High-Frequency Electronics for Superconducting Quantum Computing

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IBM Research Europe
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IBM Quantum
Contents

• Introduction to superconducting quantum computing
• Road map for quantum computing
• Scalability of the quantum architecture
• High-frequency cryogenic electronics for quantum
• Conclusions
Quantum Volume
Measuring the performance of near-term quantum computers.

Qubits added: 0
Error rate decrease: 10x
Quantum volume increase: **500x**

Quantum Volume depends upon
- Number of physical QBs
- Connectivity among QBs
- Available hardware gate set
- Error and decoherence of gates
- Number of parallel operations

IBM Quantum
We are in the early stages of a rapidly advancing new computing technology.
Scaling quantum technology

27 qubits
*Falcon*

Path to 1 million qubits and beyond
*Large scale systems*
# Scaling quantum technology

<table>
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[IBM Quantum](https://www.ibm.com/quantum)
Scaling quantum technology

**Technical highlights**
- Flagship device reached QV64
- Better quantum volume with optimized lattice connectivity
- Laser annealing to increase yield of devices
# Scaling quantum technology

## 65Q Hummingbird

### Technical highlights
- Deployed on 9/1
- Readout multiplexing, 8:1
- Low-latency signal processing

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- Key advancement
  - Optimized lattice
  - Scalable readout

- Key advancement
  - Novel packaging and controls
  - Miniaturization of components
  - Integration

- Key advancement
  - Build new infrastructure, quantum error correction

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**IBM Quantum**
# Scaling quantum technology

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**IBM Quantum**

### Technical highlights
- Spurious mode mitigation
- TSV technology
- Multi-level wiring - a lot more wiring for individual qubit control
- Real-time classical compute

**127Q Eagle**

**Key advancement**
- Optimized lattice
- Scalable readout
- Novel packaging and controls

**Technical highlights**
- Build new infrastructure
- Quantum error correction

**IEEE**
Scaling quantum technology

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**Technical highlights**
- Increased density of cryo-infrastructure and controls
- Cryo-flex cables

**IBM Quantum**

**Key advancement**
- Miniaturization of components

**Build new infrastructure, quantum error correction**
Scaling quantum technology

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**1,121Q**

*Condor*

**Technical highlights**

- Push error rate to 0.0001

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**IBM Quantum**

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**IEEE**
Superfridge

First of its kind dilution refrigerator to enclose $>>1000$ to $1$ million qubits
Scaling quantum technology

1 Million+ Qubits

Large Scale Systems

Technical highlights

- Cryogenic electronics
- Reduced qubit footprint
- Superfridge - Bigger fridge for cooling
- Quantum motherboard – integrated processor with isolators/amplifiers

IBM Quantum

Path to 1 million qubits and beyond

Large scale systems

Build new infrastructure, quantum error correction
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Quantum computer architecture

Microwave electronics

Qubit control and readout managed through classical electronics at room-temperature

Cryostat

Stages

- 3K
- 0.9K
- 0.1K
- 10 mK

Cooling power

- ~ 3 W
- ~ 100 mW
- ~ 1 mW
- < 100 µW

Refrigerator to cool qubits to 10 - 15 mK with a mixture of $^3$He and $^4$He

Qubit chip

PCB with the qubit chip at 15 mK protected from the environment by multiple shields

Chip with superconducting qubits and resonators

Cooling power

~ 100 mW

< 100 µW
Quantum computer architecture

Quantum system functions:
- **Biasing**: Initialization and tuning of energy levels
- **Control**: Application of quantum gates
- **Readout**: Detect qubit states

Adapted from D. Riste’ et al., arXiv:1411.5542v1
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Quantum computer architecture

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Quantum computer scalability

RF electronics in QCs:
- RF AWGs
- Baseband AWGs
- RF digitizers
- RF attenuators
- RF filters
- RF circulators
- RF cables
- InP/InAs LNAs
- QNL amplifiers

- Number of these components scales linearly with number of qubits

Adapted from D. Riste’ et al., arXiv:1411.5542v1
Quantum computer scalability

External electronics does not scale:

- Form factor & costs (racks of AWGs)
- Thermal load on fridge
- Power consumption (about 80 dB attenuation from 300 K to 10 mK)
- With n qubits we can expect at least 2n coax cables
- Reliability of discrete components

Adapted from D. Riste’ et al., arXiv:1411.5542v1
Quantum bits:
- Single qubit quantum gates are rotations of the state vector around the Bloch sphere
- We need to control the axis and angle of rotation
- Implemented in a two-state quantum system
Control of Transmon Qubits

