Cryogenic infrastructure for 400 qubits and beyond

2023 CEC/ICMC

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IBM Quantum

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

Motivation, and why we need cryogenics

Quantum computing

A fault tolerant quantum computer can perform valuable computations no other computer can. Simpler error mitigation may be sufficient for something useful. Requires qubits...

Superconducting qubits

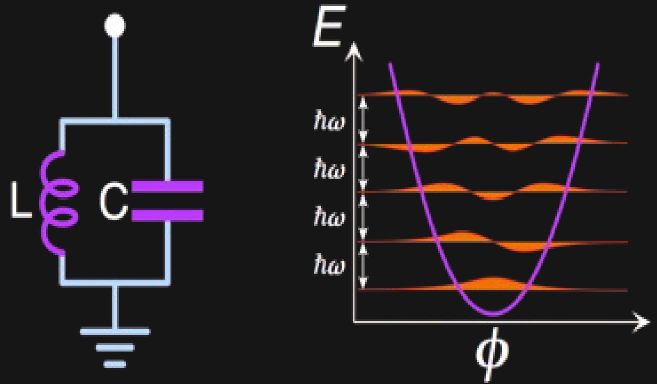
We can leverage fabrication from semiconductor industry, and electronics from telcom (mostly 4-8 GHz "C-band"). Requires low temperatures...

Cryogenic temperatures

We want low-loss qubits (< 1 K for superconducting materials) and qubits to stay in the ground state with minimal perturbations (< 20 mK for ~5 GHz qubits).

Superconducting qubits are non-linear LC oscillators

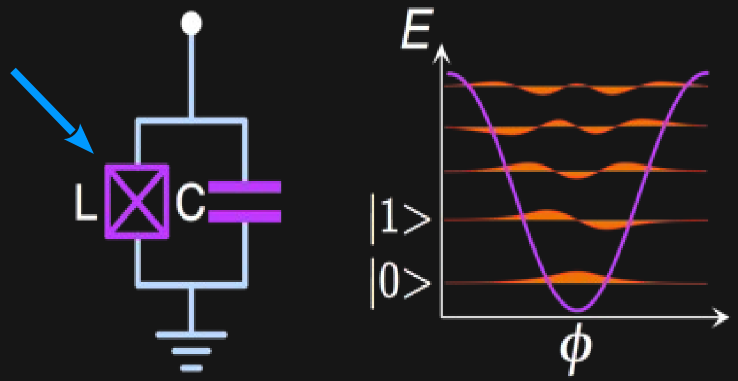
Linear LC



$$E_{01} = E_{12} = \ldots = \hbar\omega$$

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

Non-linear LC

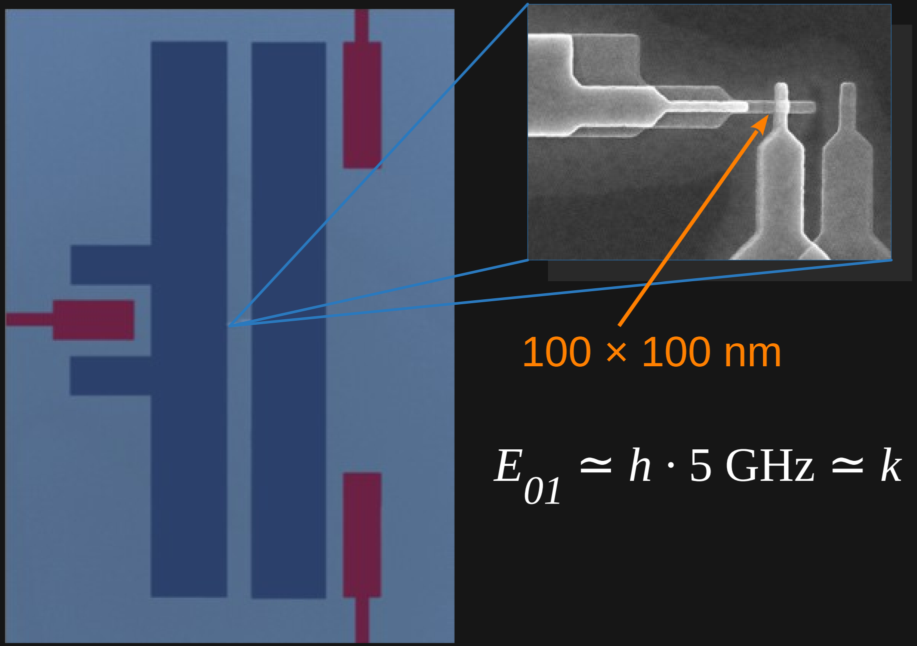


$$E_{01} = E_{12} + \alpha$$

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

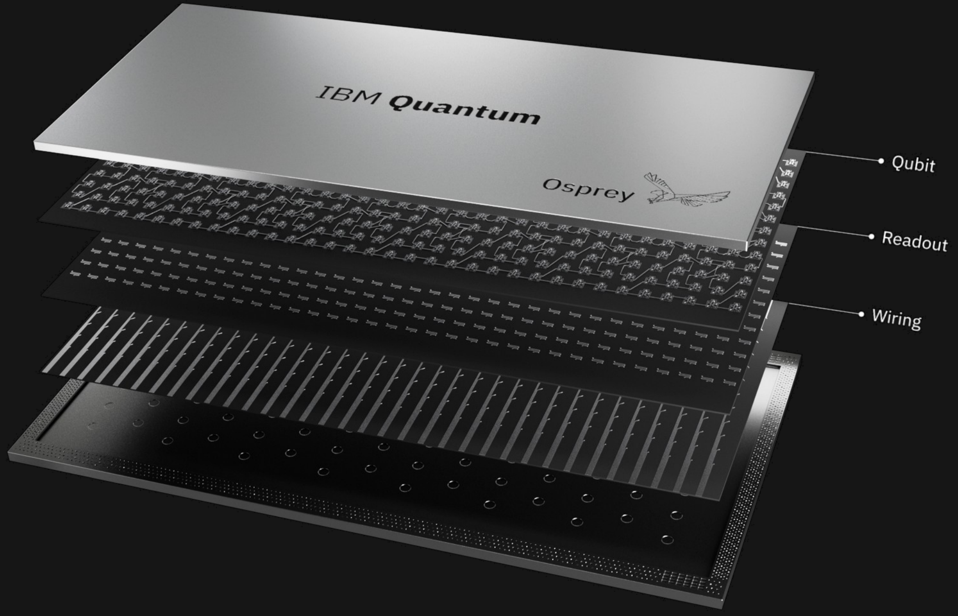
"Transmon" superconducting qubit

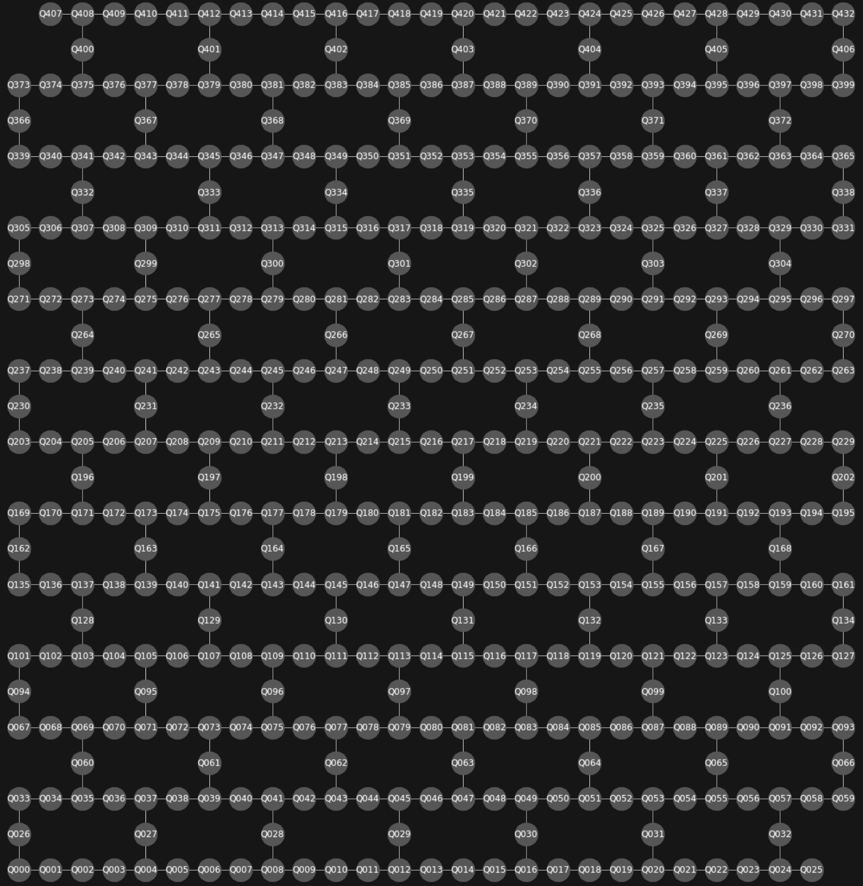


$$E_{01} \simeq h \cdot 5\ \mathrm{GHz} \simeq k \cdot 240\ \mathrm{mK}$$

Koch, 10.1103/PhysRevA.76.042319

Osprey (433 qubits)





