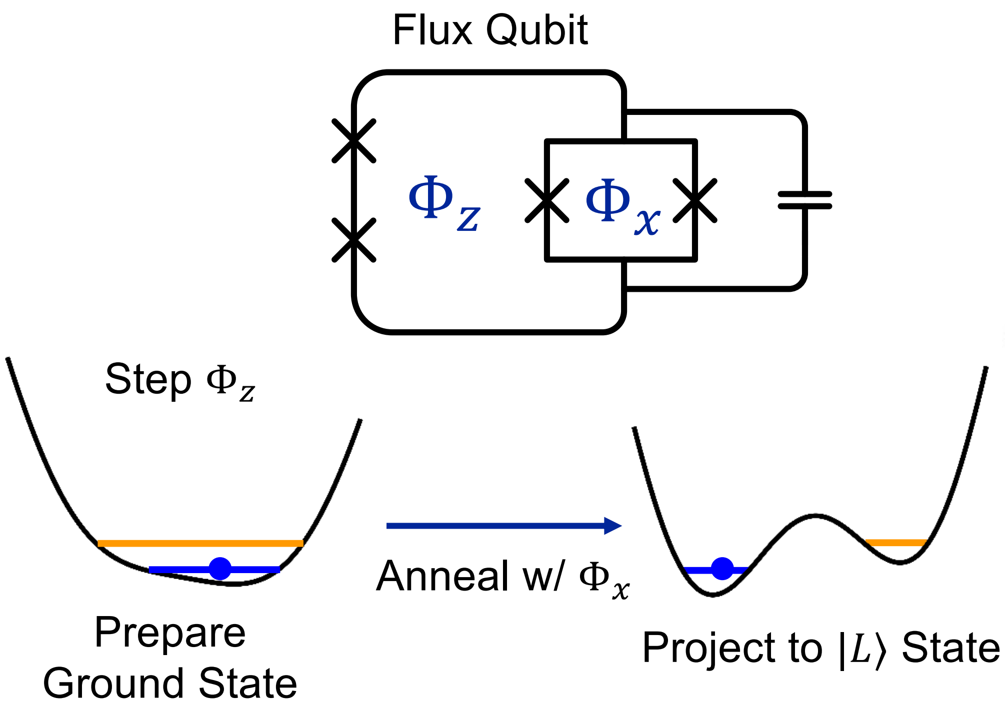
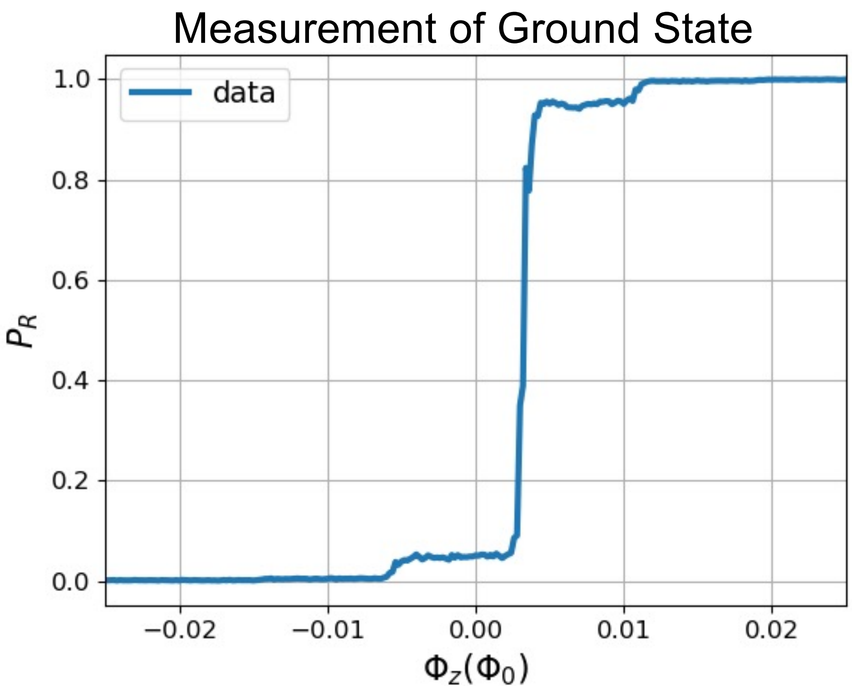


- T_1 of the state identified in spectroscopy is consistent with the measured using the dispersive resonator readout.
- This supports the conclusion that we are reading out the excited state of the flux qubit
- Excitation probability does not decay all the way to zero suggesting a significant thermal population in $|1\rangle$

Readout of Ground State Revealed Shoulders on the Flux Qubit Φ_z S-Curve





- Unexpected behavior exhibited in the S-Curve of the ground state.
- Expected to see a smooth transition from reading $|L\rangle$ to $|R\rangle$ as we swept the tilt on the flux qubit potential using Φ_z
- Within a small region near the 50/50 point, we saw "errors" in the ground state readout
- Needed to develop a model to explain this behavior

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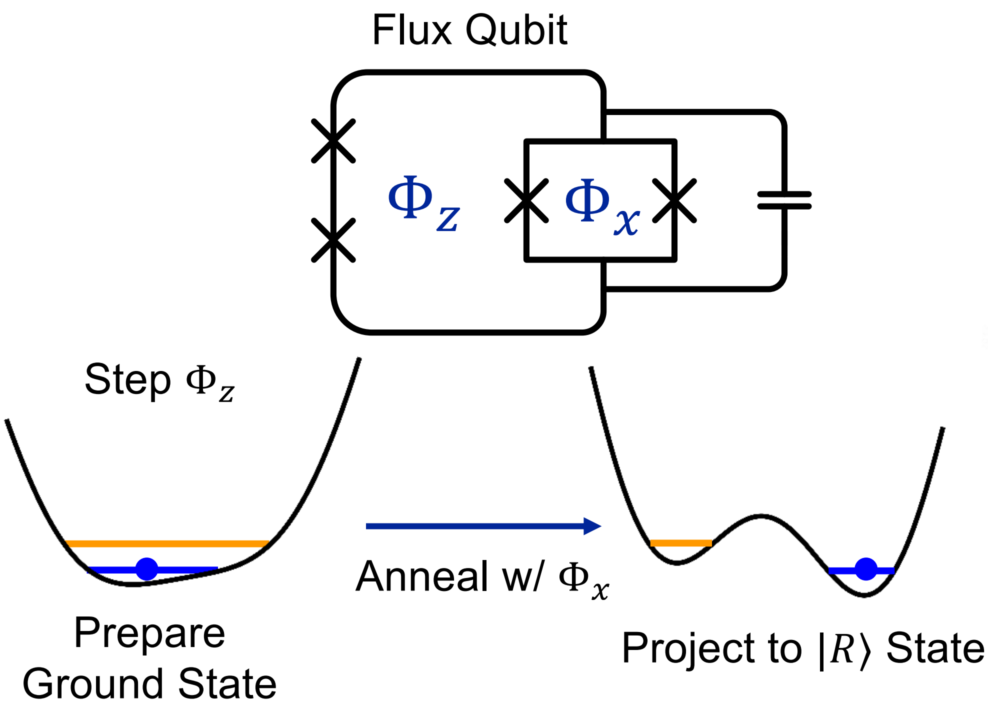
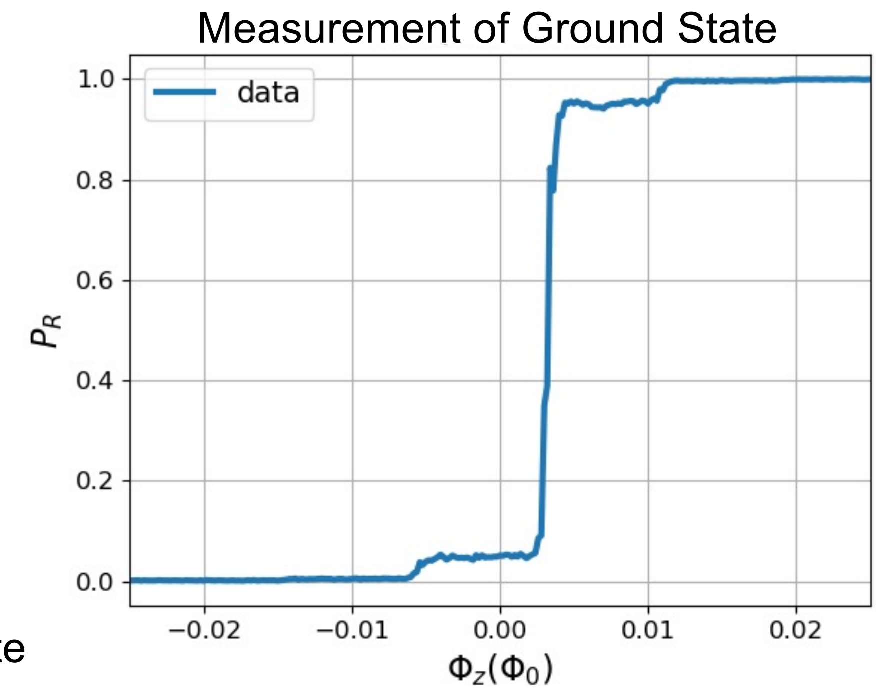
Readout of Ground State Revealed Shoulders on the Flux Qubit Φ_z S-Curve

