Qudit-based quantum computing with SRF cavities at Fermilab

Tanay Roy
SQMS division, Fermilab
1 August 2023
Why Quantum Computing?

1.2 × 10^{18} calculations / sec

Not efficient for all problems
Why Quantum Computing?

1. Prime Factorization

762904558518855853

Not efficient for all problems

1.2 \times 10^{18} \text{ calculations / sec}

Shor’s factoring algorithm 1994

Hard


Image: mit.edu
Why Quantum Computing?

1. Prime Factorization

762904558518855853

Not efficient for all problems

1.2 × 10^{18} calculations / sec

Shor’s factoring algorithm 1994

HARD

? × ?

2. Quantum Simulation

Simulate one QM system with another

Image: mit.edu

Image: needull.com
Why Quantum Computing?

1. Prime Factorization

762904558518855853

Shor’s factoring algorithm 1994

1.2 \times 10^{18} \text{ calculations/sec}

Not efficient for all problems

Build a Quantum Computer

2. Quantum Simulation

Simulate one QM system with another

Image: mit.edu

Image: needull.com
Basic Requirements for a Quantum Computer

- Quantum two level systems
- Create arbitrary states
- Measure quantum states
- Couple multiple qubits
- Scalable architecture
Different Platforms

- **Trapped ions**
  - [Image](laserfocusworld.com)
  - [NV centers](phys.org)
- **Superconducting circuits**
  - [Image](SQMS)
  - [NMR](chemie.tu)
  - [Neutral atoms](NIST)
- **Photonic crystals**
  - [Image](phys.org)
  - [Quantum dots](sciencemag.org)

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Different Platforms

Trapped ions

Superconducting circuits

Photonic crystals

<table>
<thead>
<tr>
<th>Organization</th>
<th>Year</th>
<th>Qubits</th>
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Sources:
- laserfocusworld.com
- SQMS
- phys.org
- sciencemag.org
Different Platforms

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Different Platforms

Trapped ions

Superconducting circuits

Photonic crystals

Organization | Year | Qubits
---|---|---
Xanadu | 2022 | 216
Quandela | 2023 | 12
QuiX | 2022 | 20
Different Platforms

Trapped ions

Superconducting circuits

Photonic crystals

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<td>Electron-on-helium</td>
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Challenges: Decoherence

Relaxation ($T_1$)

$\alpha |0\rangle + \beta |1\rangle$

$|0\rangle$
Challenges: Decoherence

Relaxation ($T_1$)

\[ \alpha |0\rangle + \beta |1\rangle \]

\[ |0\rangle \]

Dephasing ($T_\phi$)

Incoherent mix of $|0\rangle$ and $|1\rangle$

Long coherence
Challenges: Gates and Connectivity

- Fast & high-fidelity
- Coherence time
  - Gate time
- All-to-all
- Linear chain
- Square lattice
- Heavy hexagon
- Octagonal
Superconducting Circuits

Josephson Junction

\[ I(t) = I_0 \sin \delta(t) \]
\[ V(t) = \varphi_0 \dot{\delta}(t) \]

Lossless nonlinear inductor

\[ L_J(I) = \frac{\varphi_0}{(I_0^2 - I^2)^{1/2}} \]
Superconducting Circuits

Josephson Junction

\[ I(t) = I_0 \sin \delta(t) \]
\[ V(t) = \varphi_0 \dot{\delta}(t) \]

Lossless nonlinear inductor

\[ L_J(I) = \frac{\varphi_0}{I_0^2 - I^2} \frac{1}{2} \]
Transmon: Anharmonic Oscillator

Harmonic Oscillator

Anharmonic Oscillator

\[ |0\rangle, |1\rangle, |2\rangle \]
Transmon: Anharmonic Oscillator

Harmonic Oscillator

Anharmonic Oscillator

$|0\rangle$, $|1\rangle$, $|2\rangle$
Operating Temperature

\[ f_{01} \approx \frac{1}{2\pi \sqrt{L_J C}} \]
\[ \sim 5 \text{ GHz} \]

\[ k_B T \ll \hbar f_{01} \]