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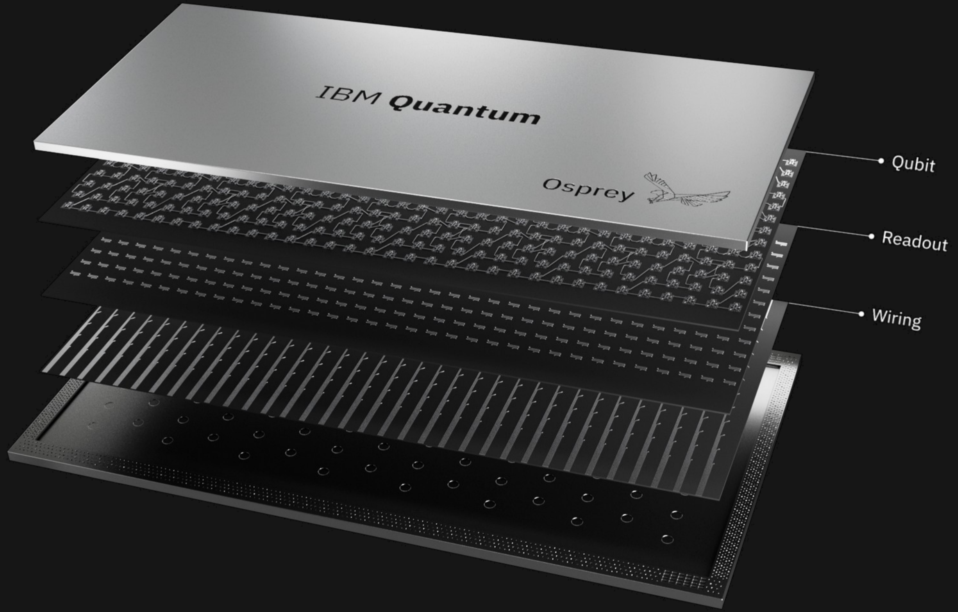
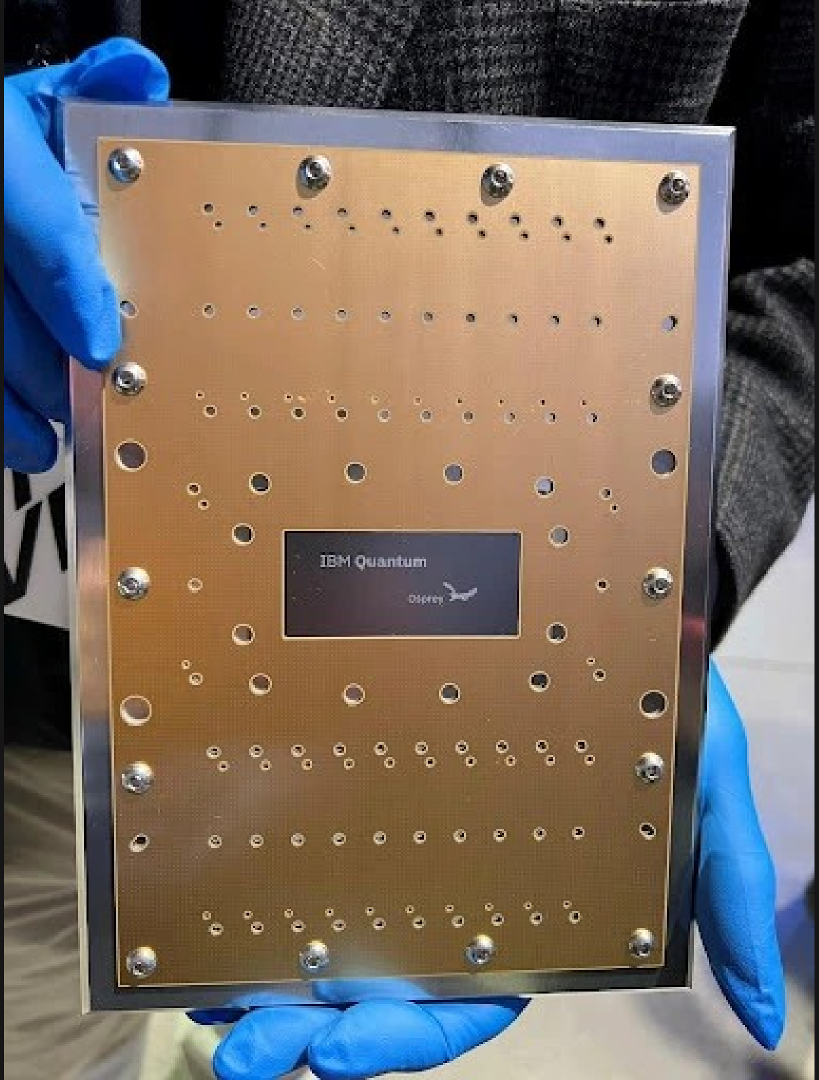
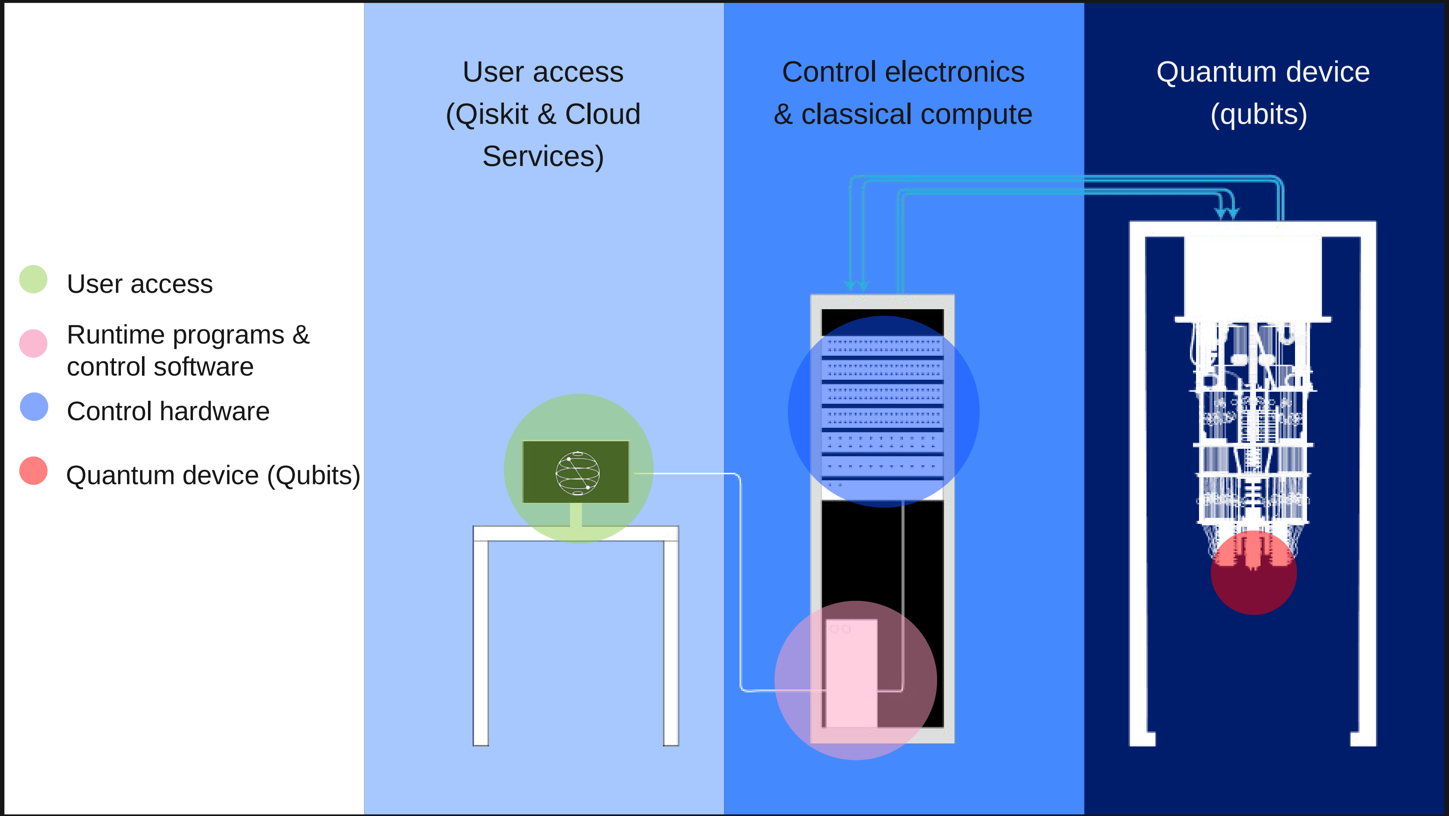




Basic elements of a quantum system



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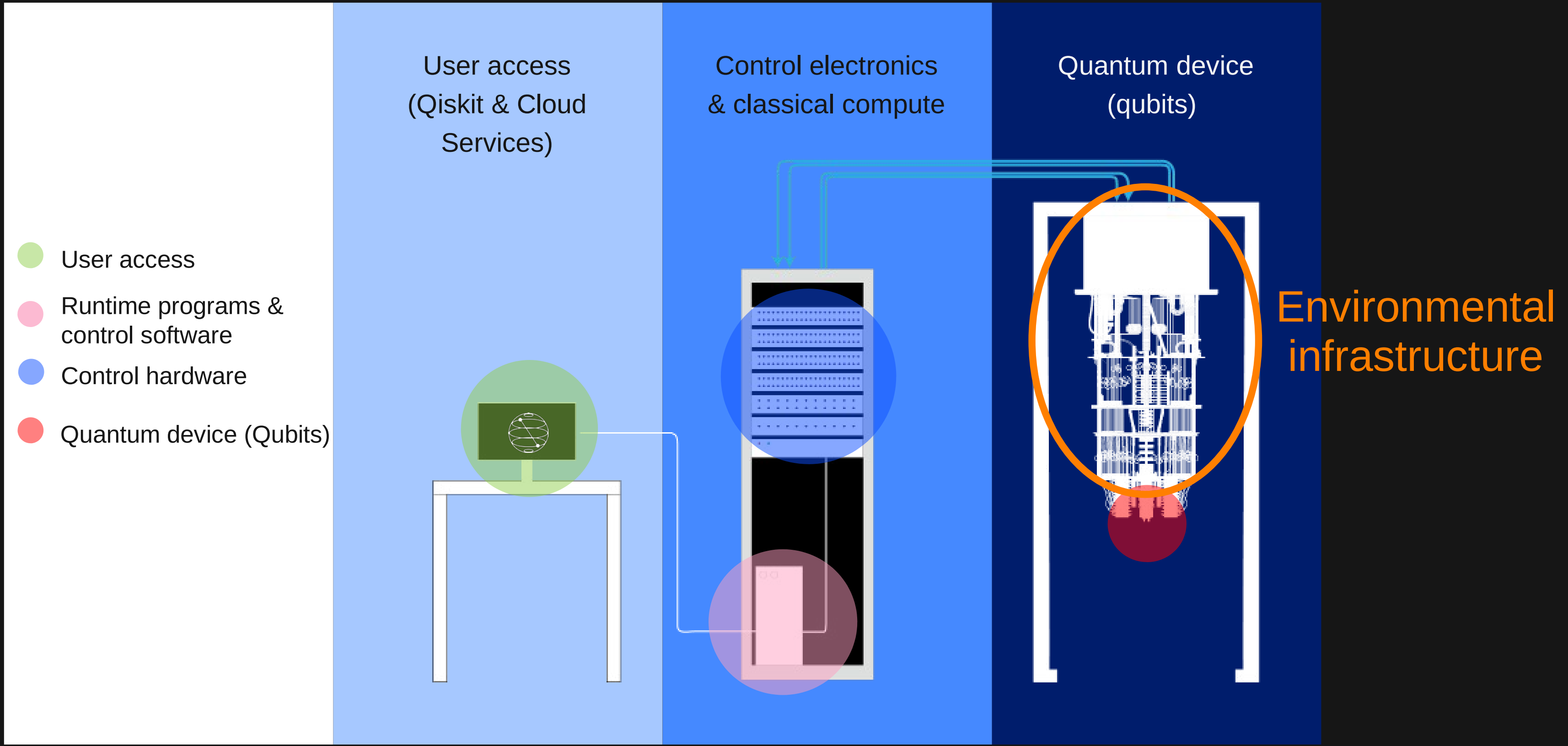
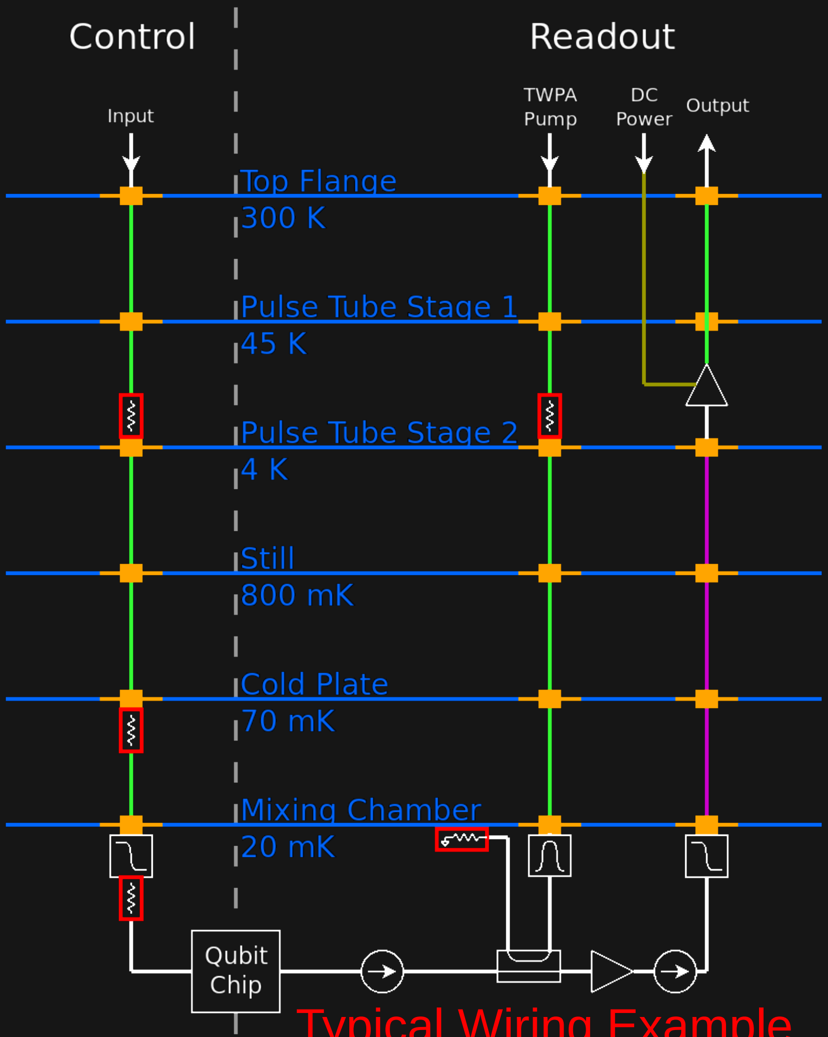


Wiring requirements in Osprey

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



Typical Wiring Example

Quantum systems using coaxial cable wiring (and SMA connectors)

IBM

Google

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

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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)