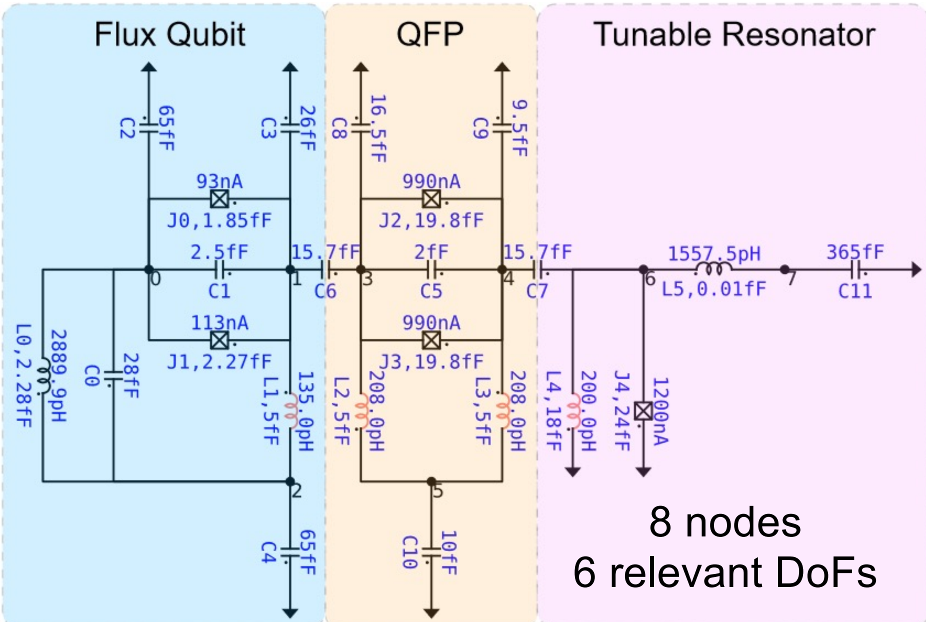




- Unexpected behavior exhibited in the S-Curve of the ground state.
- Expected to see a smooth transition from reading $|L\rangle$ to $|R\rangle$ as we swept the tilt on the flux qubit potential using Φ_z
- Within a small region near the 50/50 point, we saw “errors” in the ground state readout
- Needed to develop a model to explain this behavior

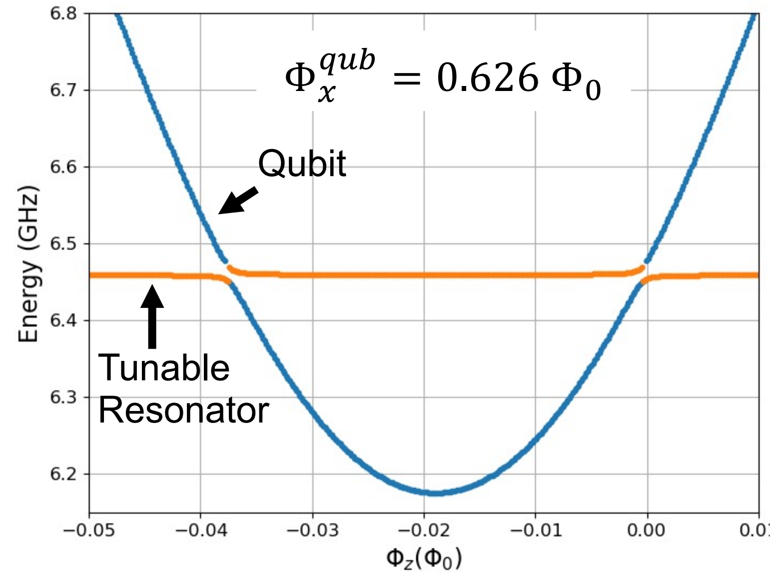
NORTHROP GRUMMAN

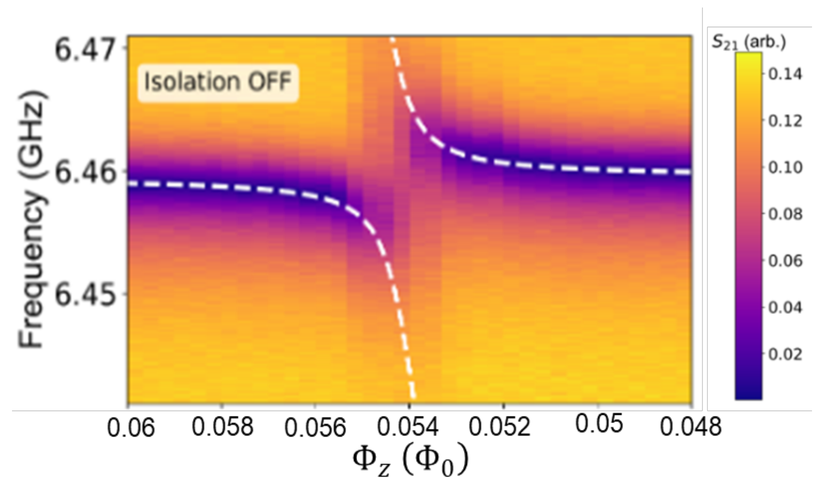
NGSC's Circuitizer Used to Model Flux Qubit Readout Circuit



*Grover, et al., PRX Quantum **1**, 020314 (2020)

Circuitizer

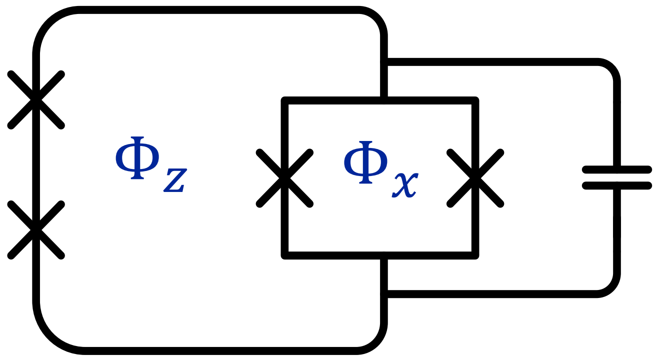




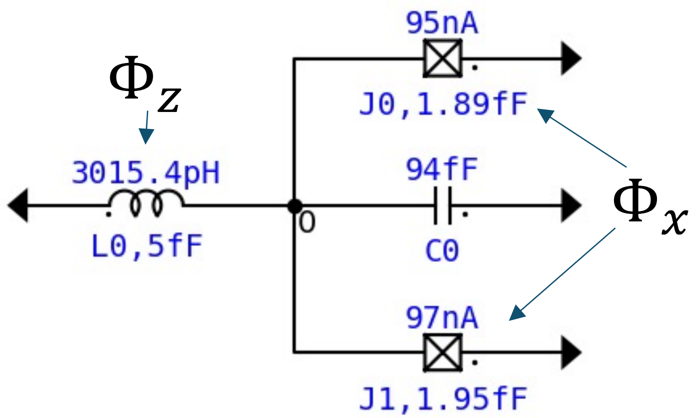
- Handles Josephson junctions, capacitors, inductors, and some composite elements
- Automatically constructs the Hamiltonian of the circuit with support for of external flux and voltage bias control
- Employs QuTip for eigensolving and time-evolution
- Circuitizer is Northrop Grumman proprietary software

