Hardware Challenges facing Quantum Computing with Superconducting Qubits

Quantum Computing: Devices, Cryogenic Electronics, and Packaging

Daniel Tennant
Oct 24th, 2023

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Outline

What types of problems are there to solve

- Narrow Quantum Advantage versus problems requiring full fault tolerance
- What performance specifications does this require?

Superconducting Transmon Qubits

- Non-linear superconducting circuits → Qubit
- Measurement
- Device architecture

Hardware Challenges

- 10's of qubits to 100's of qubits to 1000's of qubits
- Hardware Advances
- Promises and limits of dilution refrigeration
- Roadmap Forward

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What types of problems are there?

Big Famous Problems
- Factorization of large numbers

Requires
- 100 Millions of physical qubits
  - PRA 86, 032324 (2012)
- Fault tolerant processors

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Candidate Problems for nQA
- Hybrid Classical-Quantum Methods
  - VQA, Variational Quantum Algorithm
- Simulation
  - Strongly interacting quantum systems
- Optimization
  - Industrial
  - Financial
  - Machine Learning

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Requires
- 100’s to 1000’s of physical qubits
- > 99% single and 2-qubit gates
  - Dupont, PRXQ 3, 040339 (2022)
  - Dalzell, Quant. 4, 264 (2020)

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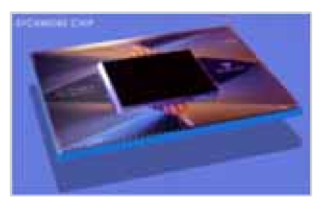
Snap shot of the current moment

Google
- Nature 574, 505 (2019)
  - 53 qubit processor
  - tunable transmons and couplers
  - Sim 1Q: 0.16%, Sim 2Q: 0.93%, Sim RO: 3.8%
- Nature 614, 676 (2023)
  - 72Q device
  - Sim 1Q: 0.08, Sim 2Q: 0.8%, Sim RO: 2.9%



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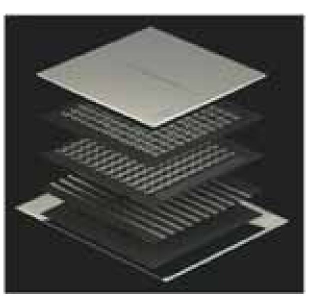

IBM
- Nature 618, 500 (2023)
  - 127Q device
  - fixed frequency transmon
  - Sim 1Q: 0.0675%, Sim 2Q: 1.15%, RO: 1.53%

https://newsroom.ibm.com/2021-11-16-IBM-Unveils-Breakthrough-127-Qubit-Quantum-Processor

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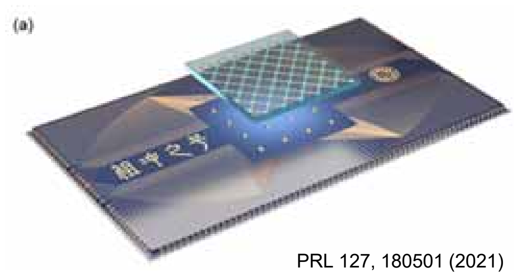
Current Processors



PRL 127, 180501 (2021)

Chinese National Laboratory System
- PRL 127, 180501 (2021)
  - 66Q device
  - tunable couplers
  - Sim 1Q: 0.14%, Sim 2Q: 0.59%, Sim RO: 4.52%

https://investors.rigetti.com/node/7911/html

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- Quantum Enhanced Greedy Solver for Optimization Problems, arxiv:2303.05509 (2023)
  - Aspen M3 - 79Q device
  - Sim 1Q: 0.60%, Sim 2Q: 4.9%, RO: 4.6%
- Recently announced Ankaa 84Q processor
  - new architecture with tunable couplers for enhanced performance

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Fundamental limits on Gate Performance

Gate times set error limits
- gate fidelity limited at long times by finite coherence times - as well as having complete circuit fit in coherence window
- short time limit - expanded bandwidth of short control pulses

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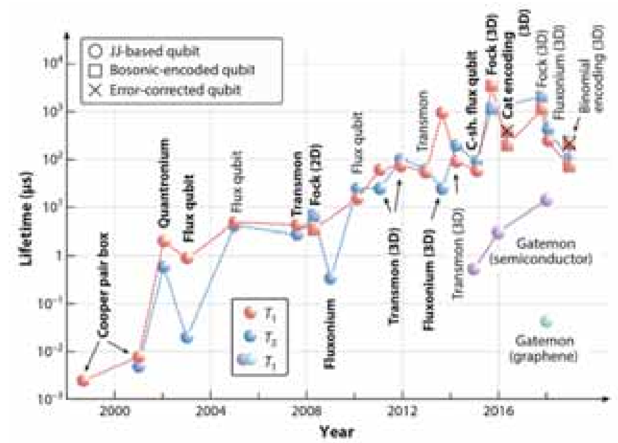
These performance metrics are fundamentally limited by the coherence time of the qubits