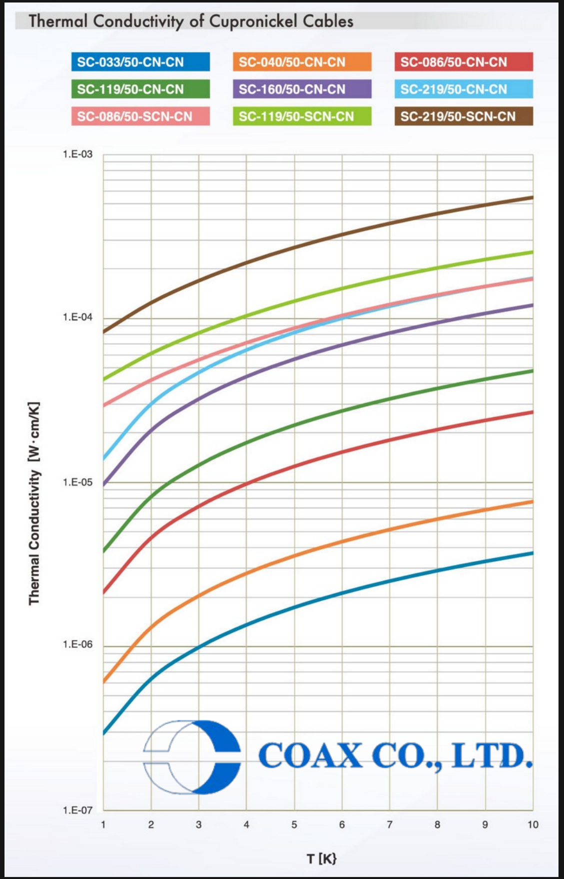
System sizing thermal limitations

Cryostat heatloads:

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

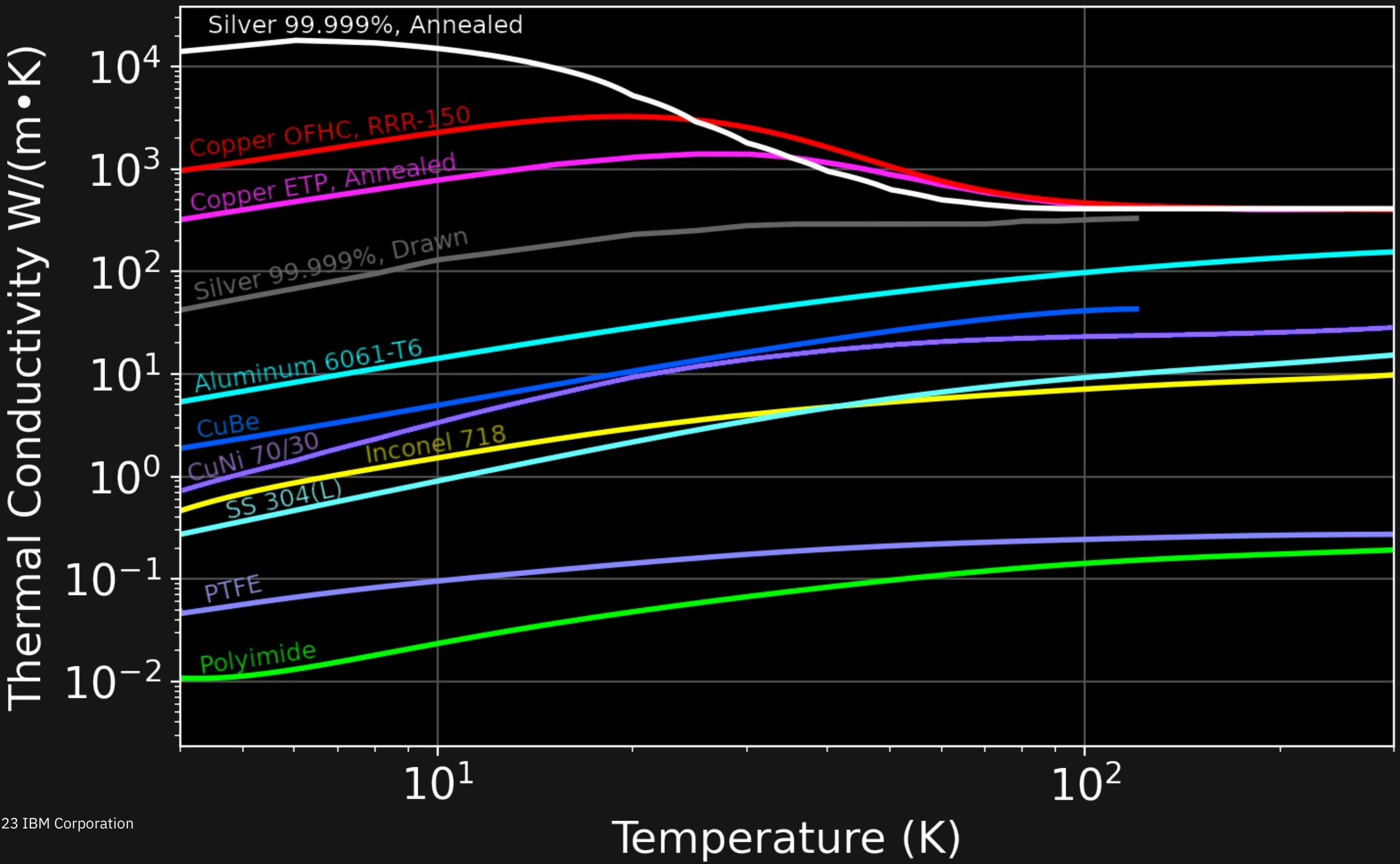
Sizing a system accurately requires thermal conductivity data of materials used in cabling, and an understanding of cryostat cooling capacity and interplay between stages.

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

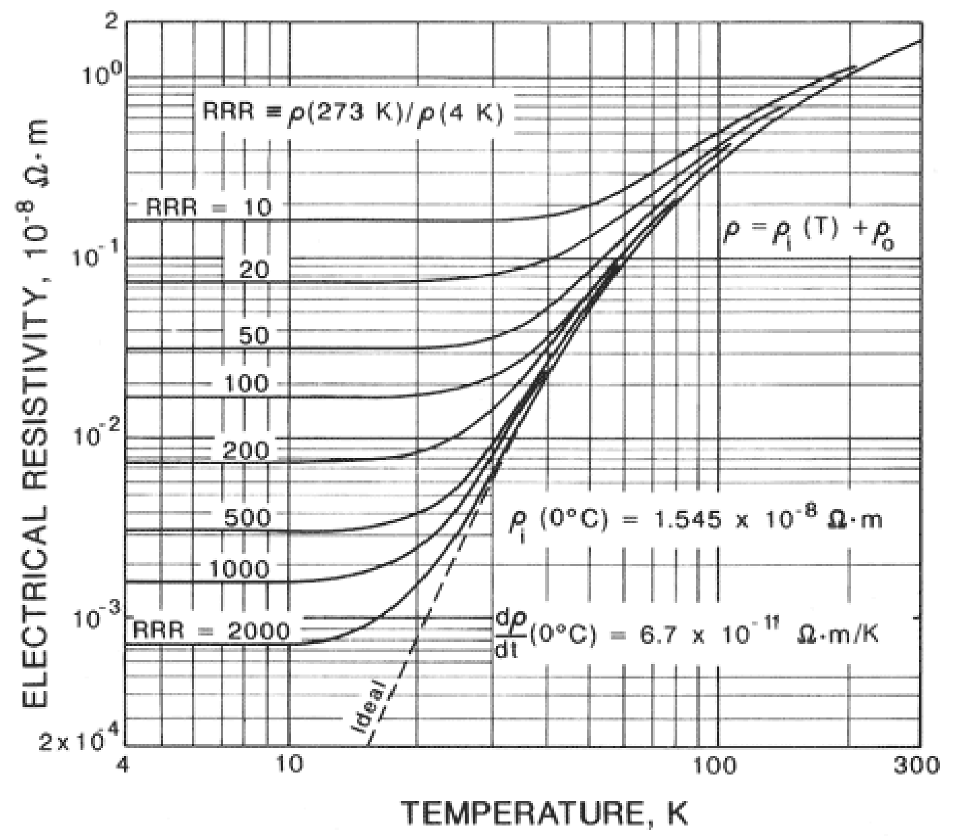


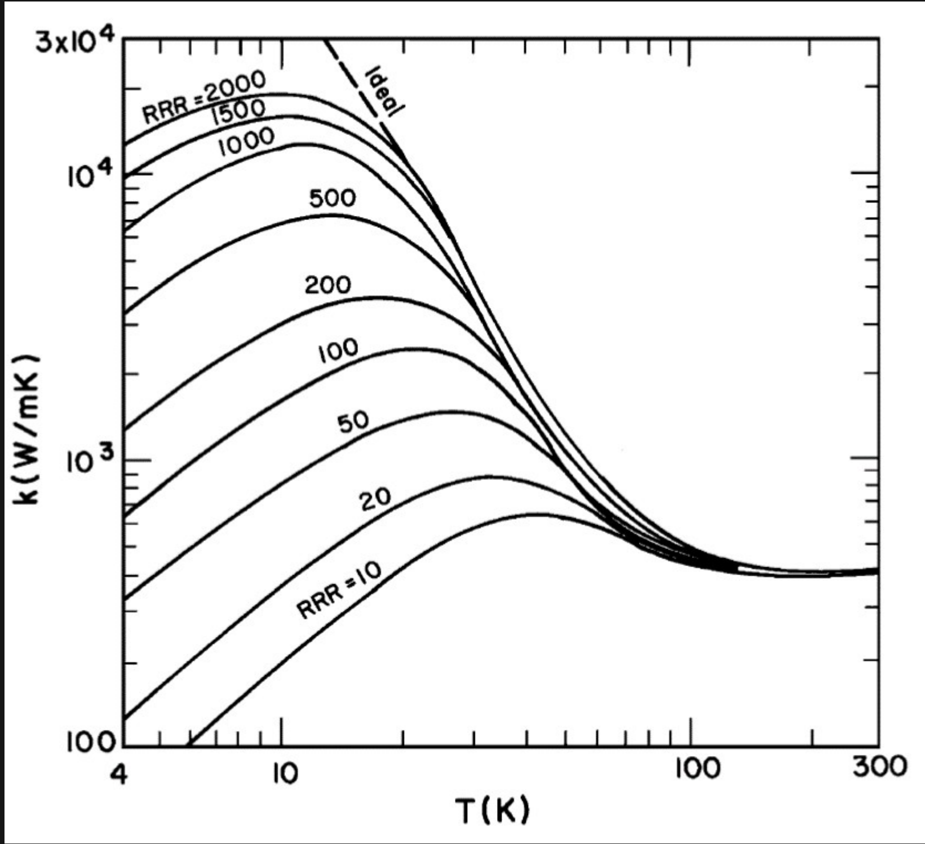
For similar analysis at 100 qubits, see Krinner, 10.1140/epjqt/s40507-019-0072-0