Build a Circuitizer Model of the Flux Qubit

Flux Qubit Schematic



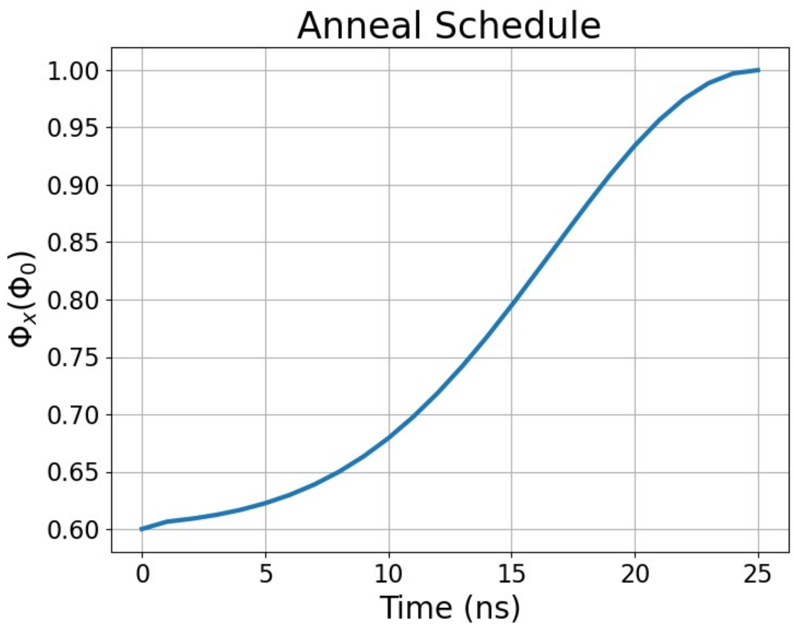
Circuitizer Schematic

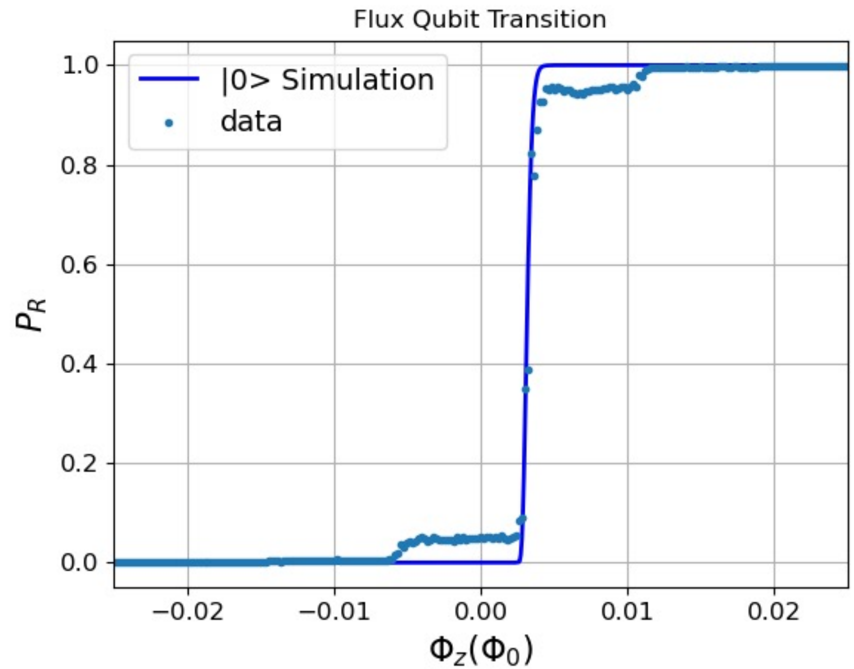


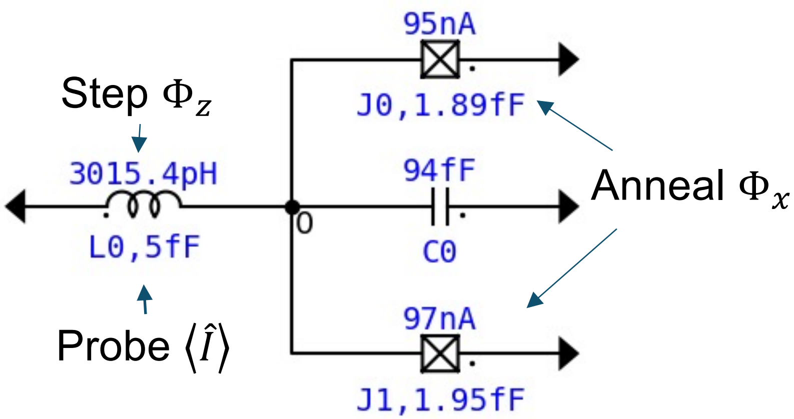
- Model the junctions in the big loop with an equivalent inductance
- Parasitic capacitances are included in the inductor and JJ elements
- Fluxes can be applied to junctions and inductors in Circuitizer

NORTHROP GRUMMAN

Time-Dependent Simulations of the Measurement of the Ground State Differed from the Data







- Using Circuitizer and QuTip, we can model the time-evolution of the $|0\rangle$ state.
- P_R determined from POVM of the final evolved state based on sign of $\langle \hat{I} \rangle$
- Majority of the offset of the 50/50 point arises from junction asymmetry, although a 1.3 mΦ_0 offset included in simulation.
- "Shoulders" on S-curve not seen in simulation of $|0\rangle$ state evolution

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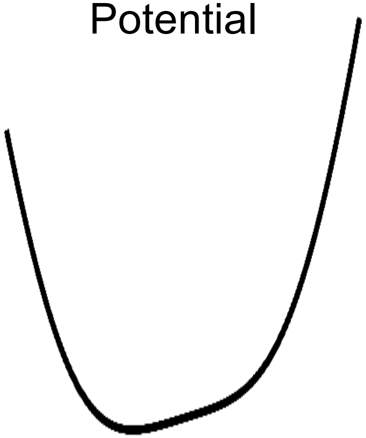
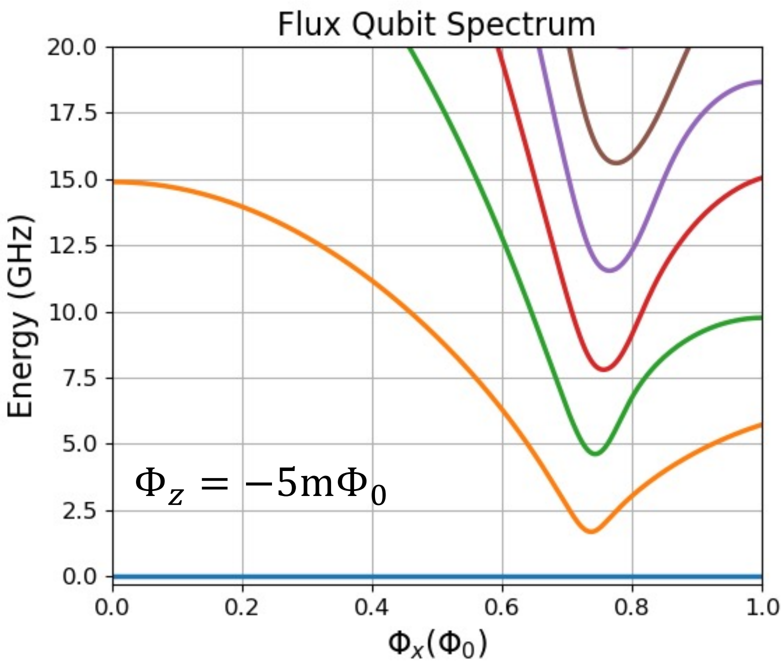
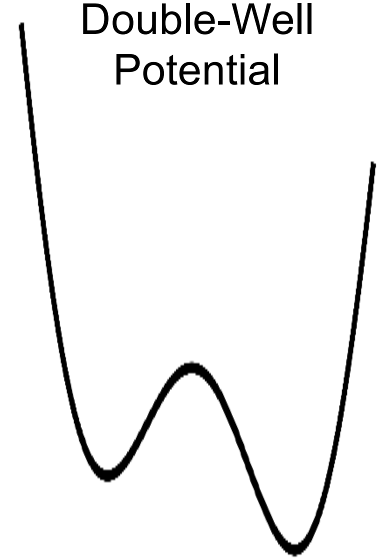
Circuitizer Model of the Energy Eigenstates Show Large Energy Gaps Along Annealing Path