- Energy Relaxation - T_1
- Dephasing - T_2



Kjaergaard Ann. Rev. Cond. Mat. Phys. 11, 369 (2020)

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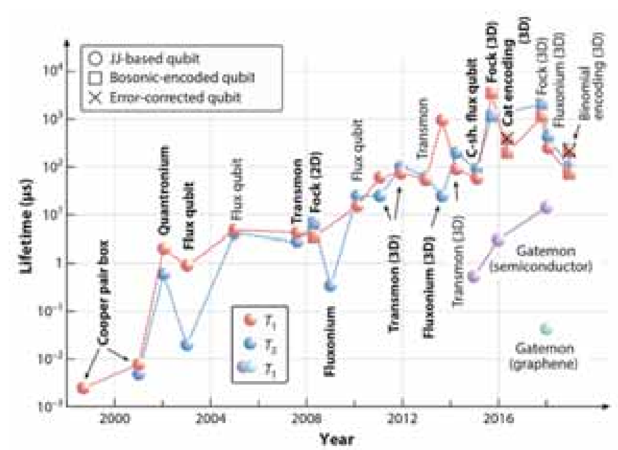
Google - mean T1: 20 us, T2-cmpg: 30 us
IBM - T1: 293 us, T2: 157 us
Zuchongzhi - T1: 30.6 us, T2: 5.3 us
Rigetti Aspen M-3 - T1: 25 us, T2: 28 us



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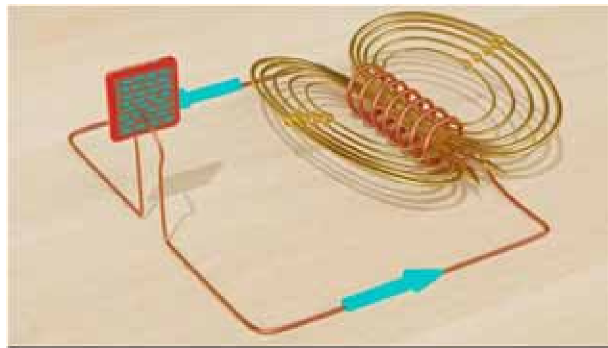
What's special about superconducting materials?

Electrons in Superconducting Materials behave more like a collective quantum coherent light source, such as a laser, than individual electrons



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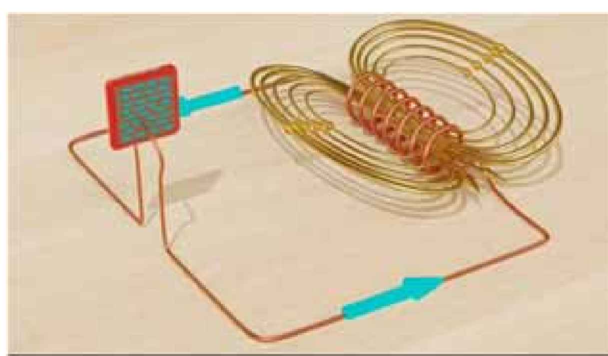
Degrees of freedom in superconducting circuits, the electrical charge and magnetic flux, can be described as the conjugate variables of a single quantum object

$$[\hat{x}, \hat{p}] \rightarrow [\hat{q}, \hat{\phi}] = i\hbar$$



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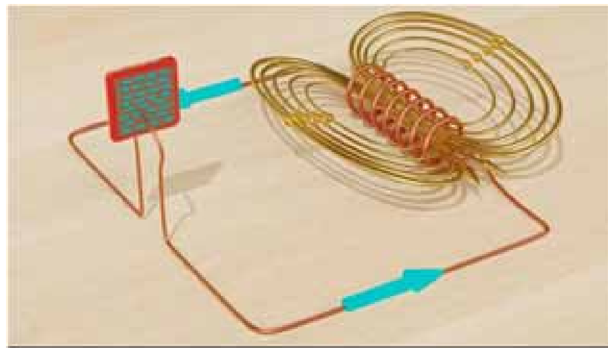
Resistive-less dynamics