Metals dominate cable thermal conductivity



Copper conductivity can vary greatly at low T





Calatroni, https://cds.cern.ch/record/2646487

Electric currents have limited penetration into conductors

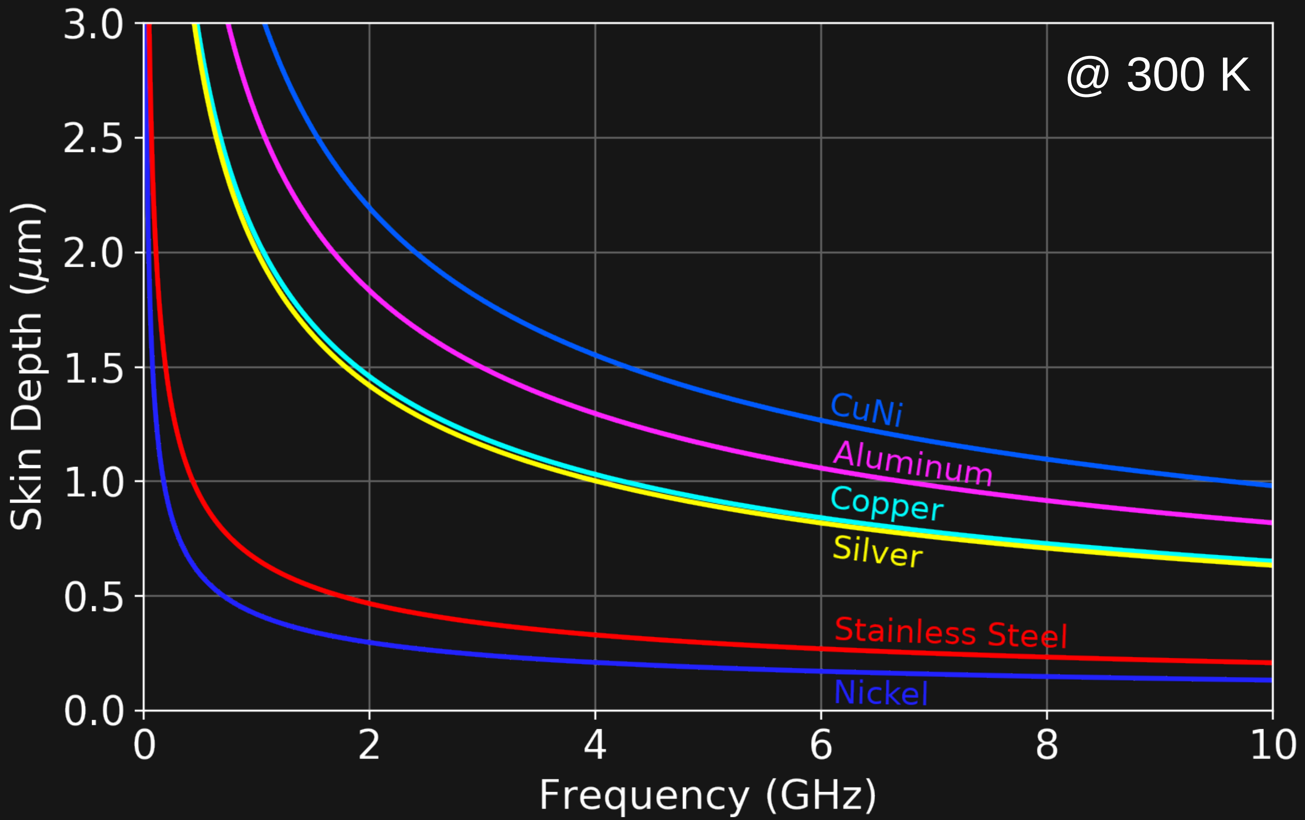
Current density is greatest near conductor surface, penetration is exponentially suppressed by skin depth

$$\delta_s = \sqrt{\frac{2}{\mu\sigma\omega}}$$

μ = magnetic permeability

σ = conductivity

ω = frequency



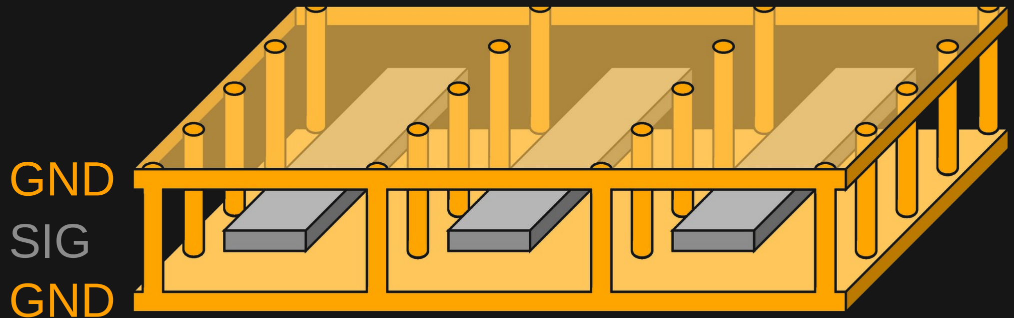
Conductors only need to be a few skin depths thick to minimize loss

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



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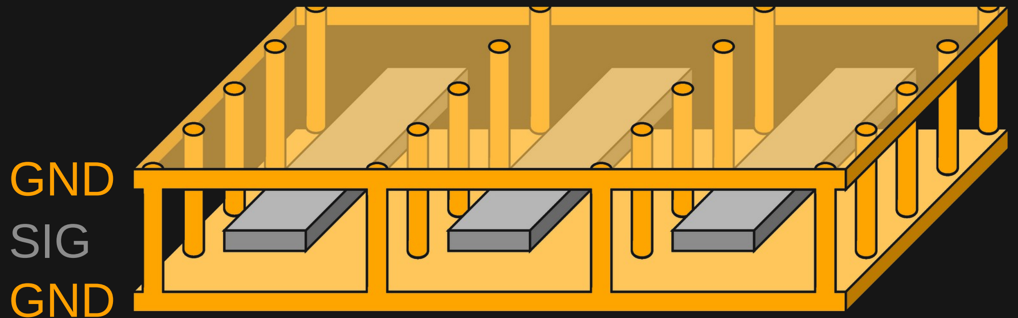

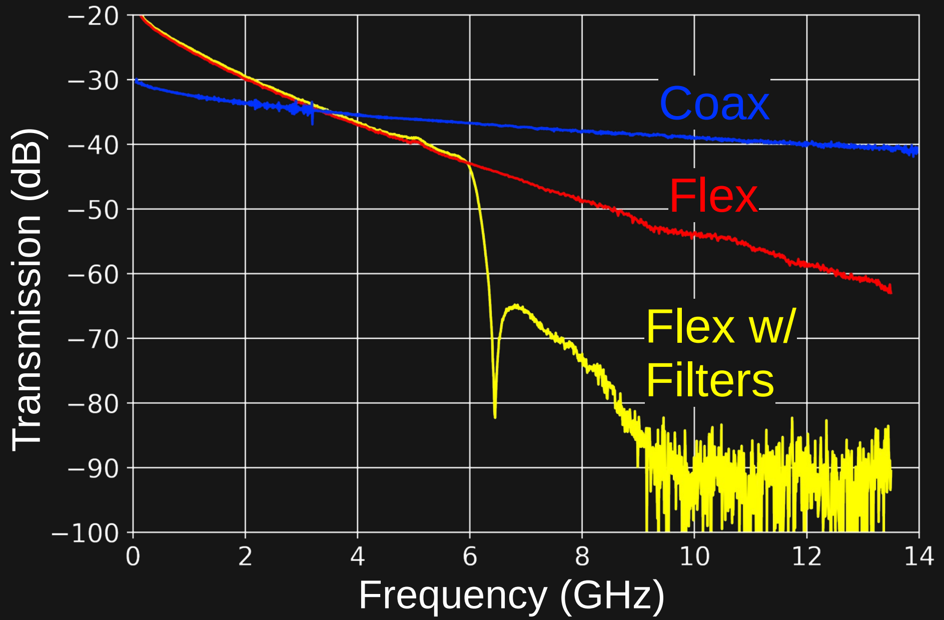

RF flex construction

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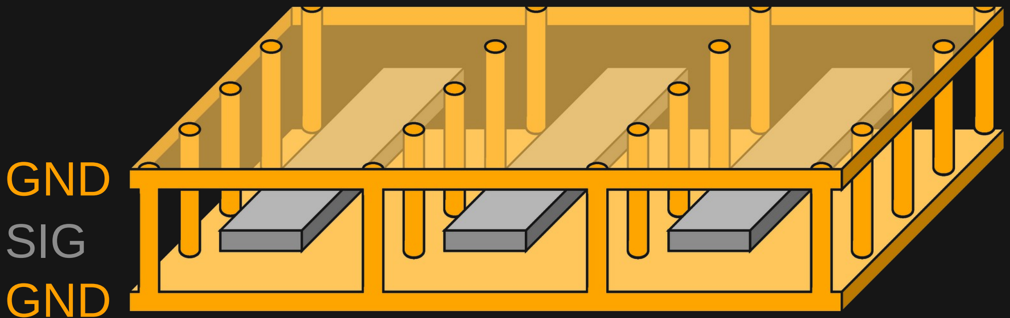
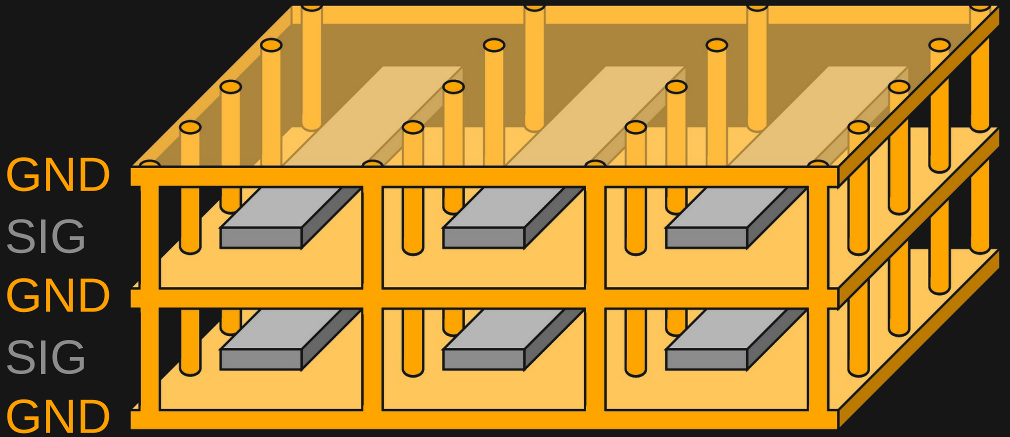
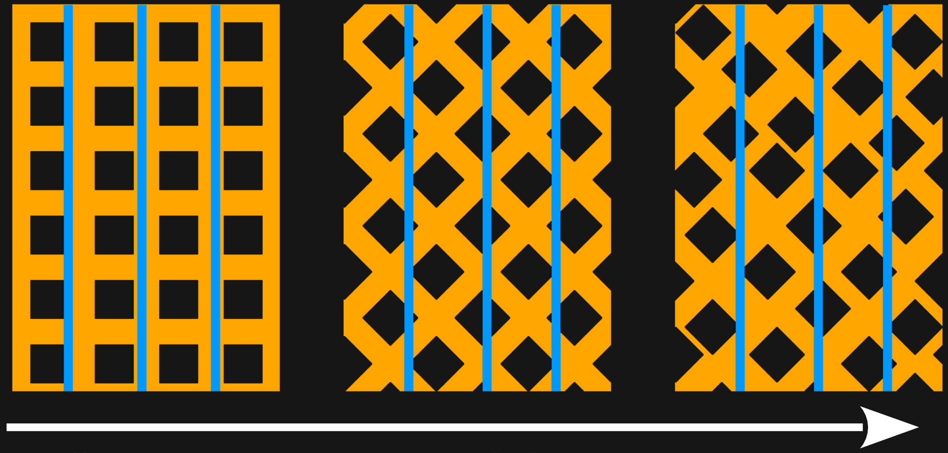
Additional signal layers improve thermal cost per channel
G-S-G-S-G...



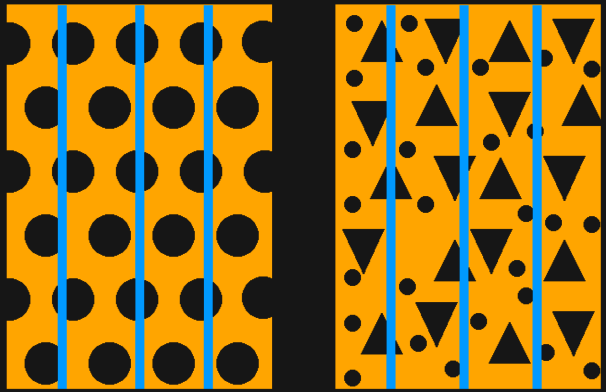


Mesh ground planes for reduced thermal load



Adjust geometry for minimal impedance variation

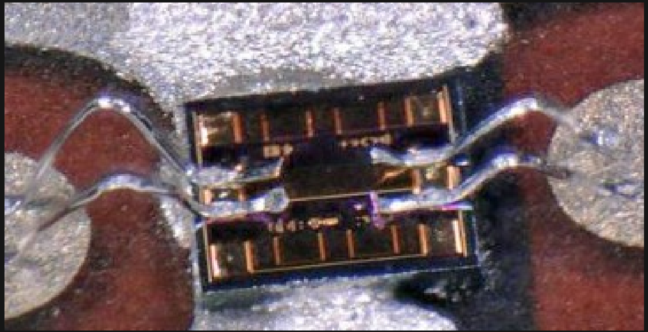
Many patterns to explore...