20 mK \quad \sim 240 \text{ mK}

\sim 50 \text{ fF} \quad \sim 20 \text{ nH}
Operating Temperature

$$f_{01} \approx \frac{1}{2\pi \sqrt{L_J C}}$$

$\sim 5$ GHz

$$k_B T \ll \hbar f_{01}$$

20 mK \sim 240 \text{ mK}

Anharmonic Oscillator

\[ \Delta E_1 \]

\[ \Delta E_2 \]

\[ \Delta E_3 \]

\[ |0\rangle \]

\[ |1\rangle \]

\[ |2\rangle \]

\[ \approx 50 \text{ fF} \]

\[ \approx 20 \text{ nH} \]

Dilution fridge \sim 10 \text{ mK}
Circuit QED Architecture

- Qubit
- Cavity
- Read-out line

Dilution fridge ~ 10 mK

2.5 cm

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Circuit QED Architecture

\[ H = \frac{\omega_q}{2} \sigma_z + \omega_c a^\dagger a + g (a^\dagger \sigma^- + a \sigma^+) \]

\[ \approx \frac{\omega_q}{2} \sigma_z + \omega_c a^\dagger a + \frac{\chi}{2} (a^\dagger a) \sigma_z \]

\[ = \frac{\omega_q}{2} \sigma_z + \left( \omega_c + \frac{\chi}{2} \sigma_z \right) a^\dagger a \]

\[ \Delta = \omega_q - \omega_c \]

\[ g \ll \Delta, \chi = 2g^2 / \Delta \]

Dilution fridge \( \sim 10 \) mK
Circuit QED Architecture

State Probabilities:

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

Phase Resonance Curves:

\[ 0^\circ \quad 90^\circ \]

Frequency vs. Phase:

Probability vs. Phase:

Dilution fridge ~ 10 mK
Traditional Multi-qubit Architecture

Linear or planar geometry

Computational space: $2^N$

Can we do better?

UCSB, Nature 519 (7541)

IBM
Traditional Multi-qubit Architecture

Linear or planar geometry

Computational space: $2^N$

Can we do better?

Scaling: $d^N$, $d > 2$

Qudit

UCSB, Nature 519 (7541)

IBM
Problem of Relaxation

Linear or planar geometry

$T_1 \sim 100 \, \mu s$  \hspace{1cm} Q: a few $10^6$

Can we do better?

UCSB, Nature 519 (7541)

IBM
Zoo of Cavities

Yale, U. Pittsburgh

Weizmann

Under exploration

U. Chicago, Rutgers
Romanenko et al. PRApplied 13, 034032

1.3 GHz SRF: \( Q > 10^{11} \) at 1 K \( \Rightarrow \) \( T_1 > 2 \) s

5 GHz SRF: \( Q > 10^{10} \) at 10 mK \( \Rightarrow \) \( T_1 > 300 \) ms

>1000 times better than transmons
High-Q 3D Cavities as Qudits

Romanenko et al. PRApplied 13, 034032

$T_{11}^{\uparrow} > 300 \text{ ms}$

$T_{1n}^{\uparrow} > T_{11}^{\uparrow} / n$

$T_{12}^{\uparrow} > 150 \text{ ms}$

$T_{110}^{\uparrow} > 30 \text{ ms}$

Still much better than transmon qubits
Transmon vs. Cavity Drive

Qubit: $\alpha|0\rangle + \beta|1\rangle$

Qudit: $\alpha_0|0\rangle + \alpha_1|1\rangle + \cdots + \alpha_d|d\rangle$

$\text{Re}(\alpha)$

$\text{Im}(\alpha)$

$\tilde{D}(\alpha)$
Qudit Operation

$|0\rangle \xrightarrow{\mathcal{D}(\alpha = 1)} \alpha_0 |0\rangle + \alpha_1 |1\rangle + \cdots + \alpha_d |d\rangle$