Single-Well Potential

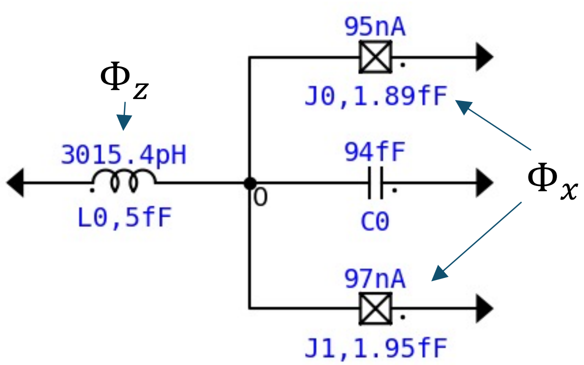




Double-Well Potential



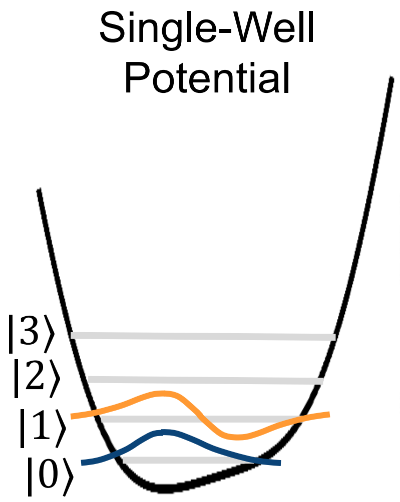
Flux Qubit Schematic

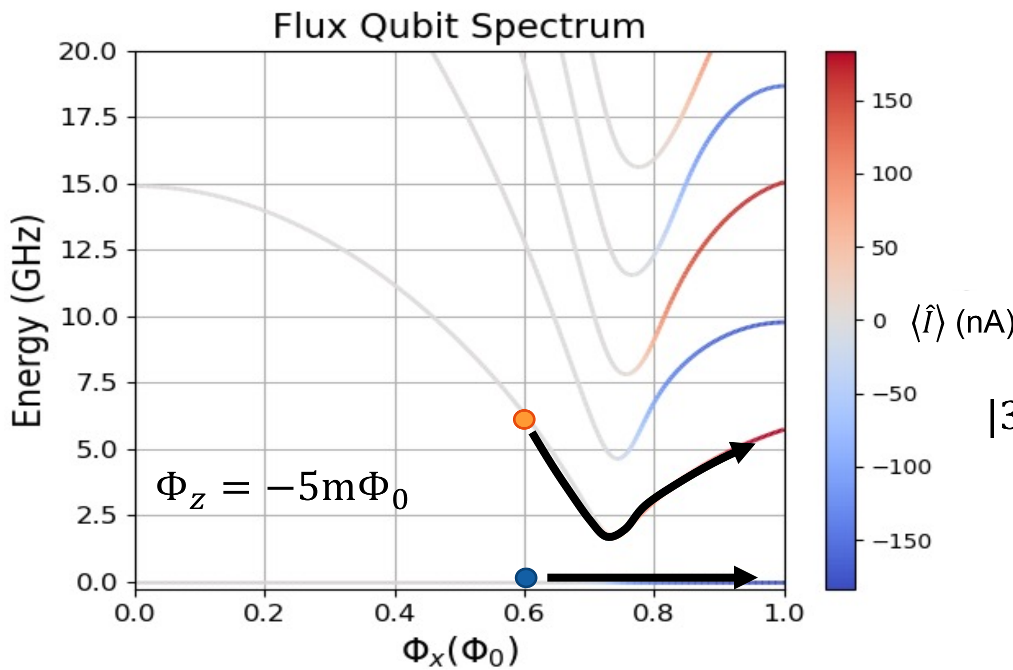


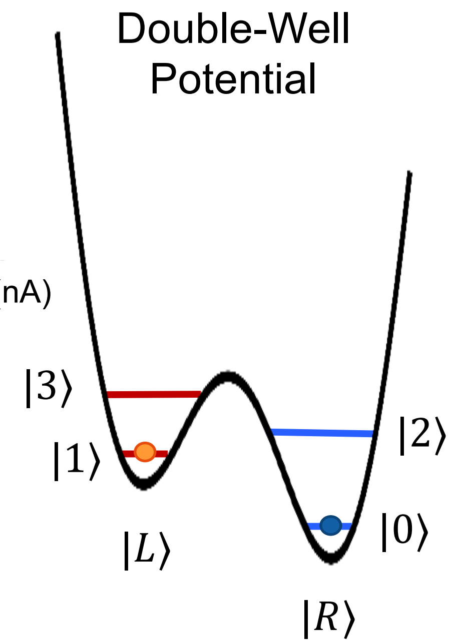
- At low Φ_x, the flux qubit has a single-well potential with photonic energy levels
- At high Φ_x, the potential forms a double-well where energy levels localize to one circulating current state or another
- Applying an offset to Φ_z breaks the degeneracy and creates an energy gap that is large with respect to the 25 ns anneal time

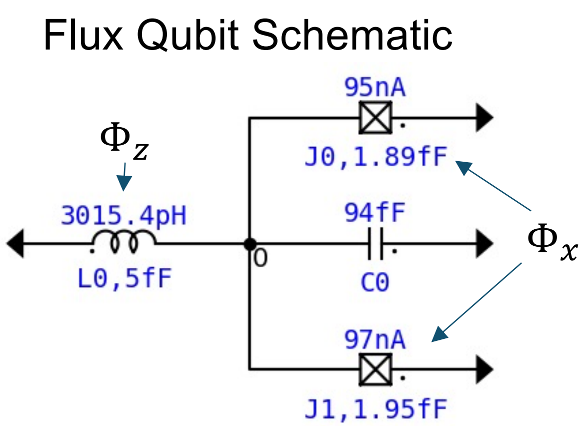
NORTHROP GRUMMAN

Calculation of Persistent Currents Show $|0\rangle$ and $|1\rangle$ Project to Opposite Circulating Current









- Using Circuitizer we can calculate the expectation value of the current in the loop inductor, $\langle \hat{I} \rangle$, for each state
- At low Φ_x, the states have very low $\langle \hat{I} \rangle$
- When a small Φ_z offset is applied, levels develop alternating polarity of $\langle \hat{I} \rangle$ at high Φ_x

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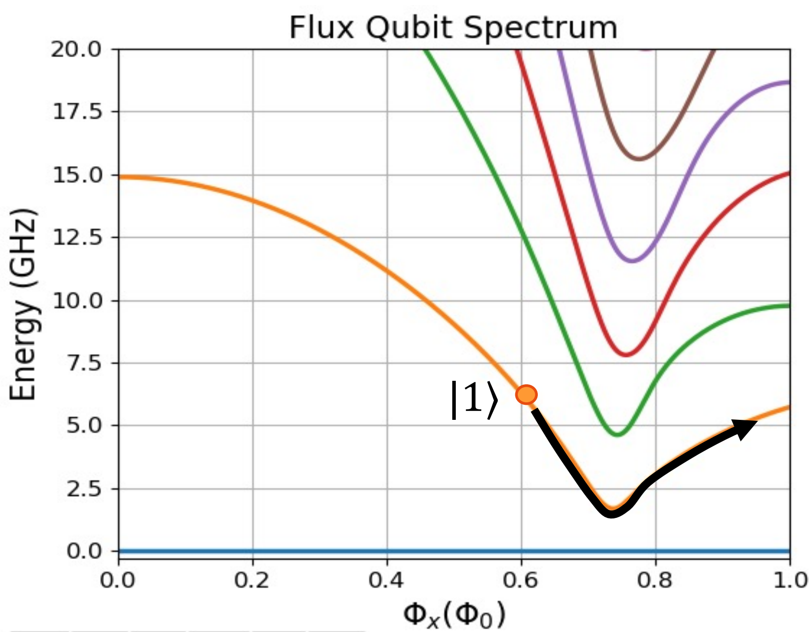
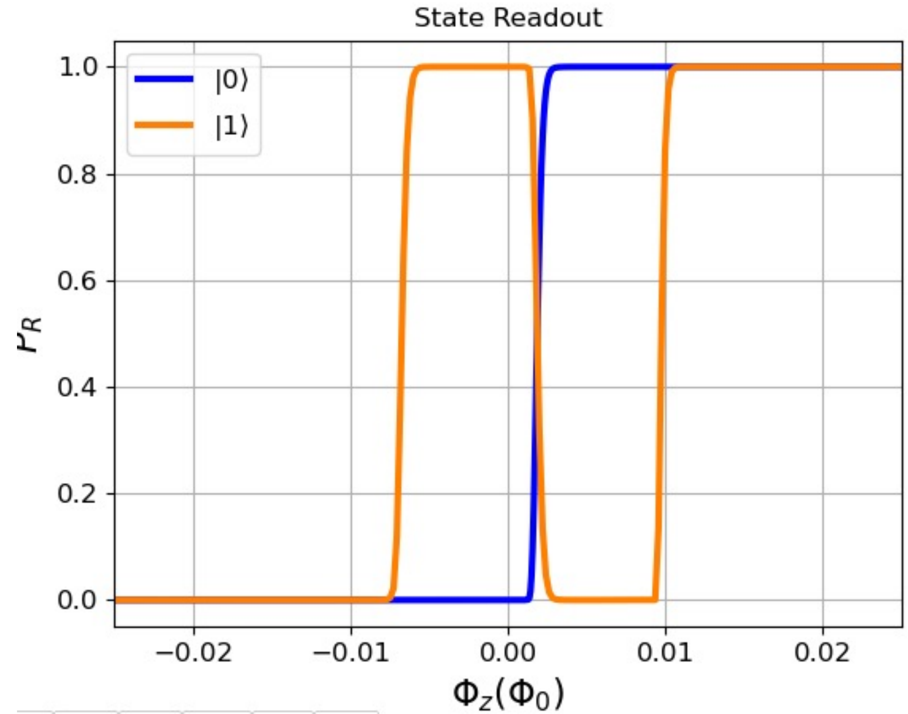
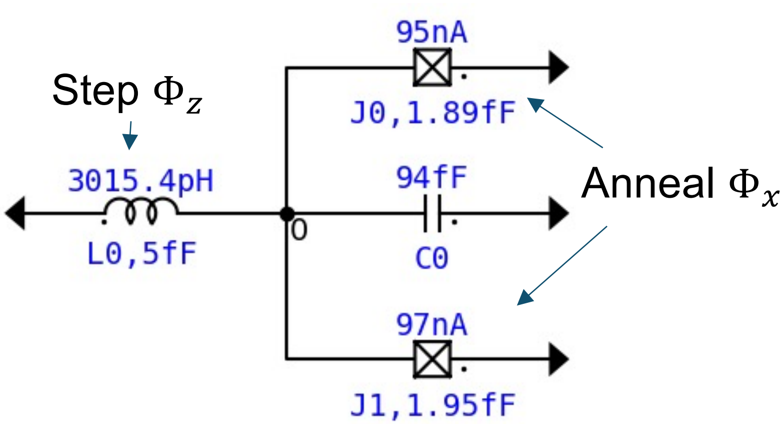
Simulation of the Evolution of the $|1\rangle$ State Shows an Inversion of the Readout Result Near 50/50 Point