Flex attenuators/filters

XMA POWERED BY Omni Spectra

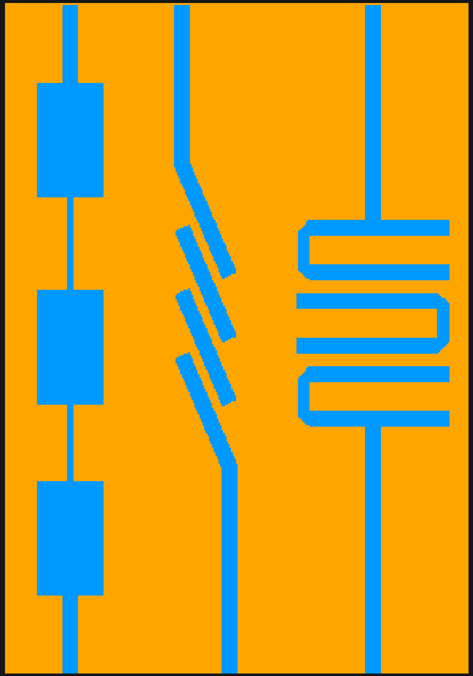
Chip attenuators



Mini-Circuits

LTCC filters

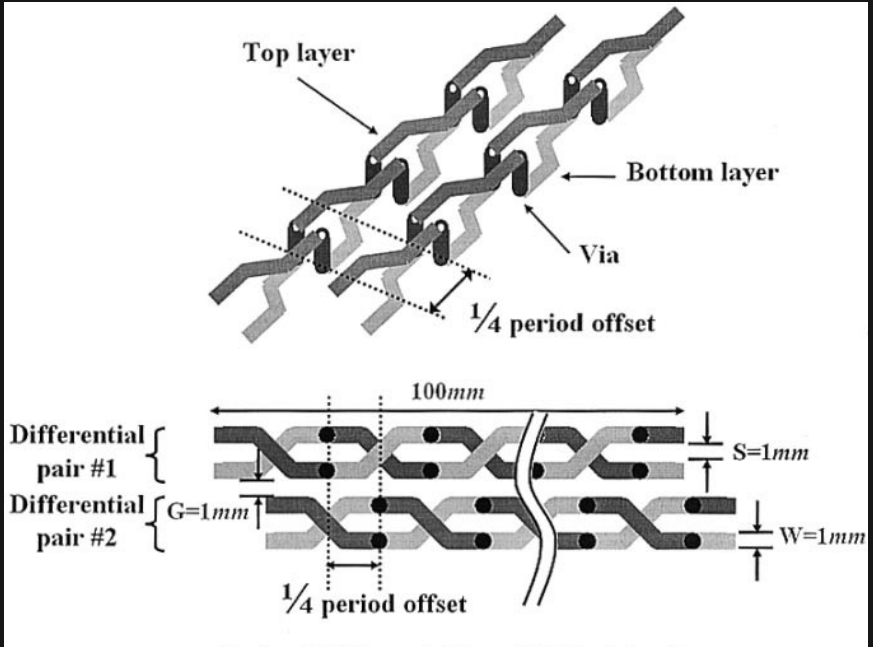
Integrated patterned filters



Can wirebond, bump-bond, solder, or embed filters and attenuators

Differential geometry for lower frequencies

"Twisted" differential pairs



Twisted differential line (TDL) with offset

Kam, 10.1109/LMWC.2003.815181

...for lower frequency applications:

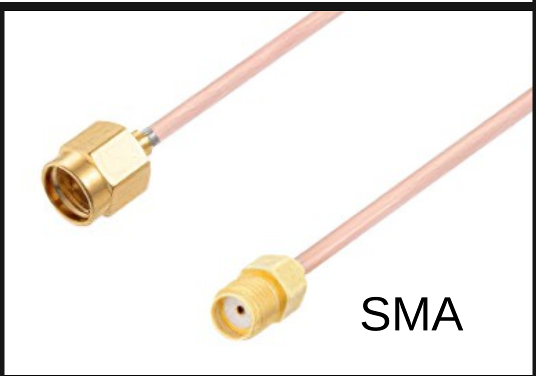
- Flux bias (SQUID/JRM-based amplifiers, tunable qubits)
- Fast flux gates
- Serial communication links