$|n\rangle \rightarrow e^{i\theta} |n\rangle$

Selective number-dependent arbitrary phase (SNAP) gate

PRL 115, 137002 (2015)
Qudit Operation

|0⟩ → \mathcal{D}(\alpha = 1) \alpha_0 |0⟩ + \alpha_1 |1⟩ + \cdots + \alpha_d |d⟩

|1⟩ → e^{i\pi} |1⟩

Quantum state

|n⟩ → e^{i\theta} |n⟩

Selective number-dependent arbitrary phase (SNAP) gate

PRL 115, 137002 (2015)
Universal Gate Set

Qudit: $\alpha_0 |0\rangle + \alpha_1 |1\rangle + \cdots + \alpha_d |d\rangle$

SNAP gate

Qudit: $\alpha_0 e^{i\theta_0} |0\rangle + \alpha_1 e^{i\theta_1} |1\rangle + \cdots + \alpha_d e^{i\theta_d} |d\rangle$

Unconditional operation on cavity

Conditional operation on cavity enabled by a transmon

Cavity drive + SNAP

Universal control
First Milestone

Incorporate Transmon into a TESLA cavity
First Milestone

Incorporate Transmon into a TESLA cavity
First Milestone

Incorporate Transmon into a TESLA cavity

Achieved photon counting
Second Milestone

Prepare quantum states

\[ \tau \approx 0.95 \text{ ms} \]

Relaxation \( n = 1 \)

Wigner tomography
Multi-qudit Architecture

Crosstalk issues

Moderate-Q cavities

High-Q 3D cavities

Transmon
Manipulator
Coupler

CPU
BUS
RAM

Storage
Multi-qudit Architecture

Crosstalk issues

All-to-all coupling

Faster scaling: $d^N > 2^N$

Moderate-Q cavities

High-Q 3D cavities

Transmon

Manipulator

Coupler

CPU

BUS

Storage

RAM
Outlook

- Improve single-cell devices
  - Optimize transmon design, placement
  - Investigate other SRF cavity geometries

- Scaling up
  - Develop modular architecture
  - Connect several modules
Brand New SQMS Facility at Fermilab
Thank You!
Qubit frequency dependence

\[ H = \omega_c a^\dagger a + (\omega_q + \chi a^\dagger a) \frac{\sigma_z}{2} \]

\[ \omega'_q(\ket{0_c}) = \omega_q \]
\[ \omega'_q(\ket{1_c}) = \omega_q + \chi \]

SNAP + cavity drive

Universal control
Visualization of SNAP

Selective number-dependent arbitrary phase pulse

\[ (|0\rangle + |1\rangle + |2\rangle + \cdots)_c |0\rangle_q \]

\[ = |0\rangle|0\rangle + |1\rangle|0\rangle + |2\rangle|0\rangle + \cdots \]

\[ \downarrow \cos \omega_q t \]

\[ |0\rangle|1\rangle + |1\rangle|0\rangle + |2\rangle|0\rangle + \cdots \]

\[ \downarrow \cos \omega_q t \]

\[ -|0\rangle|0\rangle + |1\rangle|0\rangle + |2\rangle|0\rangle + \cdots \]
Visualization of SNAP

Selective number-dependent arbitrary phase pulse

\[ |3⟩ \quad |2⟩ \quad |1⟩ \quad |0⟩ \]

\[ \chi > \gamma \]

\[ (|0⟩ + |1⟩ + |2⟩ + \cdots) c |0⟩_q \]

\[ = |0⟩|0⟩ + |1⟩|0⟩ + |2⟩|0⟩ + \cdots \]

\[ \downarrow \quad \cos \omega_q t \]

\[ |0⟩|1⟩ + |1⟩|0⟩ + |2⟩|0⟩ + \cdots \]

\[ \downarrow \quad \cos(\omega_q t + \theta') \]

\[ e^{i\theta} |0⟩|0⟩ + |1⟩|0⟩ + |2⟩|0⟩ + \cdots \]

\[ = (e^{i\theta} |0⟩ + |1⟩ + |2⟩ + \cdots)|0⟩ \]