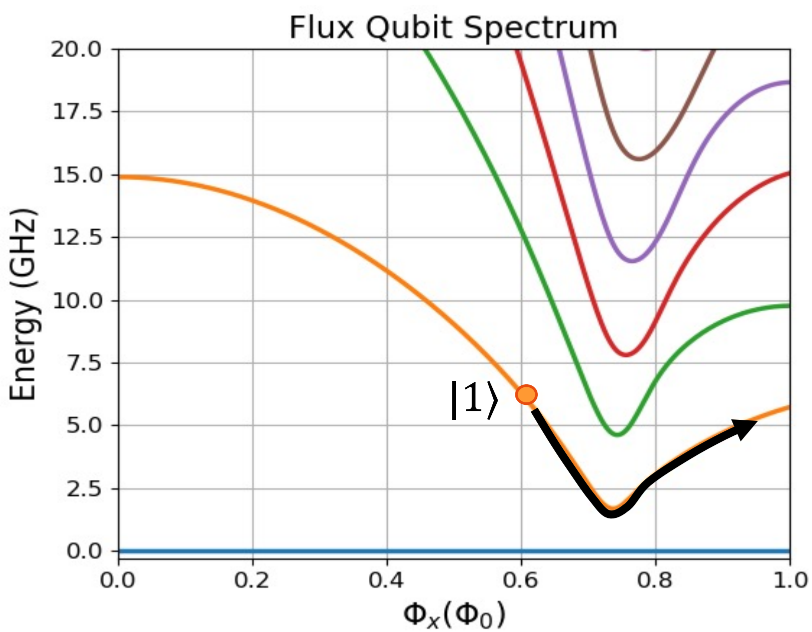


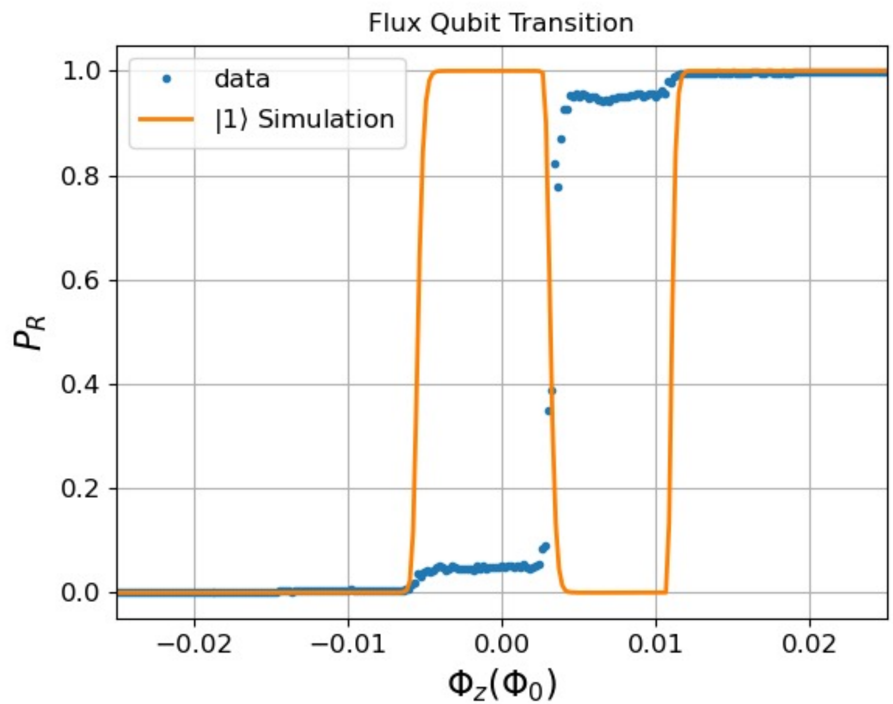


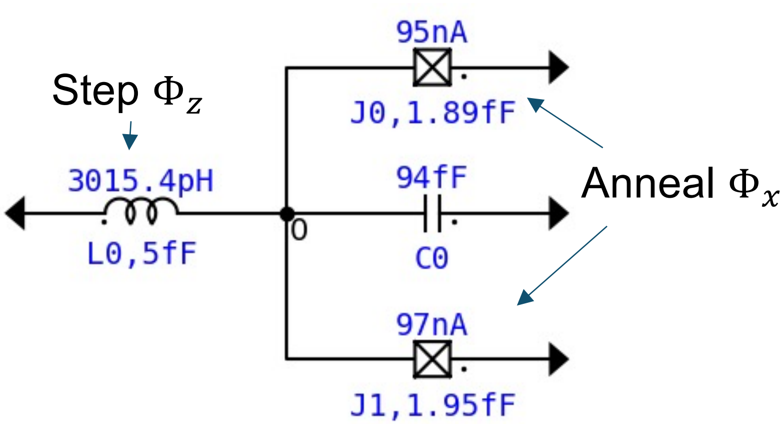
- The photonic $|1\rangle$ state evolves adiabatically into the opposite circulating current state as $|0\rangle$, but only within about 10 mΦ_0 of the 50/50 point.
- At higher Φ_z offset, $|0\rangle$ and $|1\rangle$ give the same answer as seen by the QFP

NORTHROP GRUMMAN

Fractional Occupation of |1⟩ Consistent with Observed S-Curve Shoulders



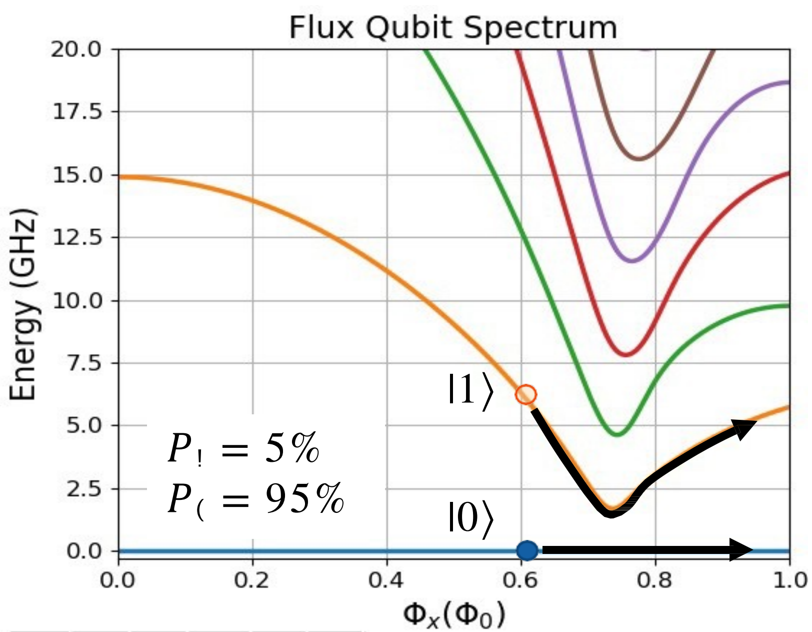


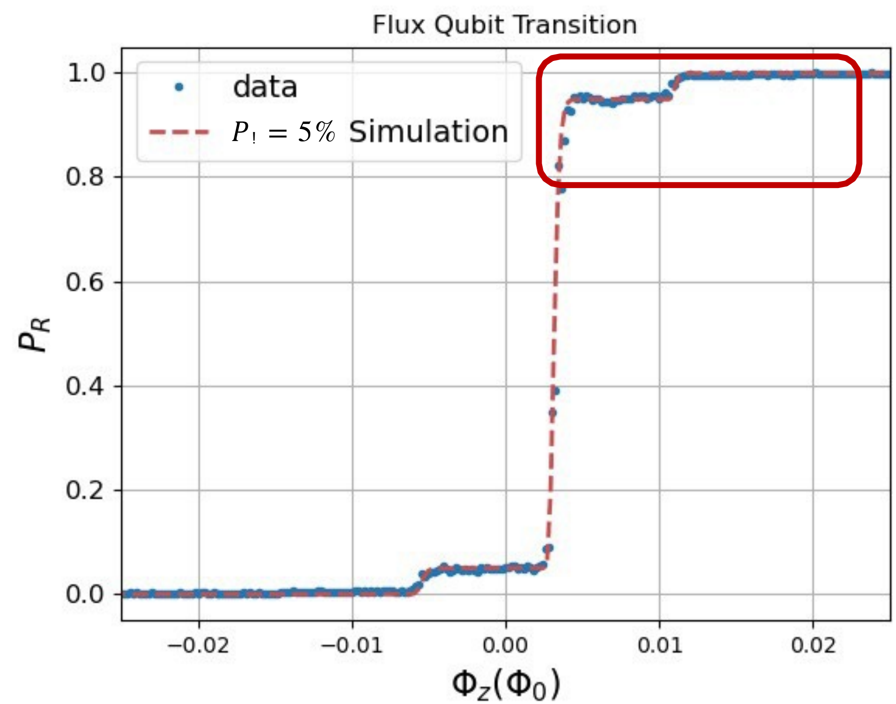


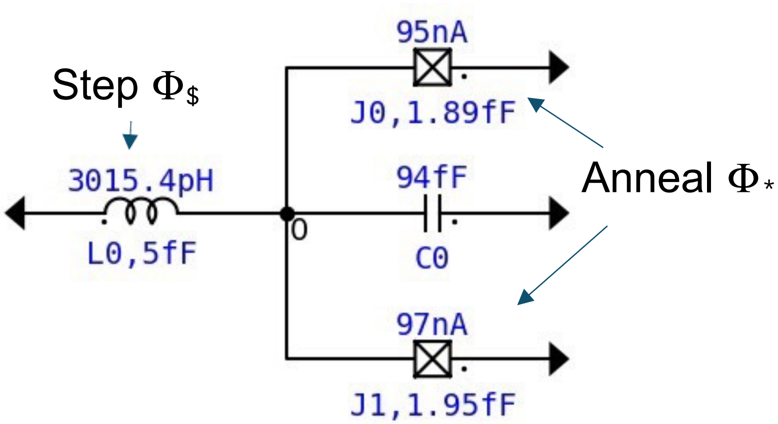
- Some equilibrium population in the |1⟩ would lead to the behavior observed in “ground state” readout.
- Closer inspection reveals more errors at larger Φ_z offset