- Doesn’t dissipate heat on chip
- Necessary for coherence properties of device



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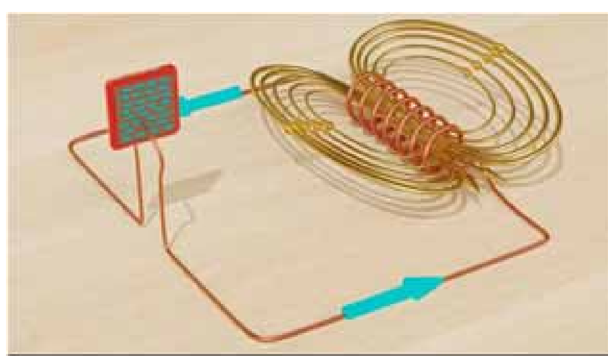
Defines operational frequency range

$$T_c = 1.2\,\mathrm{K} \rightarrow 2\Delta/\hbar \sim 100\,\mathrm{GHz}$$
$$T_{env} = 10\,\mathrm{mK} \rightarrow 1\,\mathrm{GHz}$$



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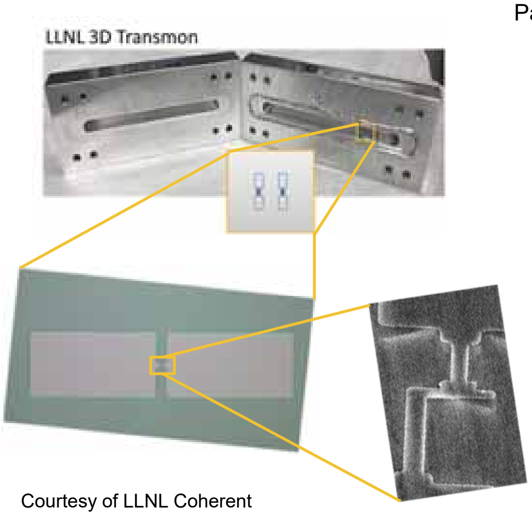
Superconducting Transmon Qubits

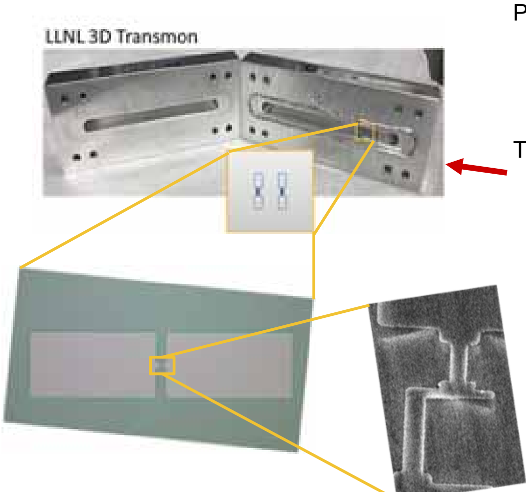


Courtesy of LLNL Coherent Quantum Device group

1 µm

Particularly simple design
- Two capacitor pads connected by nano-scale weak link, i.e. Josephson Junction

Superconducting Transmon Qubits



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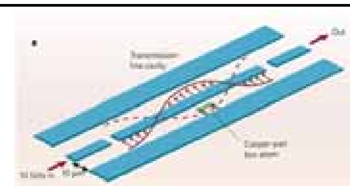
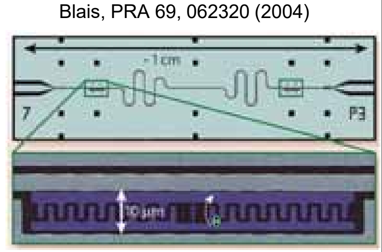
Two main architectures
- 3D cavity
- Planar devices

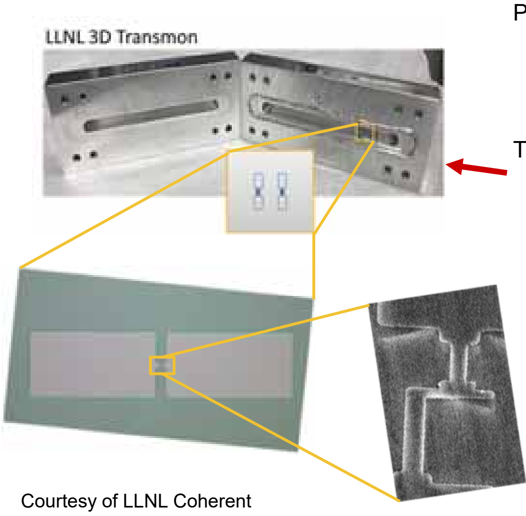


Blais, PRA 69, 062320 (2004)



Schoelkopf Nat. 451, 664 (2008)

Superconducting Transmon Qubits



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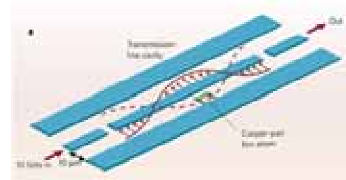