Superconducting qubits:
- Control of qubit states using resonance frequency $\omega_r$
- Harmonic oscillator: Linear/harmonic oscillator – cannot distinguish states
- Oscillator must be non-linear, anharmonic. Replace L with JJ
- Wider separation (anharmonicity) is better
- **Qubit frequency**: $\omega_{01} = 6\text{-}9$ GHz
- **Anharmonicity**: $\omega_{01} - \omega_{02} \approx 200$ MHz
Qubit control signals

- We solve Hamiltonian for the basic control setup: Applying arbitrary voltage $V_d(t)$ to qubit resonator.
- Choose axis of rotation by controlling signal phase.
- Choose angle of rotation by controlling signal amplitude.
- Implementation through IQ modulation using baseband signal at $\omega_{01}$, 10-50 ns pulse durations.
- Envelope shape control important to reduce crosstalk.
Scalable Qubit Control

Cryogenically integrated architecture


Cryogenic control IC, multi-channel DACs/AWGs, simplifies system design, reduces cost but requires <1 mW/qubit

Demonstrations today

B. Patra et al., ISSCC 2020

1.7 mW/qubit (Analog) + 330 mW (Digital)

J. Bardin et al., ISSCC 2019

2 mW/qubit (Analog)
Scalable Qubit Control

Cryogenically integrated architecture

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B. Patra et al., ISSCC 2020

J. Bardin et al., ISSCC 2019

Challenges

• Power scaling
• Dense integration, I/O still a challenge with cryo-ICs
• Synchronization
• Crosstalk
• Optimization of waveforms
• Reflections

Opportunities

• Tailored cryogenic CMOS technology (leverage steep turn-on and higher mobility)
• 3D integration
• Low-margin tailored IC designs for narrow specs
Cryogenic CMOS Technology

**Benefits to cryogenic operation of CMOS**
- Increased mobility
- Increased saturation velocity
- Reduction of the subthreshold slope
- Reduction of leakage currents
- Reduction of thermal noise
- Improved device reliability

**Drawbacks of cryogenic operation of CMOS**
- $V_T$ increase
- New PDKs required
- Reduced thermal conductivity
- Increased sensitivity to self-heating

To leverage these effects a tailored technology is required.
Quantum computer scalability

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Adapted from D. Riste’ et al., arXiv:1411.5542v1
Frequency-Domain Multiplexing

Conventional approach

- One line per qubit, can have same Larmor frequency
- Difficult to scale interconnects

FDMA

- **FDMA**: Frequency-division multiple access
- Shared control lines with different Larmor frequencies
- Can be performed for both control and readout
- **Scaling**: Frequency spacing and signal bandwidth
Development of Cryogenic LNAs

- Cryo-LNAs based on InP HEMT technology
- Tailored for low temperature by bias point tuning and design
- Noise temperature described by:

  \[ T_{\text{min}} \approx 2 \frac{f}{f_T} \sqrt{R_G T_g T_d G_d} \]

  \[ T_{\text{min}} \propto \frac{\sqrt{I_{DS}}}{g_m} \]

- Difficult to reduce both power and noise

  - ~5 W cooling power
  - 1e6 qubits
  - 1-to-10 frequency multiplexing
  - 50% power budget to readout

25 µW per LNA channel with ~30 dB gain and < 4 K noise temp.
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- Difficult to reduce both power and noise

Cha et al., Trans. on MTT, 2017
Cha et al., EDL, 2020

\( V_d = 0.1 \text{ to } 1 \text{ V} \)
New Opportunities for Cryogenic LNAs

1. Superconducting metals in gate and matching networks
2. LNA arrays for higher density
3. Access resistance is bottleneck at cryo (due to mobility increase) – focused efforts!
4. MOSHEMT architecture

\[
R_{\text{access}} = R_{\text{C (15%)}} + R_{\text{sh (15%)}} + R_{\text{barrier (60%)}} + R_{\text{side (10%)}}
\]

Tessmann et al., IEEE J. Solid-State Circuits, 2019
A Perspective of Cryogenic Technologies

Wide array of cryogenic technologies will support the scaling of quantum computing
Conclusions

• Rapid progress **towards advanced quantum systems** projected within next decade
• **Scaling of QCs** supported by new readout and control microwave electronics
• **Cryogenic ICs** for control path promising to replace standard room-temperature approach
• For readout path, **new cryogenic amplifiers** likely needed
• A need for **extremely low power** cryogenic technologies is shared by both control & readout

Further reading