NORTHROP GRUMMAN

Fractional Occupation of |1⟩ Consistent with Observed S-Curve Shoulders







- Some equilibrium population in the |1⟩ would lead to the behavior observed in "ground state" readout.
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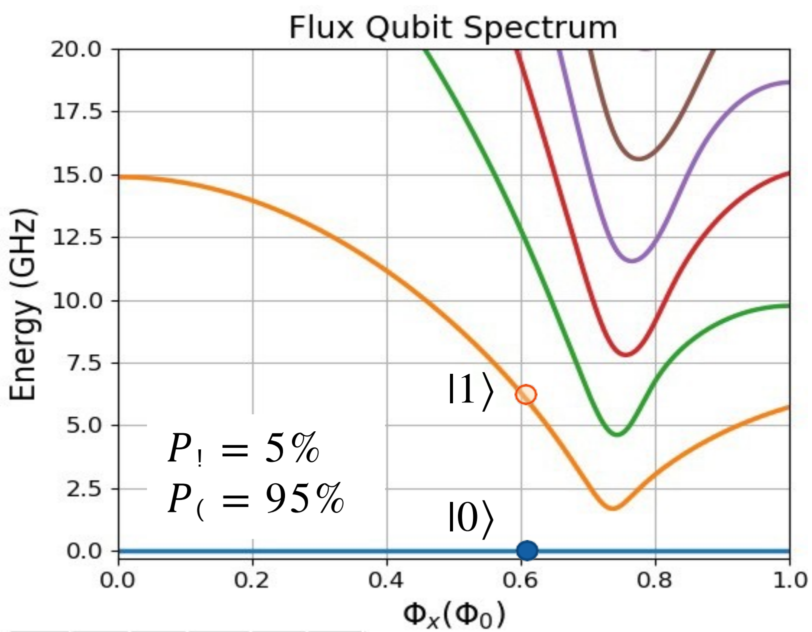
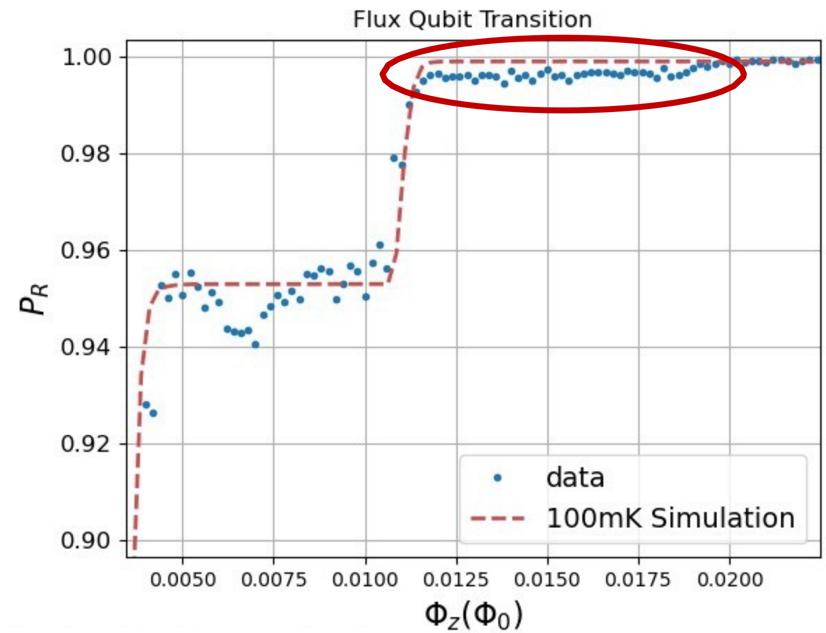
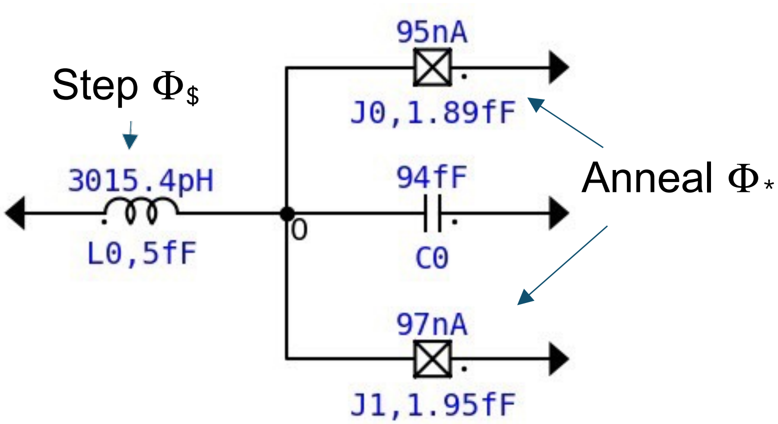
Additional Enhancement of Error at Larger Φ_z Offset Inconsistent with $|1\rangle$ Population







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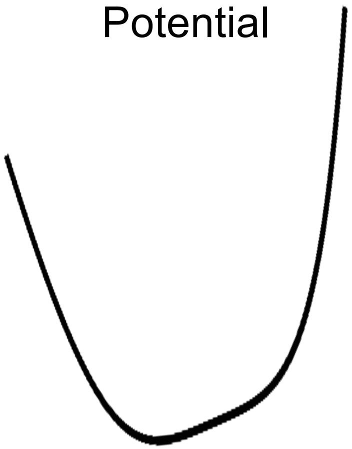
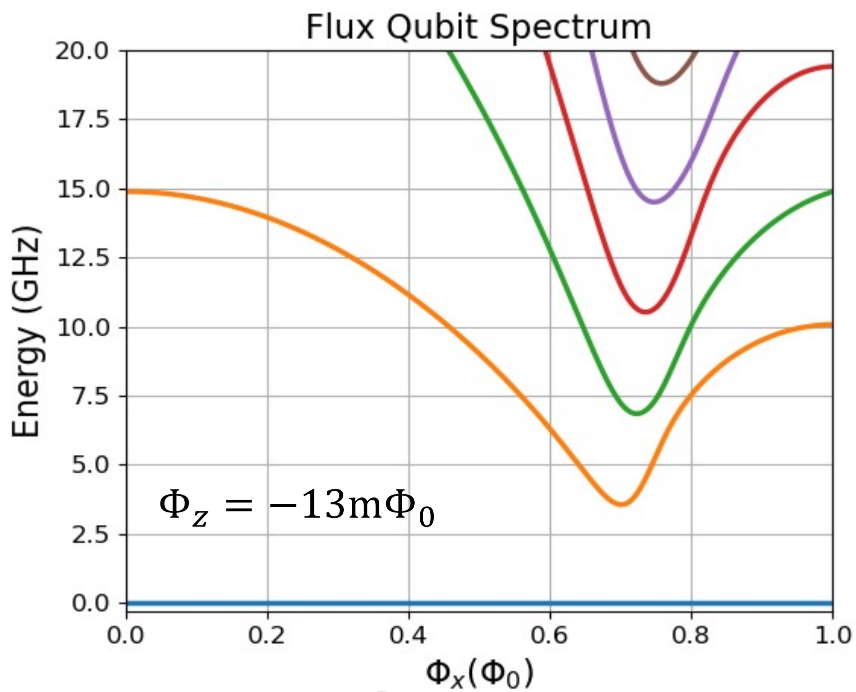
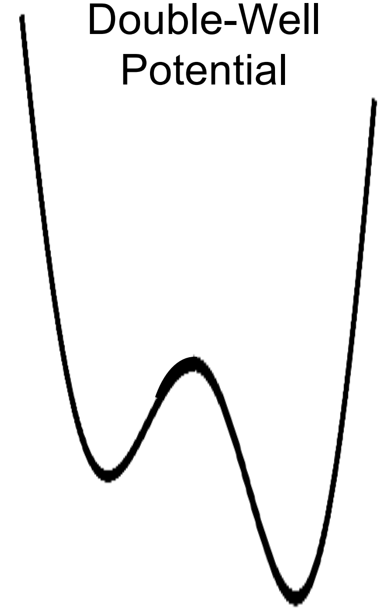
At Large Φ_z Energy Gaps Along Annealing Path Grow Even Larger