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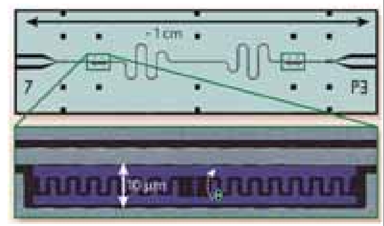

Schoelkopf Nat. 451, 664 (2008)

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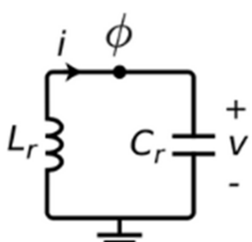
Fields, arXiv:2308.09240 (2023)

Quantum Mechanics of Superconducting Circuits

Classically

- Continuous emission and absorption of electromagnetic radiation

$$H = \frac{q^2}{2C} + \frac{\phi^2}{2L}$$



Courtesy of Krantz Appl. Phys. Rev. 6, 021318 (2019)

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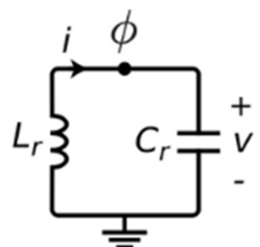

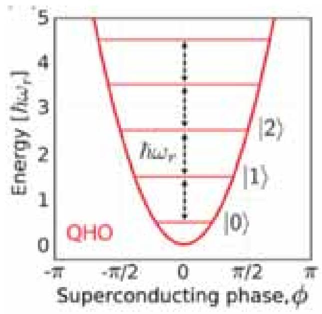

Quantum Mechanically
- Quantized energy levels
- Evenly spaced

$$\hat{H} = \frac{\hat{q}^2}{2C} + \frac{\hat{\phi}^2}{2L}$$

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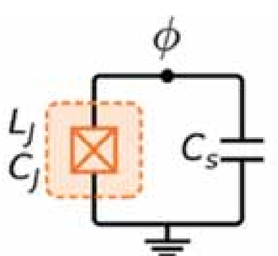

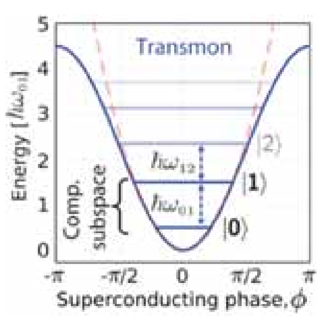

Josephson Junction
- Nonlinear, non-dissipative inductive circuit element
- Each energy transition has unique frequency

$$\hat{H} = \frac{\hat{q}^2}{2C} - E_J \cos(\hat{\phi})$$

Courtesy of Krantz Appl. Phys. Rev. 6, 021318 (2019)

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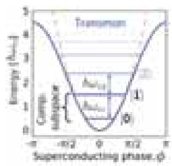
Mapping System Energy Structure to Qubit Manifold

DEVICE HAMILTONIAN

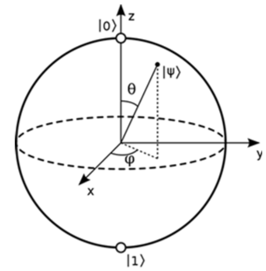
$$\hat{H} = \frac{\hat{q}^2}{2C} - E_J \cos(\hat{\phi})$$



QUBIT HAMILTONIAN

$$\hat{H} = A\sigma_z + B\sigma_x + C\sigma_y$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$



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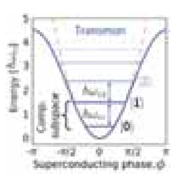

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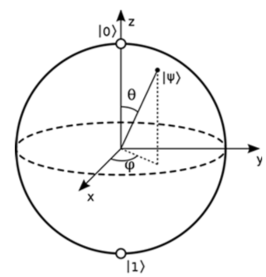

Recall $\hat{H}\,|\Psi_i\rangle = E_i\,|\Psi_i\rangle$

So…

$$\langle\Psi_0|\,\hat{H}\,|\Psi_0\rangle = E_0 \quad \text{or} \quad = -\frac{\hbar\omega_q}{2}$$

$$\langle\Psi_1|\,\hat{H}\,|\Psi_1\rangle = E_1 \quad \text{or} \quad = \frac{\hbar\omega_q}{2}$$

$$\langle\Psi_0|\,\hat{H}\,|\Psi_1\rangle = 0$$

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Mapping System Energy Structure to Qubit Manifold

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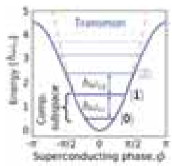