Cryo-CMOS Controller

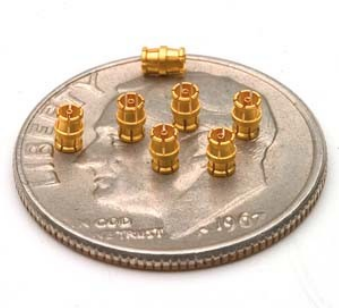
Frank, 10.1109/ISSCC42614.2022.9731538

Coaxial RF connectors

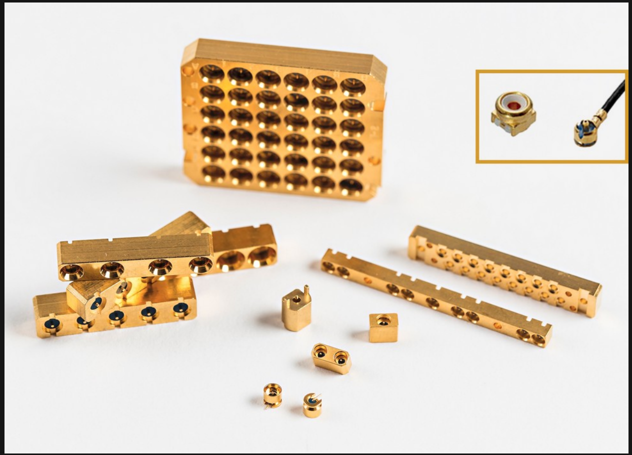
PE PASTERNACK® an INFINITE brand



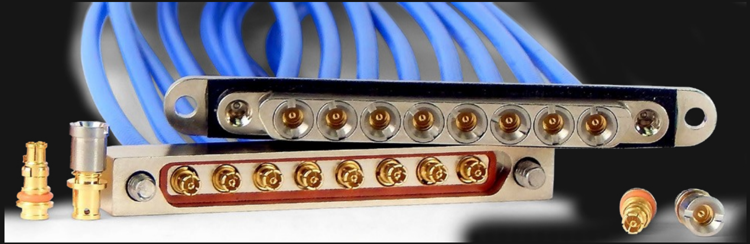
CORNING



Rosenberger



TELEDYNE DEFENSE ELECTRONICS Everywhereyoulook™



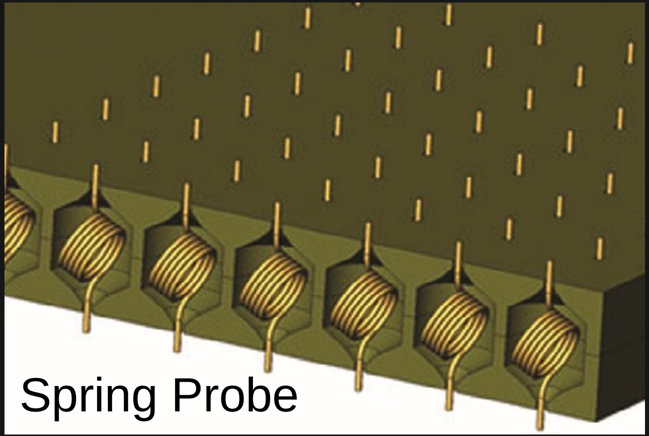
JOHNSON™

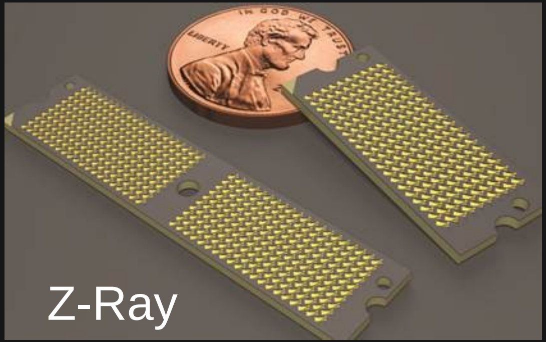
Board-to-board connectors

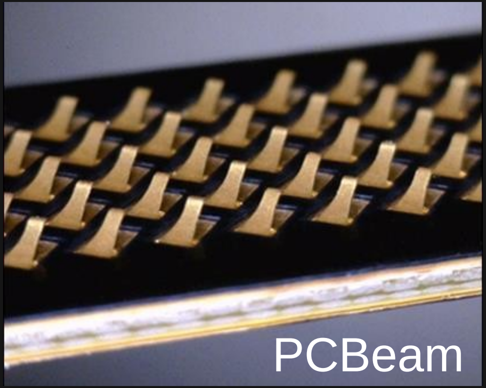
ARDENT CONCEPTS
An Amphenol Company

samtec

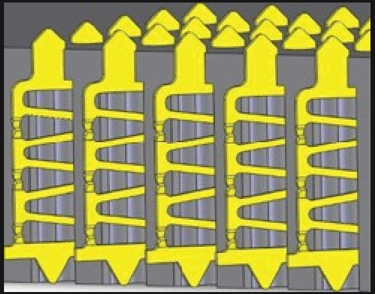
neoconix™

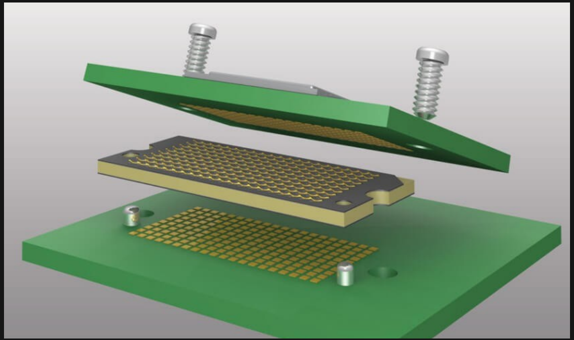


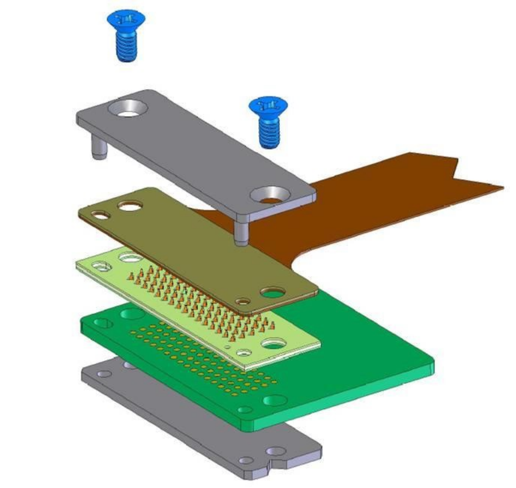




Connect-R







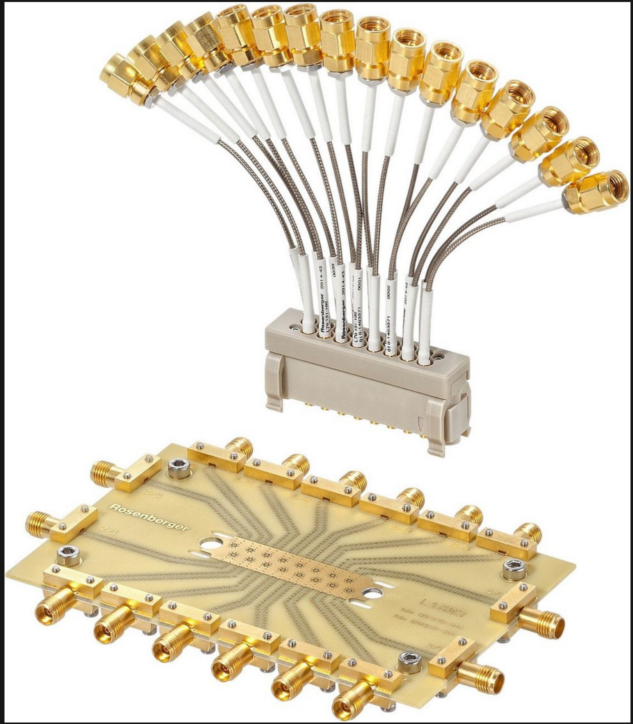
Solderless board-to-coax connectors

ARDENT CONCEPTS
An Amphenol Company

TR Multicoax

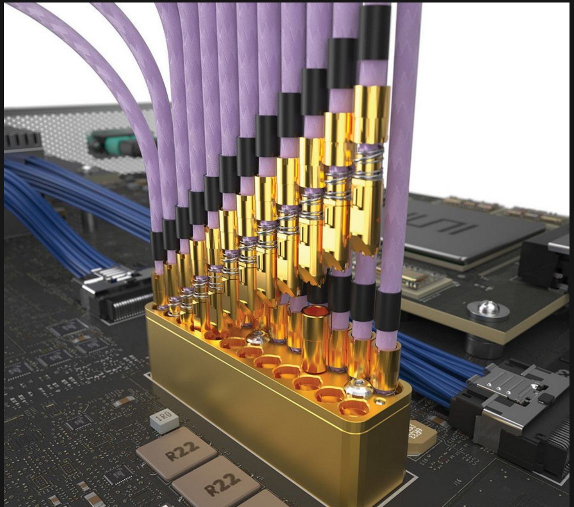
Rosenberger

Spring Loaded Coax System



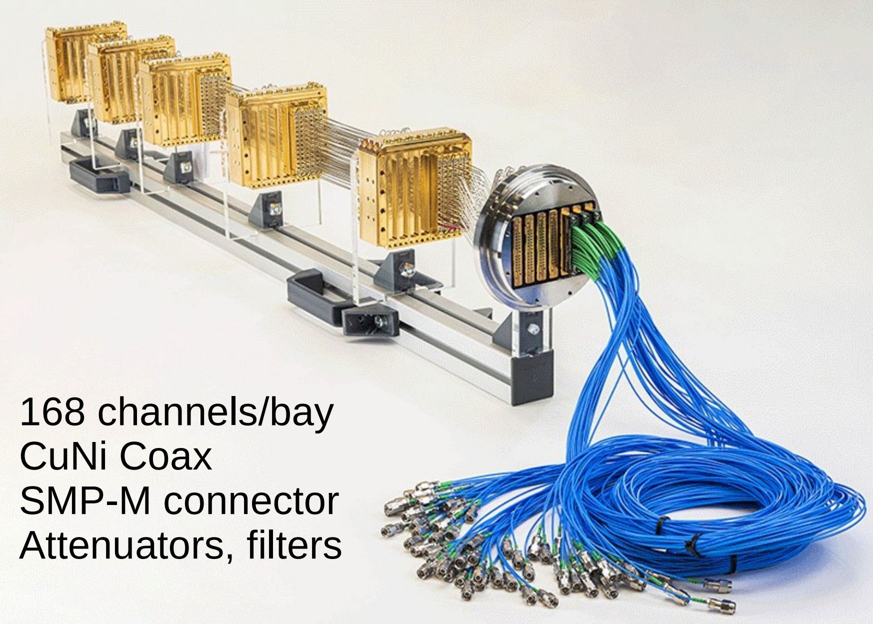
samtec

Bulls Eye



Commercially available cryogenic high-density wiring (coax)

BLUEFORS



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

ARDENT CONCEPTS
An Amphenol Company

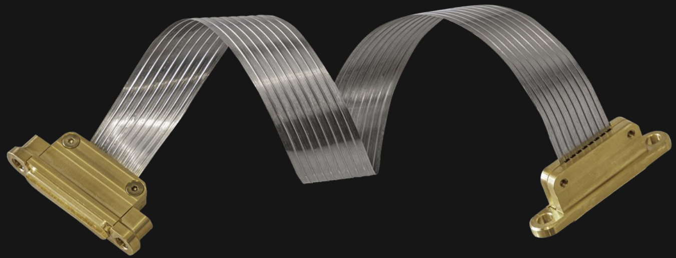
160+ channels
CuNi, NbTi coax
TR connector
Attenuators

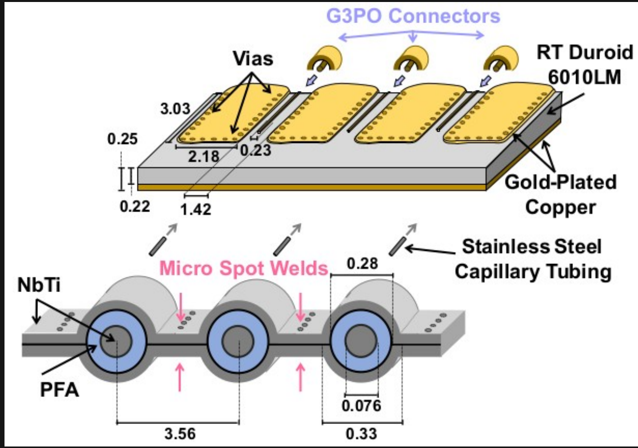
The PHOENIX Company of Chicago

CuNi coax
PkZ connector
Attenuators

Commercially available cryogenic high-density wiring (non-coax)

Maybell

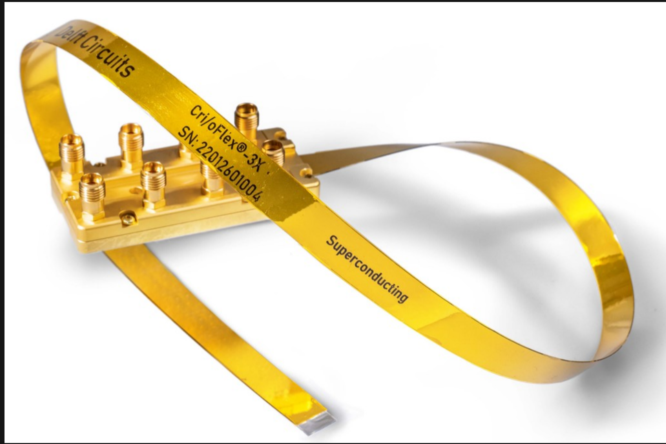




Up to 24 channels
NbTi, CuNi, SS
SMP-S connectors
Mates w/ attenuators, LNAs...

Smith, 10.1109/TASC.2020.3008591

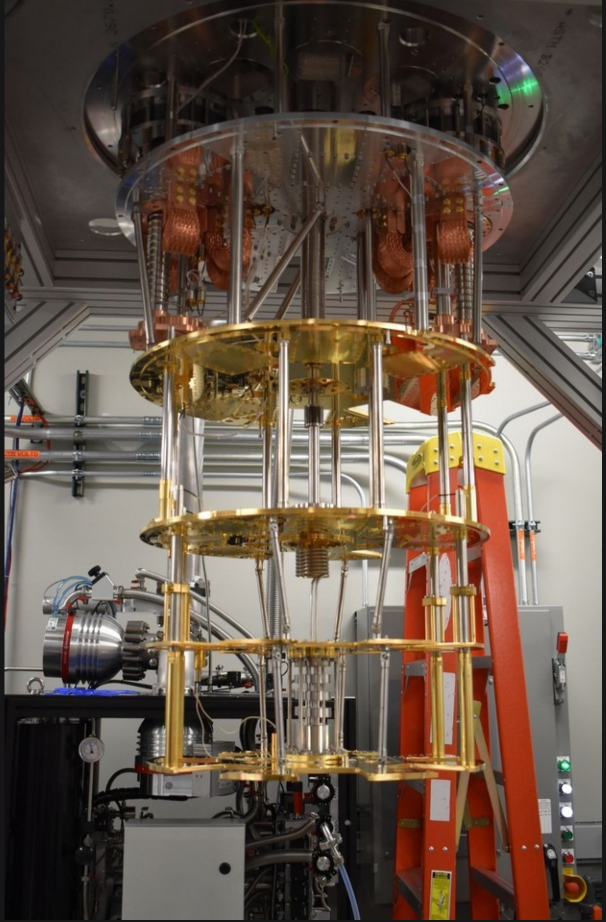
Delft Circuits
Hardware for quantum engineers



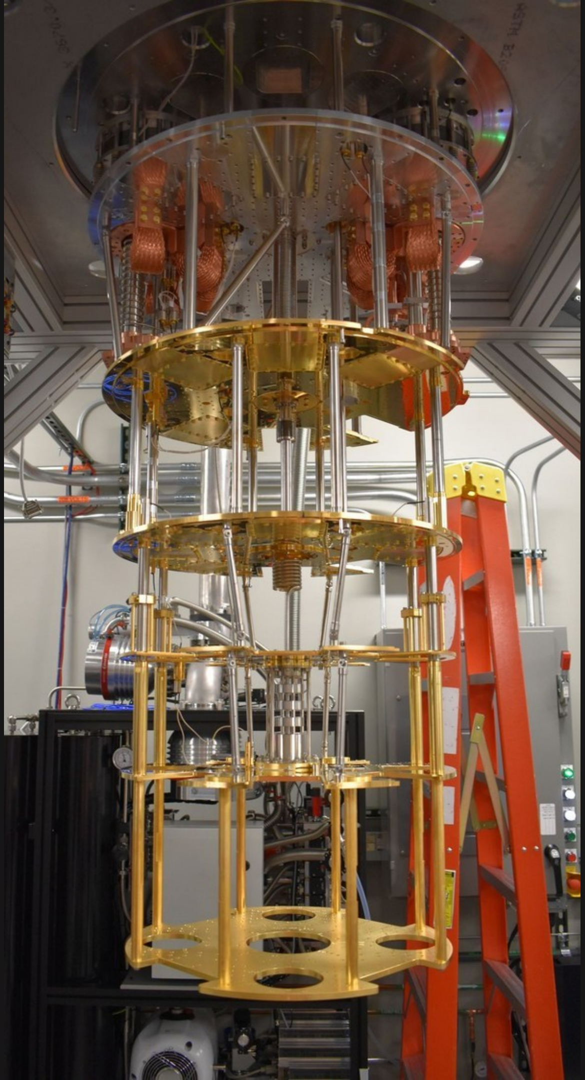
8 channels
Ag or NbTi on PI
SMA, SMP connectors
Integrated filtering

Osprey
(433 Qubits)

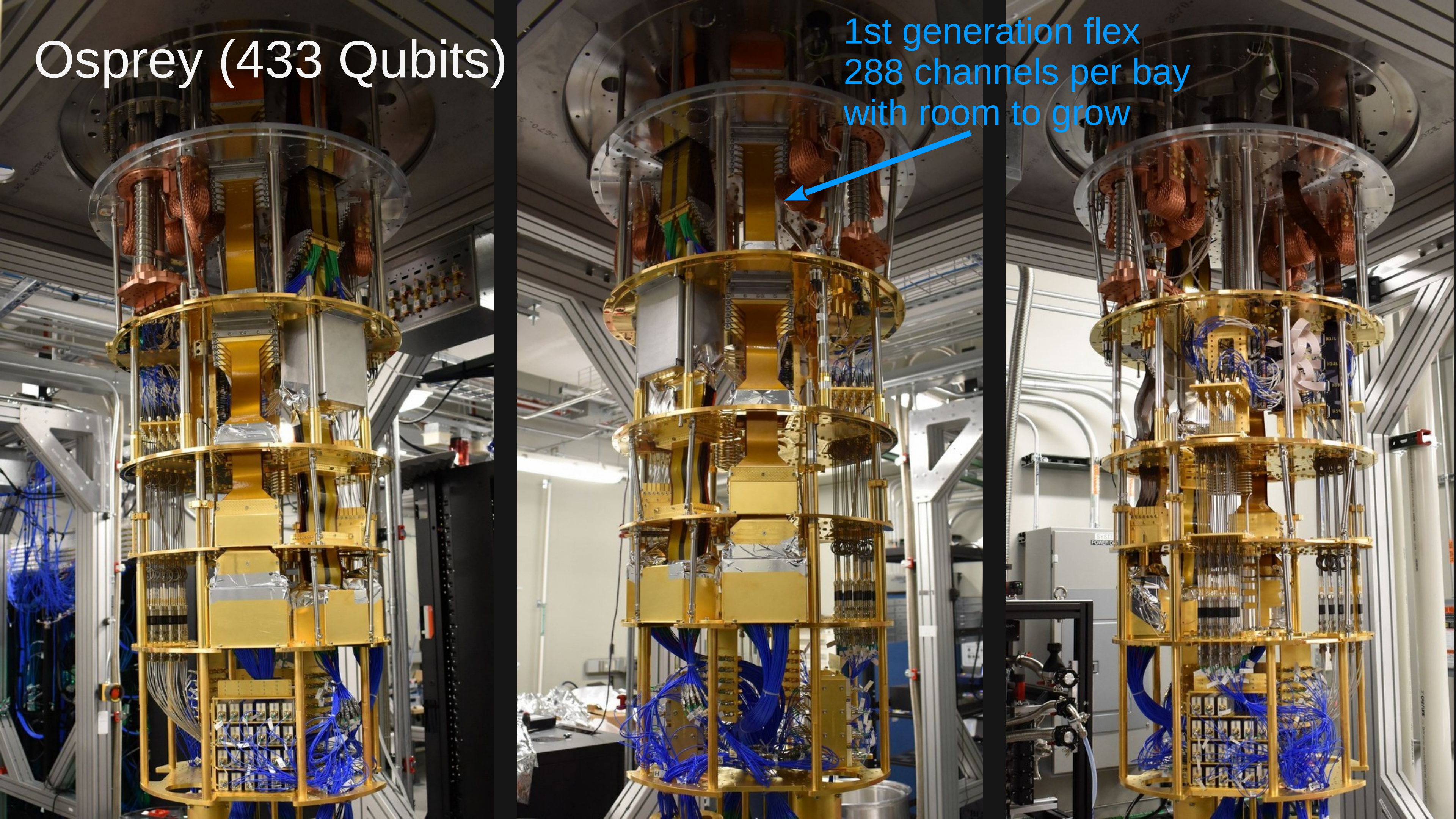
Start with standard BlueFors XLD1000, barren of any wiring



