Cryogenic infrastructure for 400 qubits and beyond

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Outline

Superconducting qubits and need for cryogenics

The 433 qubit Osprey system

Wiring, connectors, and flex for RF signal delivery

Additional needs to scale to very large systems
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<th>Section</th>
<th>Description</th>
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<td><strong>Motivation, and why we need cryogenics</strong></td>
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<td><strong>Quantum computing</strong></td>
<td>A fault tolerant quantum computer can perform valuable computations no other computer can. Simpler error mitigation may be sufficient for something useful. Requires qubits...</td>
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<tr>
<td><strong>Superconducting qubits</strong></td>
<td>We can leverage fabrication from semiconductor industry, and electronics from telcom (mostly 4-8 GHz &quot;C-band&quot;). Requires low temperatures...</td>
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<td><strong>Cryogenic temperatures</strong></td>
<td>We want low-loss qubits (&lt; 1 K for superconducting materials) and qubits to stay in the ground state with minimal perturbations (&lt; 20 mK for ~5 GHz qubits).</td>
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</table>
Superconducting qubits are non-linear LC oscillators

In a harmonic oscillator (like LC circuit), all energy levels are equally spaced. We cannot uniquely address specific energy levels.

A qubit is a two-level quantum system. By using a Josephson junction as a non-linear inductor, energy levels become unequally spaced. We can uniquely address the lowest levels, and "ignore" the higher levels.
Superconducting qubits are non-linear LC oscillators

"Transmon" superconducting qubit

Josephson Junction

$E_{01} \approx h \cdot 5 \text{ GHz} \approx k \cdot 240 \text{ mK}$

Koch, 10.1103/PhysRevA.76.042319
Osprey (433 qubits)
Osprey (433 qubits)
Basic elements of a quantum system

User access (Qiskit & Cloud Services)

Control electronics & classical compute

Quantum device (qubits)
Basic elements of a quantum system

- User access
- Control hardware
- Quantum device (Qubits)
- Environmental infrastructure
Wiring requirements in Osprey

**Control**
- RF input (1/qubit)

**Readout (MUX'd)**
- RF output (1/group)
- RF TWPA pump (1/group)
- LNA DC power (2 + GND/group)

Overall: >500 RF lines to MXC  
>100 DC lines to 4 K
Quantum systems using coaxial cable wiring (and SMA connectors)
RF wiring (>1 GHz)

Coax Advantages

- Excellent RF performance (isolation, match)
- Semi-rigid has complete coverage
- Cylindrical shell is optimal geometry (uniform return current)
- Proven across many quantum systems
- RF components readily available (filters, amplifiers, isolators, couplers...)
- Easy to reconfigure (in small numbers)

Coax Disadvantages

- Density
- Thermal conductivity (much thicker than skin depth)
- High system cost per channel
RF wiring (>1 GHz)

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**Flex Advantages**
- Many channels in one cable
- Complete design control
- Can integrate filters, attenuators...
- Engineered loss vs thermal conductivity
- Multiple signal types in one cable (single-ended RF, differential, power)
- Cost/channel decreases with density

**Flex Disadvantages**
- Requires development
  - Unique materials (for thermal)
  - Custom high-density multi-channel connectors
- Worse RF performance (isolation, loss, match)
System sizing thermal limitations

Cryostat heatloads:
- Cryostat overhead (mechanical support conduction, radiation, dilution circuit operation)
- Conduction through cabling
- Active loads (attenuation of control pulses, TWPA pumps, HEMT LNAs)

Sizing a system accurately requires thermal conductivity data of materials used in cabling, and an understanding of cryostat cooling capacity and interplay between stages.

Goal: maximize number of qubits that can operate < 20 mK

For similar analysis at 100 qubits, see Krinner, 10.1140/epjqt/s40507-019-0072-0
Metals dominate cable thermal conductivity
Copper conductivity can vary greatly at low T
Electric currents have limited penetration into conductors. Current density is greatest near conductor surface, penetration is exponentially suppressed by skin depth

\[ \delta_s = \sqrt{\frac{2}{\mu \sigma \omega}} \]

\( \mu = \) magnetic permeability
\( \sigma = \) conductivity
\( \omega = \) frequency

Conductors only need to be a few skin depths thick to minimize loss.
RF flex construction

Stripline transmission lines; signal between ground planes (G-S-G)

Via stitching ties ground planes together, and improves crosstalk

Metal layer materials are selected to minimize RF loss given available cooling capacity
RF flex construction

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Additional signal layers improve thermal cost per channel G-S-G-S-G...
Mesh ground planes for reduced thermal load

