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

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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

\[^1\text{Science 220 (4598): 671–680}\]
Quantum Annealing Relies on Quantum Mechanical Effects

Quantum fluctuations help tunnel out of local energy minima:

**Graph:**
- X-axis: Solution space
- Y-axis: Energy
- Dashed line: Quantum fluctuations
- True solution

**References:**
**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

$$H(t) = -A(t) \sum \sigma^i_x + B(t) \left( \sum h_i \sigma^i_z + \sum_{i<j} J_{ij} \sigma^i_z \sigma^j_z \right)$$

![Graph showing time vs. energy with $A(t)$ and $B(t)$](image)

Coherence is the Time Scale on Which the System's Evolution is Primarily Dictated by Quantum Mechanics

\( T_1 \) energy relaxation time

\[ |1\rangle \quad |0\rangle \]

\( T_2 \) dephasing time

\[ |1\rangle \quad |0\rangle \]
Flux Qubits Work as Spins in Superconducting Quantum Annealing

Josephson junction

X loop (enables annealing operation)

Z loop

Circulating currents in the qubit Z loop

Quantum annealing spin variable corresponds to circulating current state

| ↓⟩ | ↑⟩

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Fluctuations and Problem Hamiltonian are Controlled via Applied Magnetic Flux

\[ H(t) = -A(t) \sum_i \sigma^i_x + B(t) \left( \sum_i h_i \sigma^i_z + \sum_{i<j} J_{ij} \sigma^i_z \sigma^j_z \right) \]

X-loop

Z-loop

Driver Hamiltonian

Problem Hamiltonian
Magnetic Flux Coupling to Other Qubits
Encodes Pairwise Interactions

\[ H(t) = -A(t) \sum_i \sigma_i^x + B(t) \left( \sum_i h_i \sigma_i^z + \sum_{i<j} J_{ij} \sigma_i^z \sigma_j^z \right) \]

Driver Hamiltonian
Problem Hamiltonian

Tunable coupling to other qubits
The Answer to the Computation Must be Read Out with High Fidelity

\[ H(t) = -A(t) \sum_i \sigma^i_x + B(t) \left( \sum_i h_i \sigma^i_z + \sum_{i<j} J_{ij} \sigma^i_z \sigma^j_z \right) \]

- 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

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\(^1\)Yan \textit{et al.}, Nat. Comm. 7, 12964 (2016)
\(^2\)Novikov \textit{et al.}, arXiv:1809.04485
\(^3\)Quintana \textit{et al.}, PRL 118, 057702 (2017); AQC 2018

- No published \(T_1\) data available; https://www.youtube.com/watch?v=CrPQvDl8MIU
Readout Solution: Quantum Flux Parametron (QFP) Amplifies Small Qubit Signal and Provides Isolation

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

1Patent app. no. 16/277,560
WRspice Simulations Confirm QFP Latching

Anneal qubit into $|L\rangle$ or $|R\rangle$
Anneal QFP to sense qubit state
QFP remains latched

$\Phi_{z}^{\text{qub}}(\Phi_{0})$
$\Phi_{x}^{\text{qub}}(\Phi_{0})$
$\Phi_{x}^{\text{qfp}}(\Phi_{0})$
$I_{z}^{\text{qub}}(nA)$
$I_{z}^{\text{qfp}}(nA)$
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

- 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

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

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

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
Measuring qubit lifetimes with excited-state readout

- 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

- 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 \(\mu s\))
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- MIT Lincoln Laboratory
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