Single-Well Potential

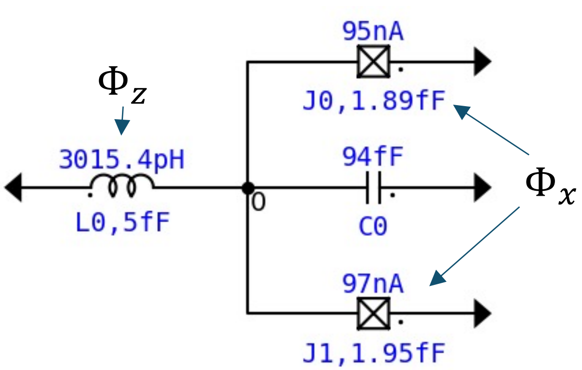




Double-Well Potential



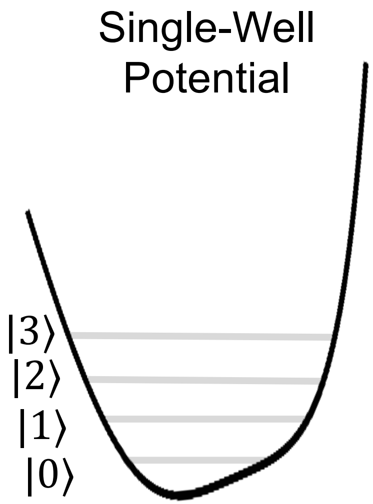
Flux Qubit Schematic

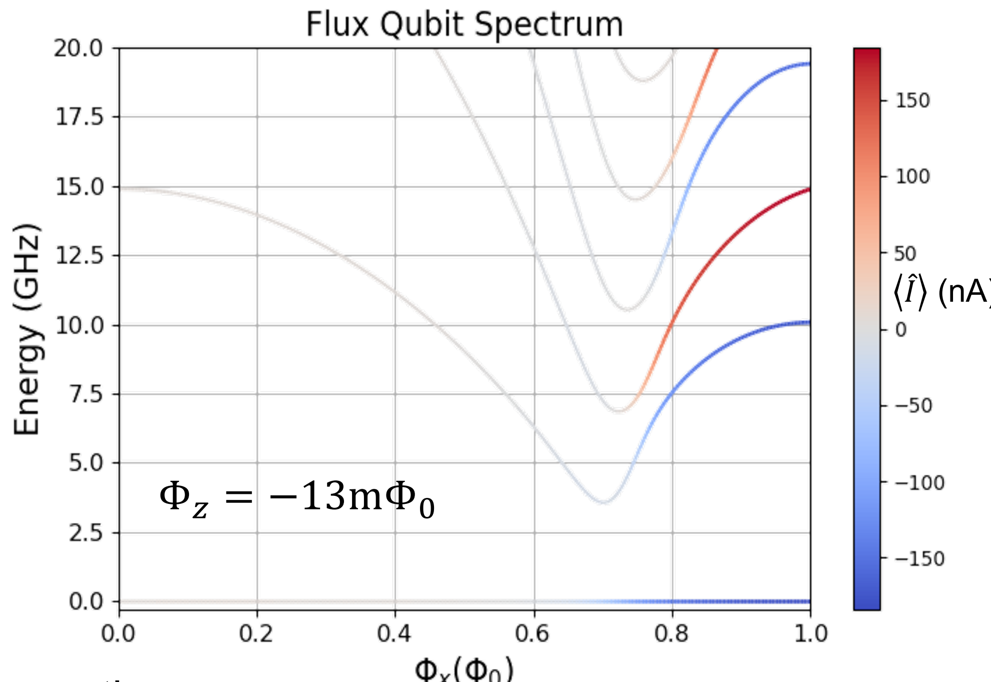


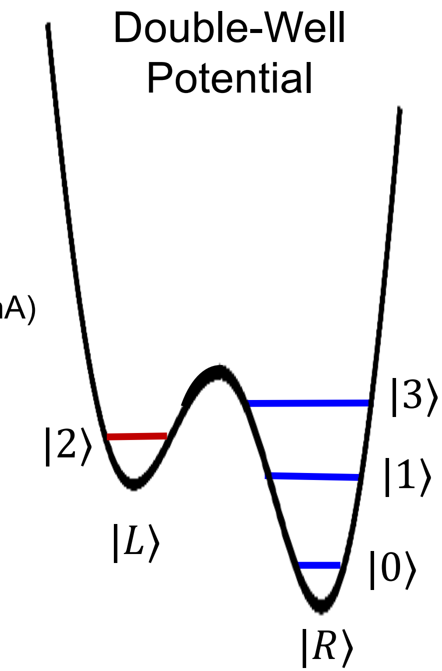
- Higher Φ_z offset gives larger energy gap between $|0\rangle$ and $|1\rangle$ which should facilitate adiabatic evolution during annealing
- However, beyond a certain Φ_z offset, $|0\rangle$ and $|1\rangle$ have the same circulating current and cannot be distinguished by the QFP

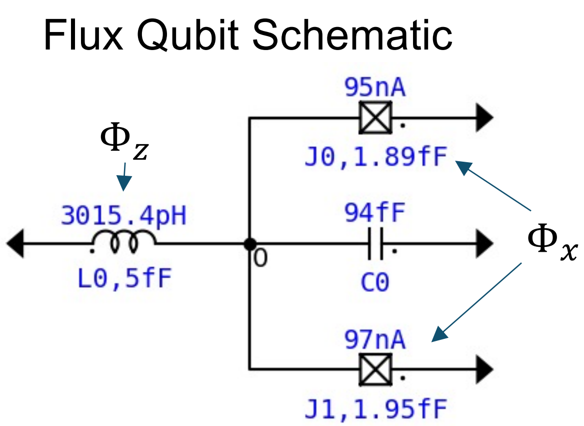
NORTHROP GRUMMAN

At Large Φ_z Offset $|2\rangle$ Projects to Opposite Circulation Current of $|0\rangle$ and $|1\rangle$









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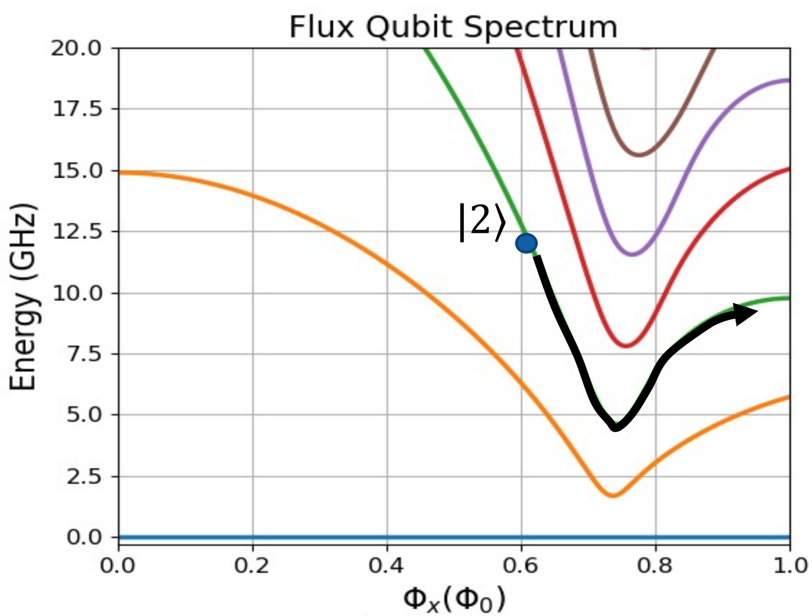
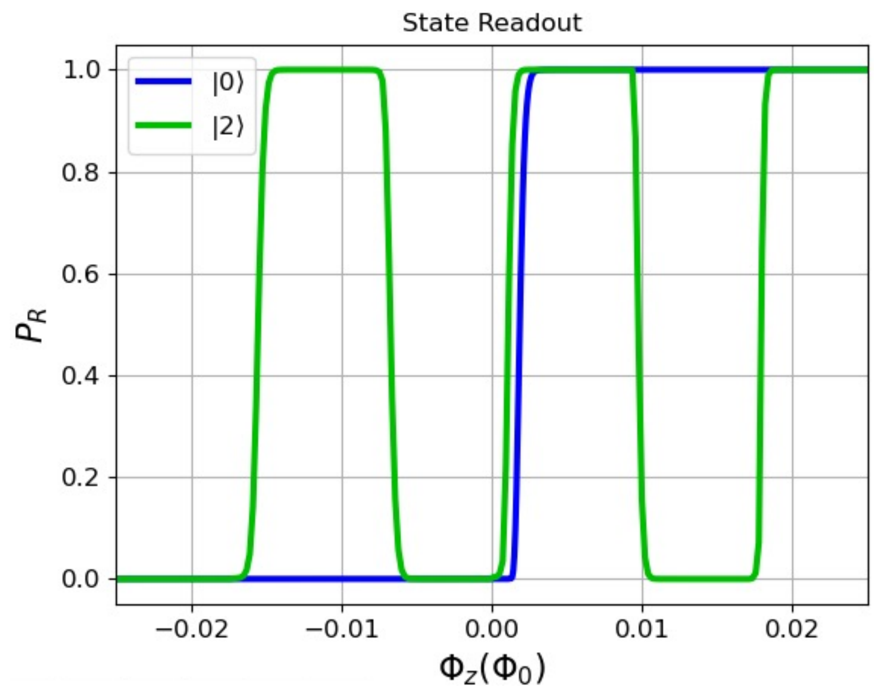
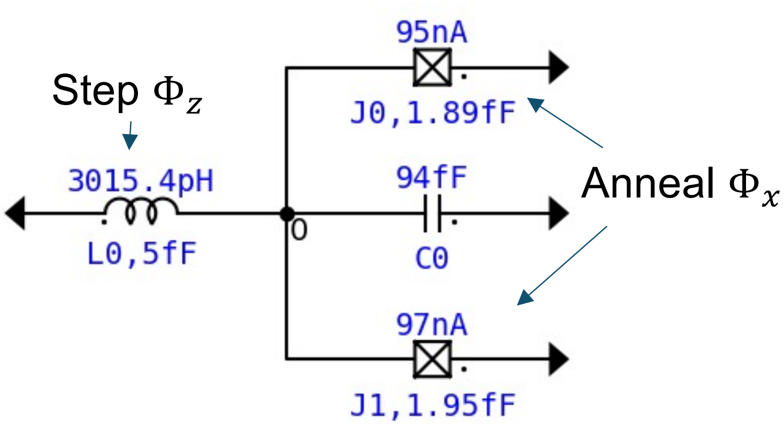
- However, beyond a certain Φ_z offset, $|0\rangle$ and $|1\rangle$ have the same circulating current and cannot be distinguished by the QFP