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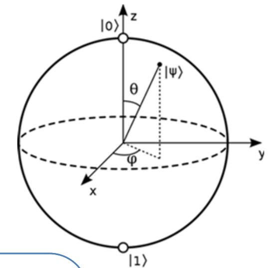

$$\hat{H} = \begin{bmatrix} -\frac{\hbar\omega_q}{2} & 0 \\ 0 & \frac{\hbar\omega_q}{2} \end{bmatrix} = -\frac{\hbar\omega_q}{2}\hat{\sigma}_z$$

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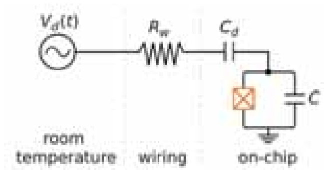
Qubit Control

$$V(t) = V_0 \cos(\omega_d t + \phi)$$

Circuit $\hat{H} = \frac{\hat{q}^2}{2C} - E_J \cos(\hat{\phi}) + \hat{q}V(t)$

Qubit $\hat{H}_0 \rightarrow -\frac{\hbar\omega_q}{2}\hat{\sigma}_z$

$$\hat{q}V(t) \rightarrow ?$$



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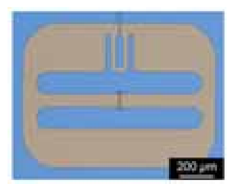

Place, Nat. Comm. 12, 1779 (2021)

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Qubit Control

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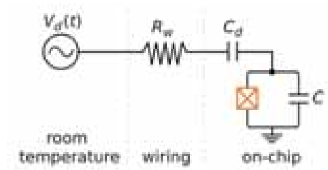

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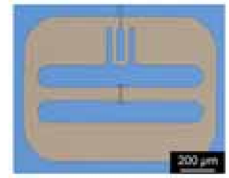

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$$\hat{q}V(t) \rightarrow ?$$

$\hat{q}\,|0\rangle = q_{zpf}\,|1\rangle$

$\hat{q}\,|1\rangle = q_{zpf}\,|0\rangle$

$q_{zpf} \propto \left(\frac{E_J}{E_C}\right)^{1/4}$

Ability to tune coupling strength!

$$\hat{q} = q_{zpf}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = q_{zpf}\hat{\sigma}_x$$

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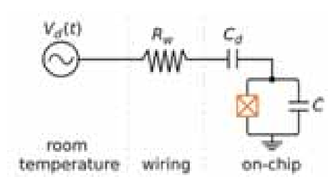
Qubit Control

$$V(t) = V_0 \cos(\omega_d t + \phi)$$



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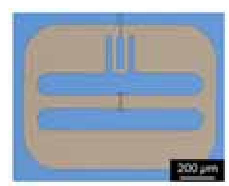

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$$\hat{q}V(t) \rightarrow q_{zpf}V_0\cos(\omega_d t + \phi)\hat{\sigma}_x$$

$$\equiv \Omega\cos(\omega_d t + \phi)\hat{\sigma}_x$$

Directly Measurable!

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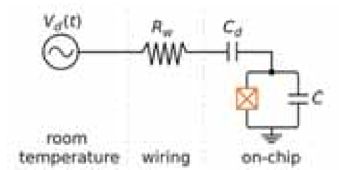

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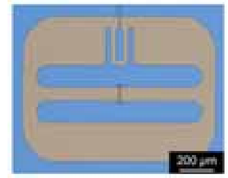

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$$\equiv \Omega\cos(\omega_d t + \phi)\hat{\sigma}_x$$

Directly Measurable!

$$\hat{H} = -\frac{\hbar\omega_q}{2}\hat{\sigma}_z + \Omega\cos(\omega_d t + \phi)\hat{\sigma}_x$$

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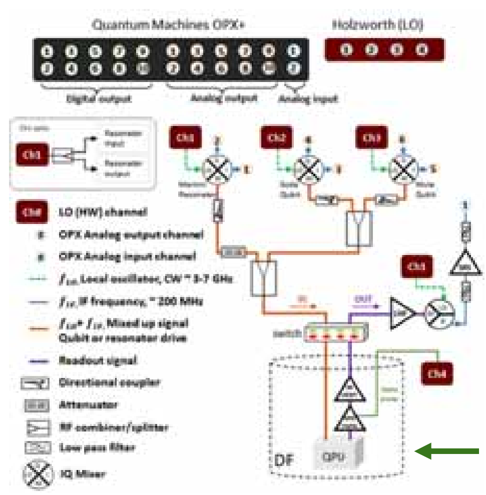
Experimental Setup

Courtesy of LLNL Coherent Quantum Device group

Dilution Refrigerator reach < 10 mK

Relies on He3/He4 endothermic process



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Experimental Setup

Courtesy of LLNL Coherent Quantum Device group

Room temperature microwave control

Local Oscillators, Arbitrary Waveform Generators, I/Q mixers, Analog to Digital Converters are common components