Mezzanine plate added below MXC

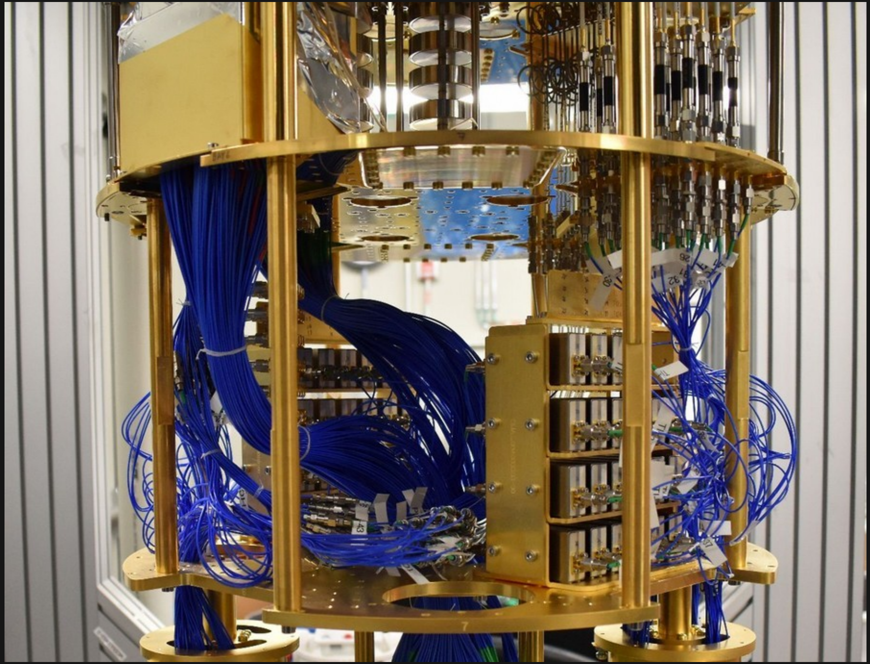


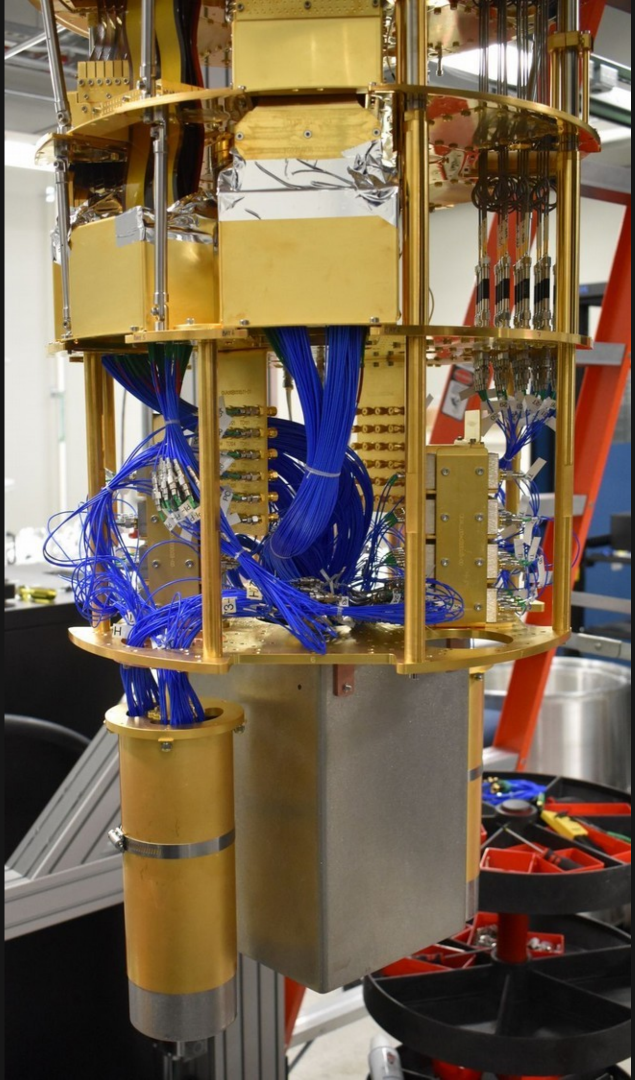
Osprey (433 Qubits)



Osprey (433 Qubits)

Transition to copper coax at MXC to interface with ferrite isolators, superconducting NbTi coax output lines



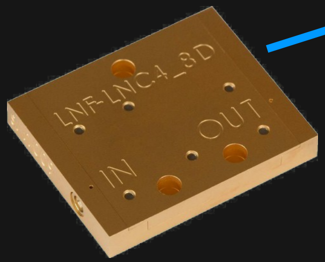


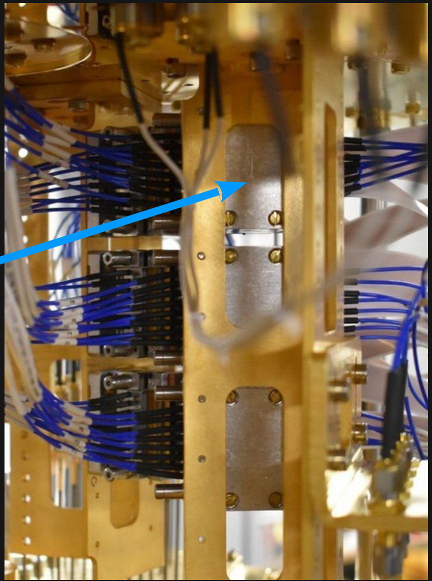
DC power for LNAs

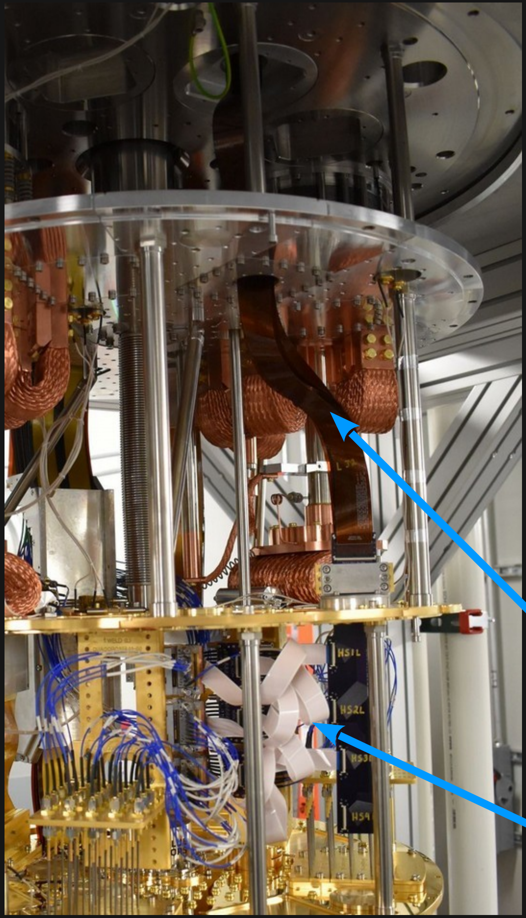
Stack up amplifiers, use ganged block of SMP-S for RF I/O

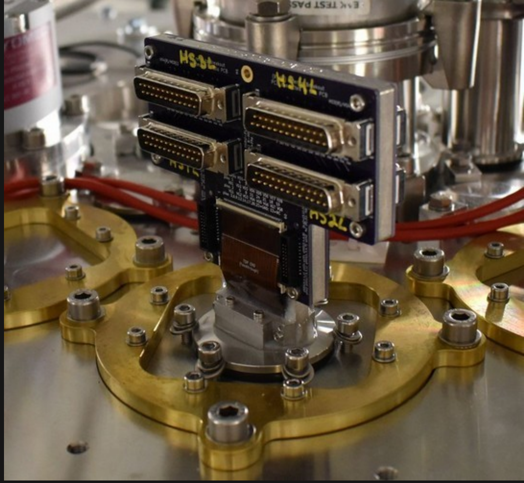
Backplane card plugs into stack for DC power

Low Noise Factory









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

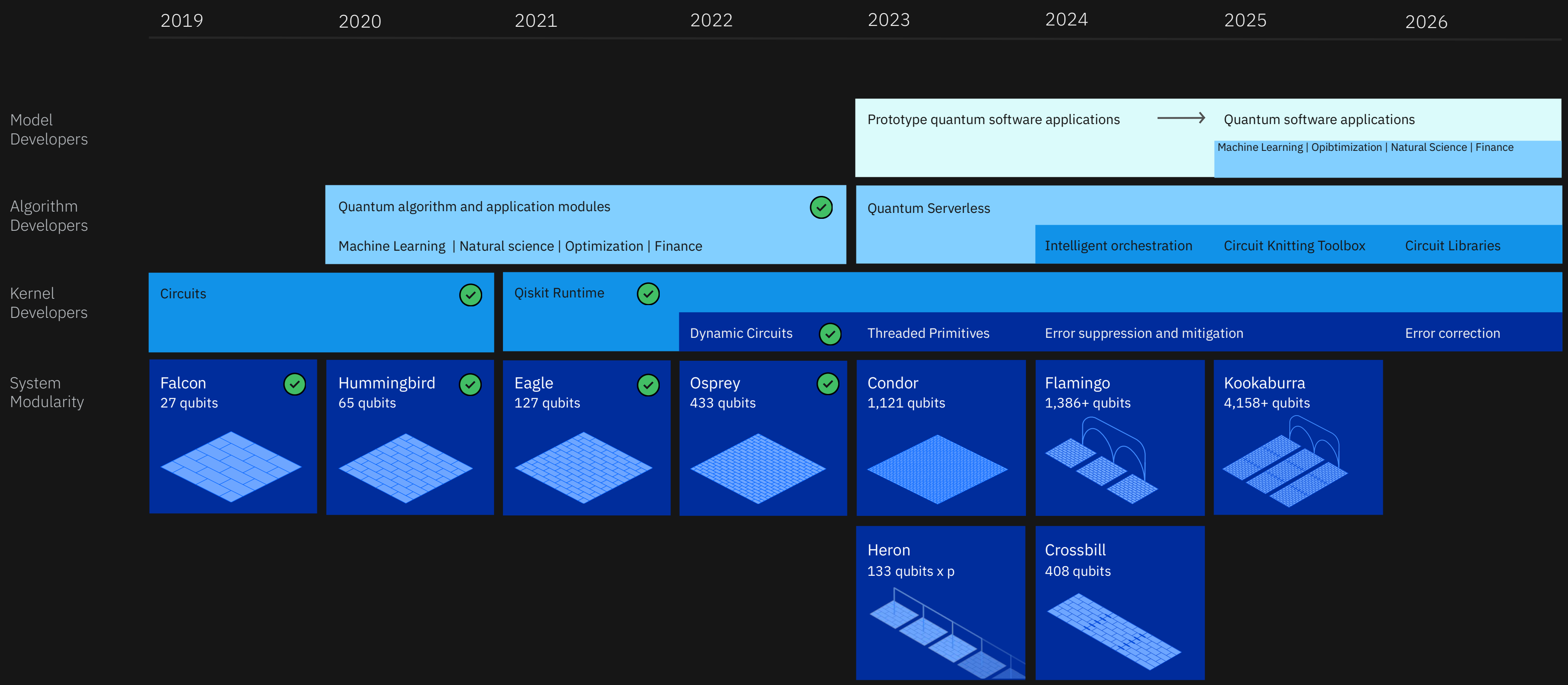
Custom flex spans thermal stages

Cheap off-the-shelf copper flex within stage

Development Roadmap

Executed by IBM
On target

IBM **Quantum**



https://www.ibm.com/quantum/roadmap

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)