NORTHROP GRUMMAN

Time-Evolution Simulation Shows Sensitivity to |2⟩ State Population



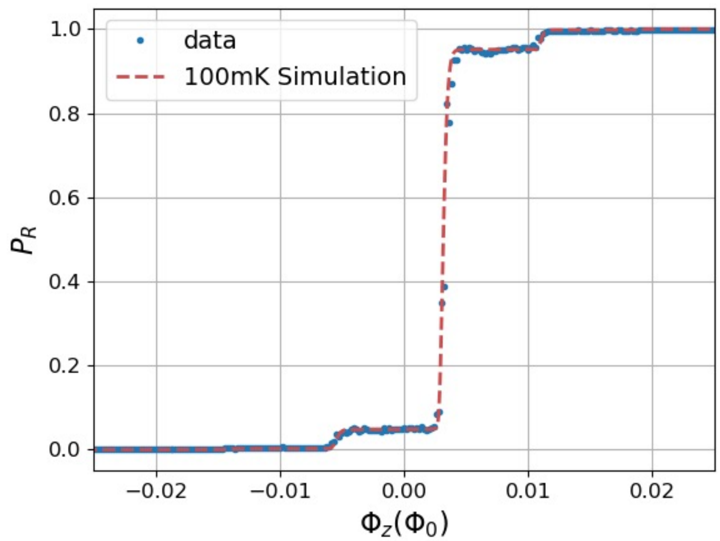


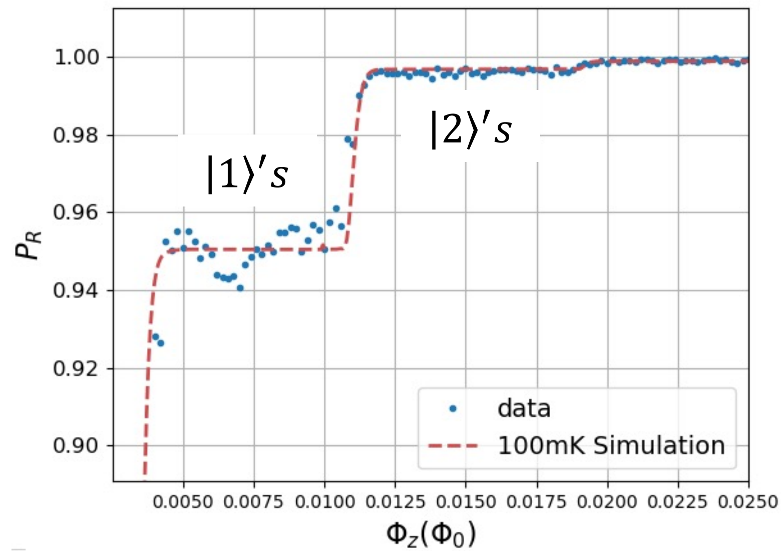


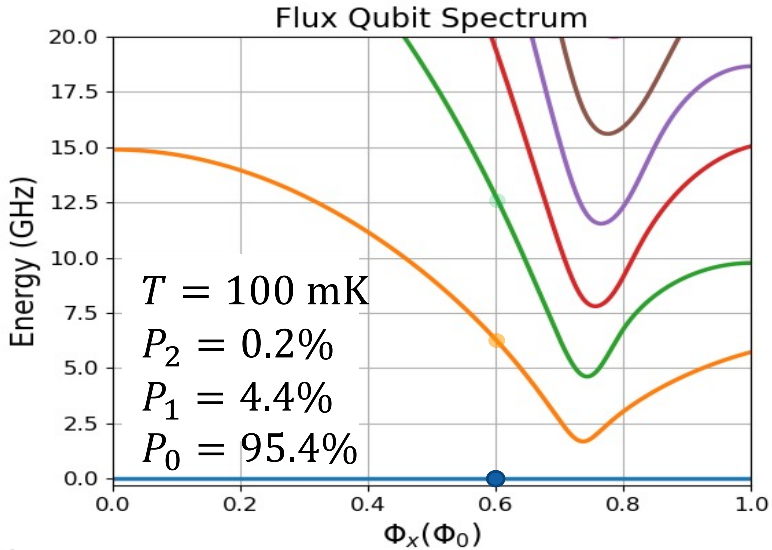
- Simulation of the time-evolved photonic |2⟩ state shows that it will project to the opposite circulating current state at higher Φ_z offsets
- We can select which excited state to sense when using QFP readout!

NORTHROP GRUMMAN

Multiple Steps in Flux Qubit S-Curve Consistent with Measurement of a Thermal State at 100 mK





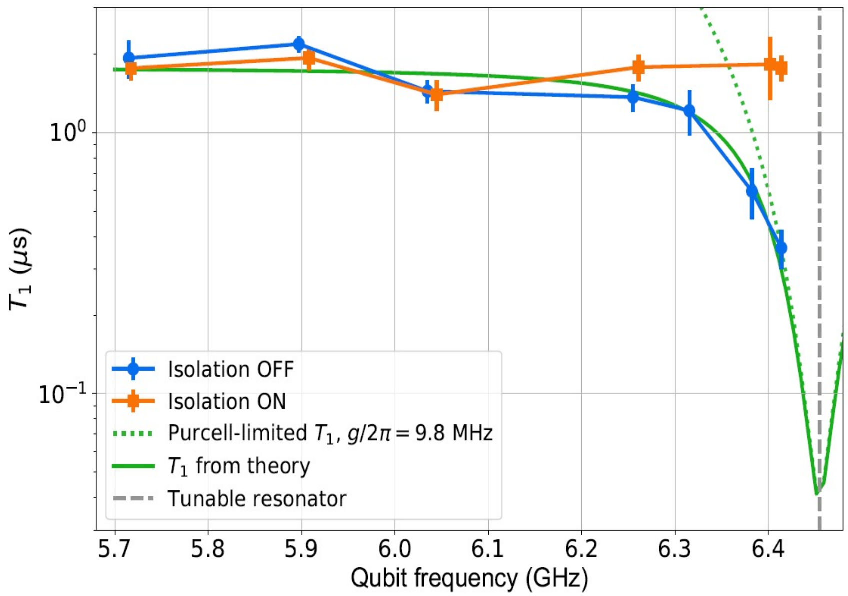


- Although mixing chamber temperature was < 30 mK, QFP readout of the flux qubit reveals significant population in the $|2\rangle$ state.
- Elevated qubit temperatures are common in superconducting qubits
  - – Serniak, et al., PRL 121, 157701 (2018)
- QFP Readout and Circuitizer simulations will be useful tools in investigating the cause and eliminating it.

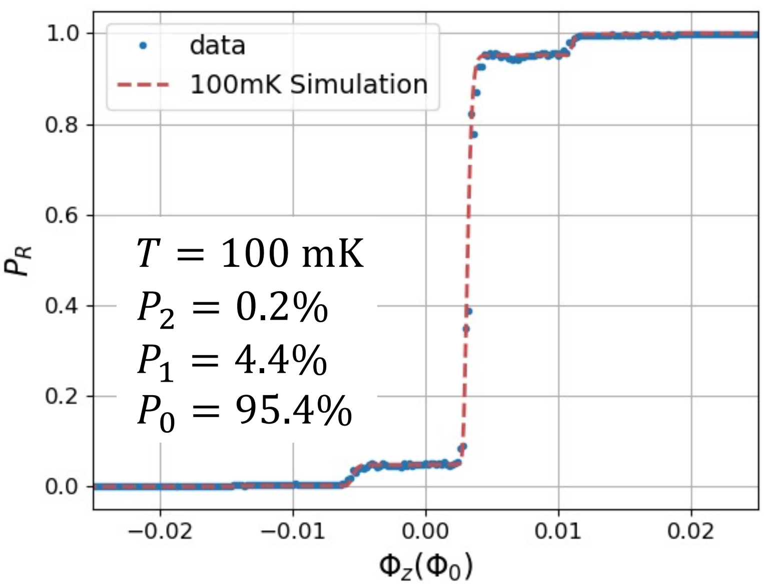
Summary

- The QFP preserves the lifetime of the qubit by providing isolation during sensitive quantum operations and amplifies the qubit signal during readout enabling fast readout.
- QFP readout is capable of sensing both the $|1\rangle$ and $|2\rangle$ states of a flux qubit.
- Measurements of the S-curve of the thermal state match the expected behavior according to a Circuitizer quantum circuit model.

Lifetime Preserving Readout



Thermal State S-Curve



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