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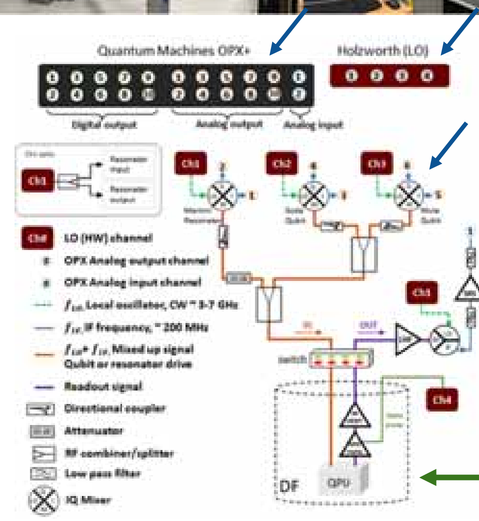

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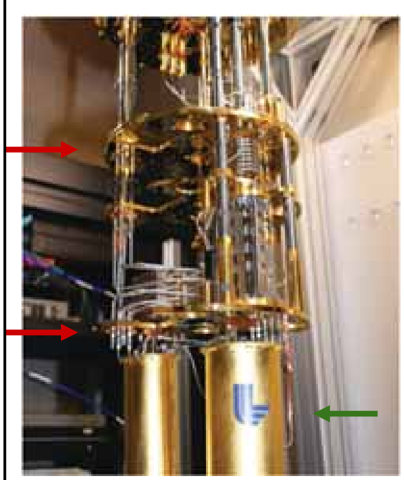

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Room temperature microwave control

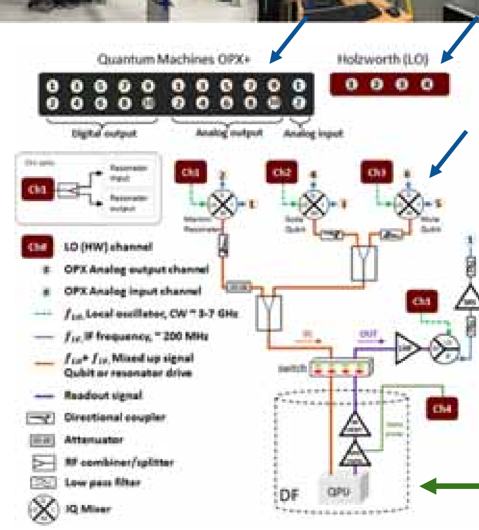
Local Oscillators, Arbitrary Waveform Generators, I/Q mixers, Analog to Digital Converters are common components

Dilution Refrigerator reach < 10 mK

Relies on He3/He4 endothermic process

Room temperature to 10 mK and back

Signal line consists of filters, attenuators, and amplifiers



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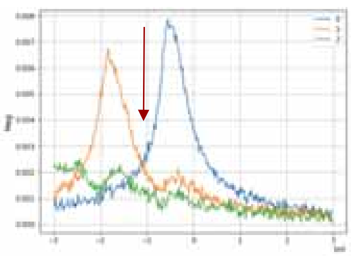
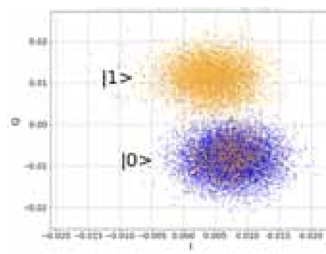
Readout Hardware

Want high amplification bandwidth, saturation power, gain, quantum limited amplifier as close to DUT as possible - also mounted on MXC

Typically followed by HEMT as 4 K stage

Qubit readout takes advantage of dispersive interaction between qubit and linear resonator





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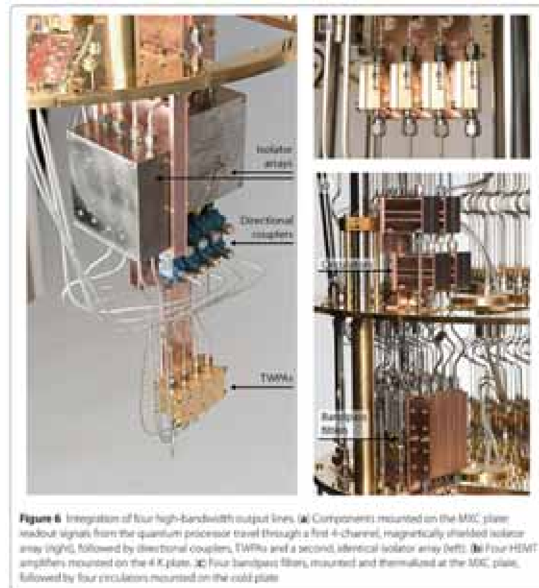