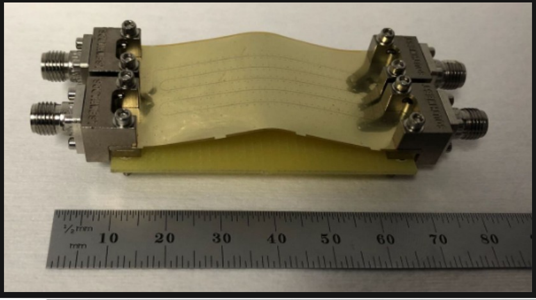
High density while maintaining high RF isolation (as dense as physically possible... the connector will always be the bottleneck)

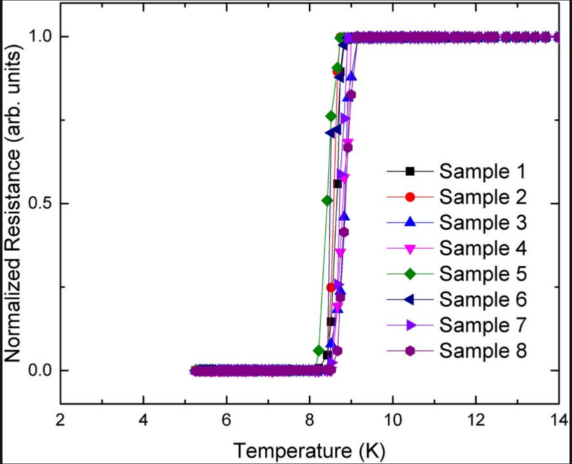
Preferably solderless

Right-angle and face-to-face options (or flex cables with sharp bend radius)

Superconducting flex

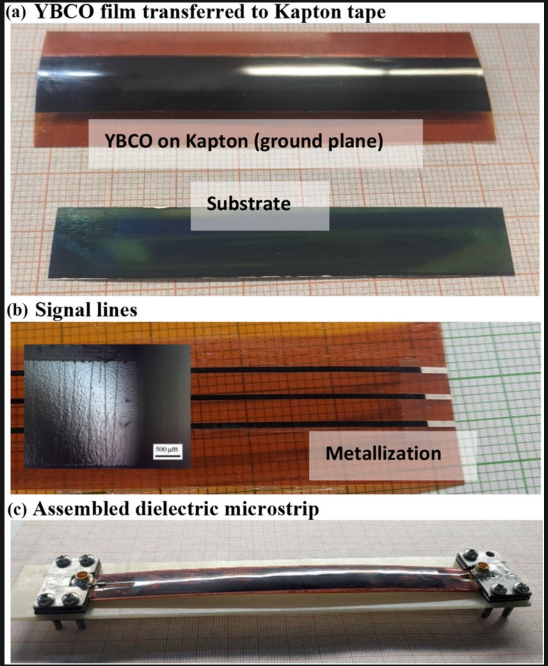
Al/Nb/Al striplines on PI

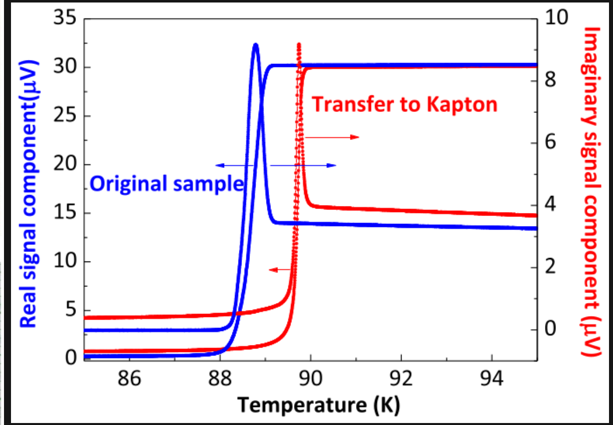




Gupta, 10.1109/TASC.2019.2904203

High Tc flex, YBCO on Kapton





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

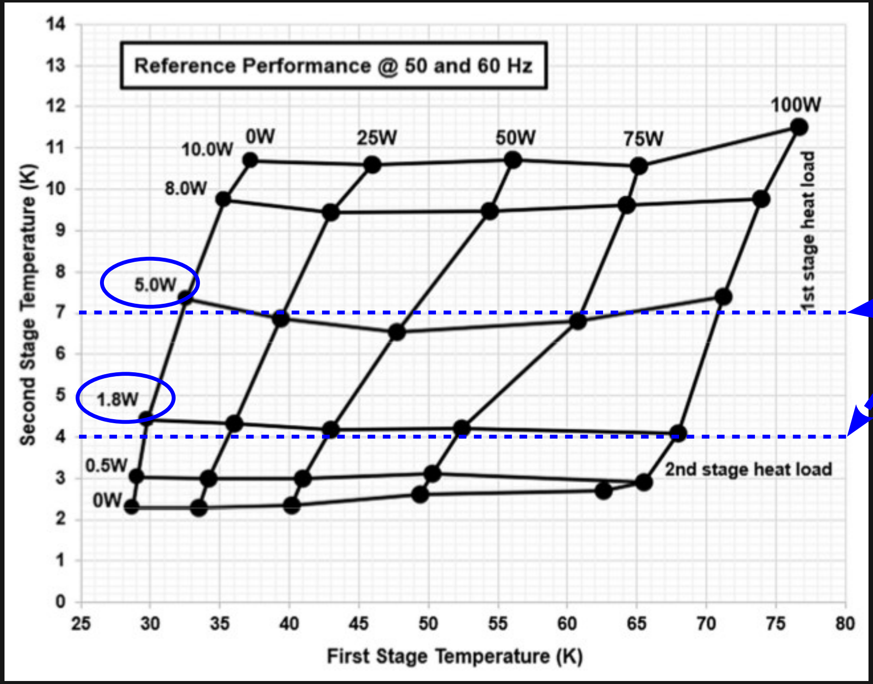
Specialized temperature stages for wiring, electronics, cryogenic infrastructure.

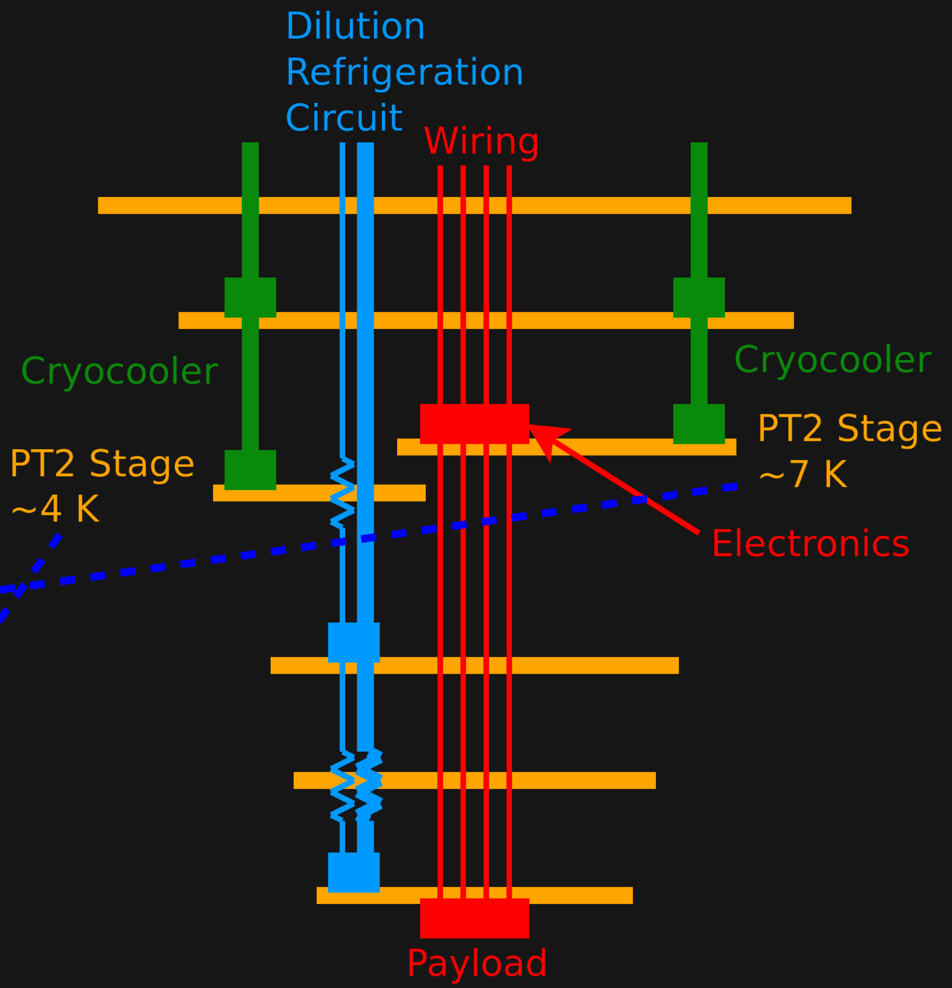
Co-design

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

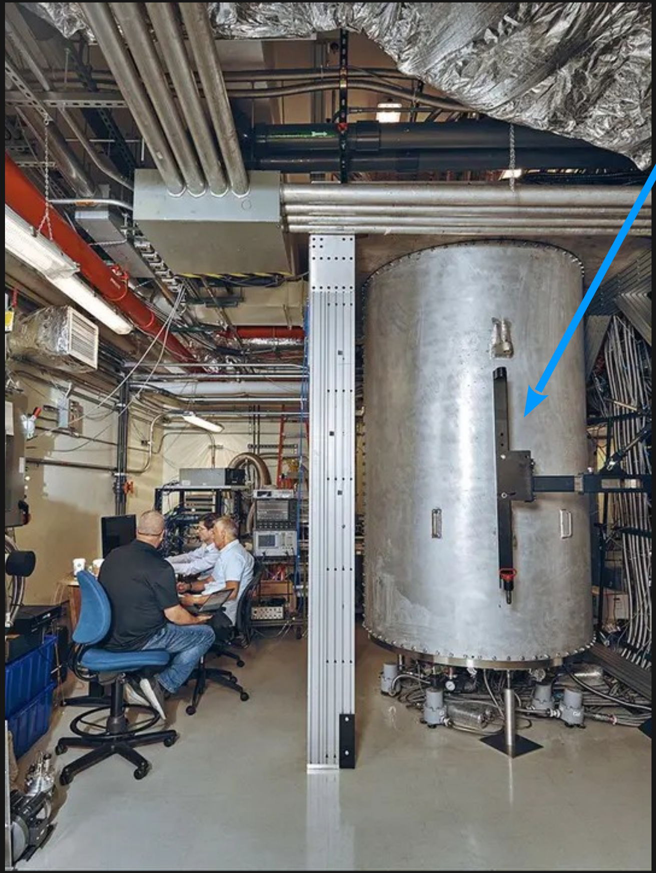
PT420 Capacity Curve





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 m^3 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

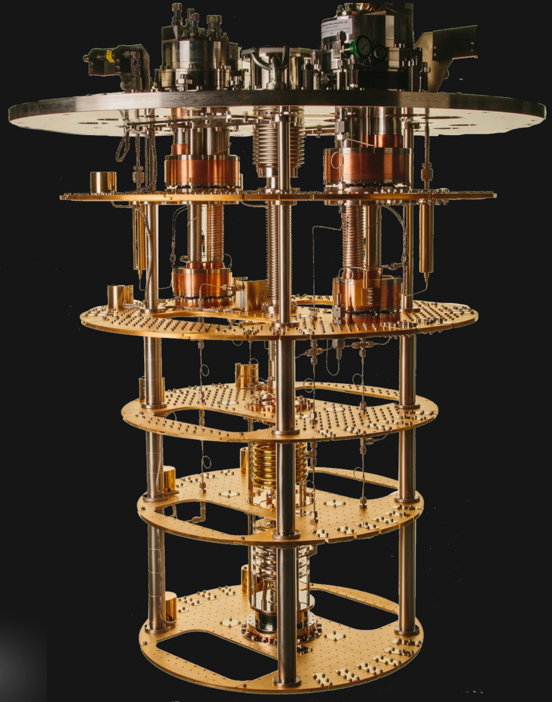
IBM Quantum System 2

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.