Adjust geometry for minimal impedance variation

Many patterns to explore...
Flex attenuators/filters

- Chip attenuators
- LTCC filters
- Integrated patterned filters

Can wirebond, bump-bond, solder, or embed filters and attenuators
"Twisted" differential pairs

...for lower frequency applications:
- Flux bias (SQUID/JRM-based amplifiers, tunable qubits)
- Fast flux gates
- Serial communication links

Kam, 10.1109/LMWC.2003.815181

Cryo-CMOS Controller

Frank, 10.1109/ISSCC42614.2022.9731538
Coaxial RF connectors

SMA

Rosenberger

Ganged SMP
Board-to-board connectors

Spring Probe

Z-Ray

PCBeam

Connect-R
Solderless board-to-coax connectors

TR Multicoax

Rosenberger
Spring Loaded Coax System

Bulls Eye
Commercially available cryogenic high-density wiring (coax)

- **BLUEFORS**
  - 168 channels/bay
  - CuNi Coax
  - SMP-M connector
  - Attenuators, filters

- **ARDENT CONCEPTS**
  - 160+ channels
  - CuNi, NbTi coax
  - TR connector
  - Attenuators

- **PHOENIX Company of Chicago**
  - CuNi coax
  - PkZ connector
  - Attenuators
Commercially available cryogenic high-density wiring (non-coax)

Up to 24 channels
NbTi, CuNi, SS
SMP-S connectors
Mates w/ attenuators, LNAs...

8 channels
Ag or NbTi on PI
SMA, SMP connectors
Integrated filtering

Smith, 10.1109/TASC.2020.3008591

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Osprey (433 Qubits)

Start with standard BlueFors XLD1000, barren of any wiring

Mezzanine plate added below MXC
Osprey (433 Qubits)

Transition to copper coax at MXC to interface with ferrite isolators, superconducting NbTi coax output lines
DC power for LNAs

Stack up amplifiers, use ganged block of SMP-S for RF I/O

Backplane card plugs into stack for DC power

KF-40 port can provide enough DC wiring for over 1000 qubits

Custom flex spans thermal stages

Cheap off-the-shelf copper flex within stage
Future wiring needs for very large systems

**Flex**

Hybrid stackups with different metals, or multiple metals on one layer (high and low conductivity metals, patterned resistors, thermally conductive dielectrics for attenuators)

Ultra-thin copper with stable RRR

Support large panel sizes, or reel-to-reel, with hybrid metal stackups

Multi-layer superconducting panels with high-conductivity noble metal terminations. Solderable copper pads would be a bonus.

**Connectors (for flex)**

High density while maintaining high RF isolation (as dense as physically possible... the connector will always be the bottleneck)

Preferably solderless

Right-angle and face-to-face options (or flex cables with sharp bend radius)
Superconducting flex
Al/Nb/Al striplines on PI

High Tc flex, YBCO on Kapton

Gupta, 10.1109/TASC.2019.2904203
Solovyov, 10.1109/TASC.2021.3057010
## Future cryostat needs for very large systems

### Modularity
Complete cryostats should come as modular units that can be tiled to grow with system needs, or swapped for repairs or scheduled maintenance.

### Liquid cryogen cooling (?)
Increase cooling power density around key areas like cryo-CMOS, moving cooling infrastructure further away. Allow for redundancy, or ability to dynamically shift cooling needs. TBD if overhead in maintaining liquifiers is worth the change.

### Supplemental stages
Specialized temperature stages for wiring, electronics, cryogenic infrastructure.

### Co-design
Cryostat to be tailored to quantum system. Quantum computing companies may act as a system integrators, working with cryogenics manufacturers to produce specialized cryostats. No more one-size fits all.
Cryogenic control electronics

**PT420 Capacity Curve**

Much greater cooling power when higher temperatures are allowed
Goldeneye

Clam shell OVC design

Symmetric stacks of cooling plates on top and bottom

48" diameter MXC plate
1.5 m³ experimental volume

18 W @ 4 K
1.5 mW @ 100 mK / DR unit
(up to 3 DR unit / plate)

15 day cooldown to 25 mK

See Pat Gumann's talk
J4Or1A-01
Room 323A at 10:00
IBM Quantum System 2
Large Cryostats

- BLUEFORS
  Kide
- Maybell
  The Big Fridge
- Oxford Instruments
  Proteox LX
Conclusions

Flex wiring provides customizable, high-density, low-cost wiring tailored to the system. Continued development in connectors, materials, and manufacturing techniques for flex will be required to reap full benefits.

Large quantum systems will ultimately require purpose-built cryostats.