Krenner et al EPJ Quant. Tech. 10, 1140 (2019)

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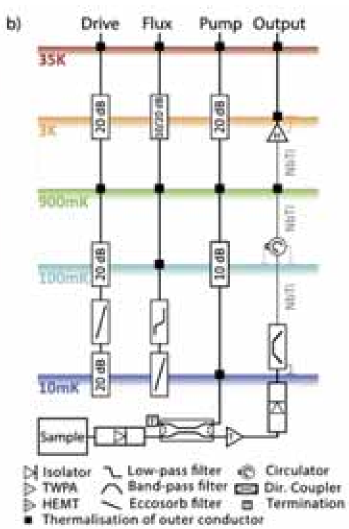
Wiring for Quantum Processors



- Considerations for wiring
  - want << 1 photon from RT past MXC through drive lines
    - at ~ 5 GHz requires ~ 60 dB attenuation
    - must balance cooling power versus thermalizing signal at lowest temperature
  - Passive heat load
    - want moderately isolated temperature stages
  - Active heat load
    - microwave signals dissipating in attenuators
    - flux-providing current dissipating in normal metal lines

Krenner et al EPJ Quant. Tech. 10, 1140 (2019), Bluefors XLD DR

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Wiring for Quantum Processors

Cooling powers
- 2 PT coolers - single dilution circuit
- 50 K - 30 W
- 4 K - 1.5 W
- Still (900 mK) - 40 mW
- Cooling plate (100 mK) - 200 uW
- Mixing Chamber (10 mK) - 19 uW

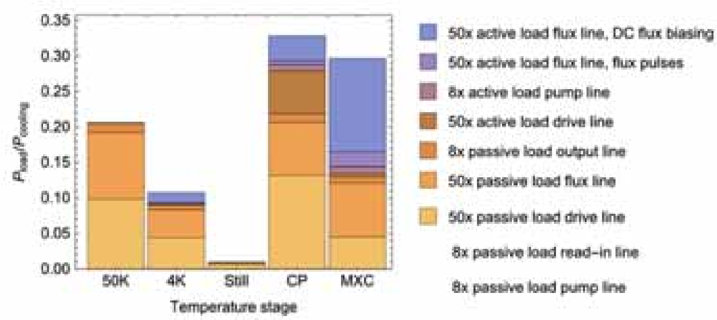

Figure 10 Total heat load budget for the operation of a 50 qubit processor. Predicted passive and active heat loads for the operation of a 50 qubit processor with individual drive and flux control. The heat loads are normalized to the measured cooling powers as presented in Table 1

Krenner et al EPJ Quant. Tech. 10, 1140 (2019), Bluefors XLD DR

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Improvements to the qubit environment

How to improve existing DRs
- superconducting flex cabling
- multiple dilution units per DR

How to connect multiple DRs
- superconducting interconnects
- transduction interconnects, GHz to optical

Better Amplifier design
- Improvements to Josephson Junction based-amplifiers
- Moving beyond JJ's as a non-linear element

Next generation Dilution Refrigerators
- Fermi Lab Colossus
- IBM Goldeneye
- Bluefors KIDE

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Superconducting Flex Cabling

- Want high electrical conductivity - low thermal conductivity between temperature stages
  - Until now provided by comprise metals, i.e. SS, CuNi
- At larger qubit count, finite resistance of normal metal overwhelms the cooling power of the lower stages
- At larger qubit count, physical footprint of SMA (or other variants) overwhelm the finite size of cryostat temperature stages

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Points to High Density Superconducting Cabling solution

- NbTi Tc ~ 9K as promising candidate
- NbTi rf cabling prohibitively expensive
- NbTi difficult to solder, brittle cabling

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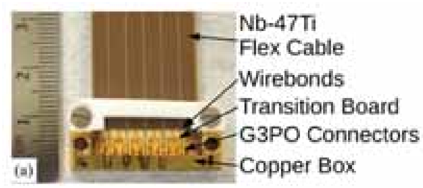
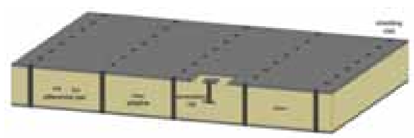


Walter, IEEE Trans. Appl. Super. Cond. 28, 2500501 (2018)

Superconducting Flex Cabling

Smith, IEEE Trans. Appl. SuperCond. 31, 1 (2021)



Tuckerman, Super. Cond. Sci. Tech. 29, 084007 (2016)

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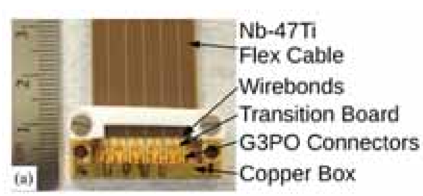
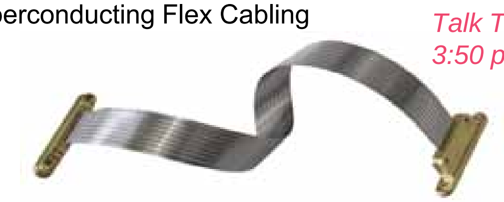


Walter, IEEE Trans. Appl. Super. Cond. 28, 2500501 (2018)

Superconducting Flex Cabling

Talk Tomorrow!
3:50 pm



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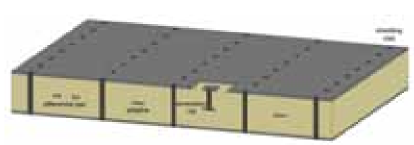

Tuckerman, Super. Cond. Sci. Tech. 29, 084007 (2016)

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Interconnects

Quantum Information I/O between cryostats

For the need to transmit quantum information over longer distances, coherent transduction to higher frequency band is necessary

Magnard, PRL 125, 260502 (2020)

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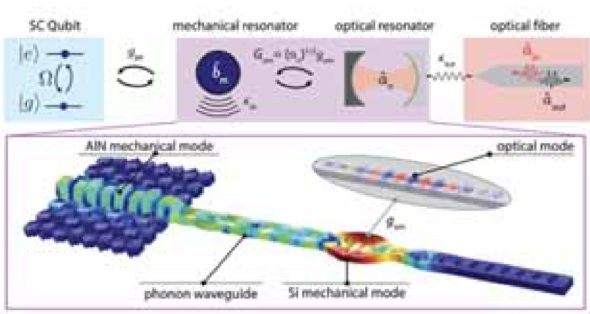

Mirhosseini, Nature 588, 599 (2020)

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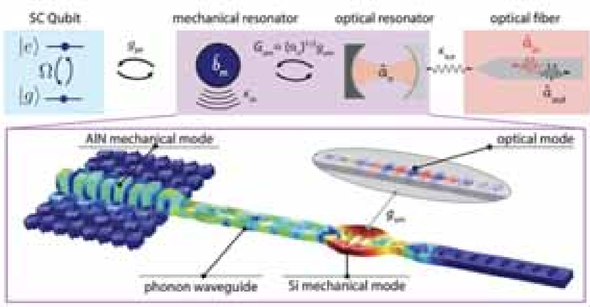

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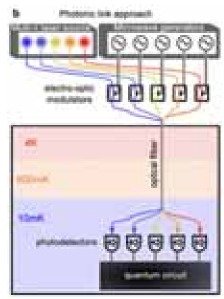

Lecocq, Nature 591, 575 (2021)

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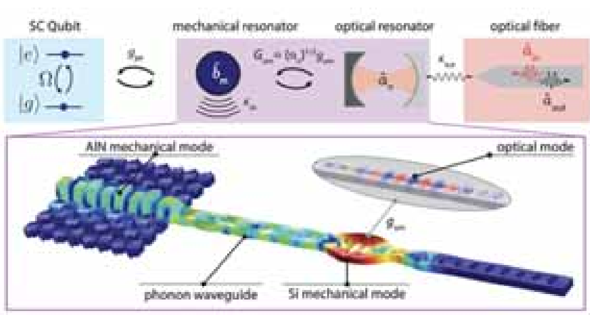

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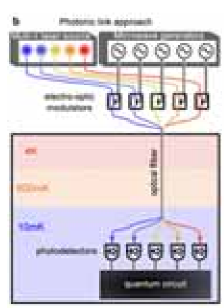
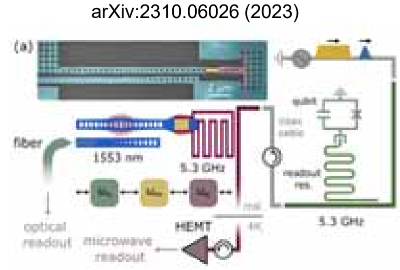


Lecocq, Nature 591, 575 (2021)

Rigetti & QphoX collaboration
arXiv:2310.06026 (2023)



Amplifier Improvements

Readout has tiny signals, ~ 0(10) photons. Need amplification!

- **quantum limited** - thermalized such that $hf > k_b T$
  - thermalized to MXC - best to be as close as possible to device to avoid insertion loss
- **high bandwidth**
  - traveling wave parametric amplifiers rather than resonant cavity based
  - more qubit readout resonators per feedline
- **high gain**
  - goes without saying
- **high saturation power**
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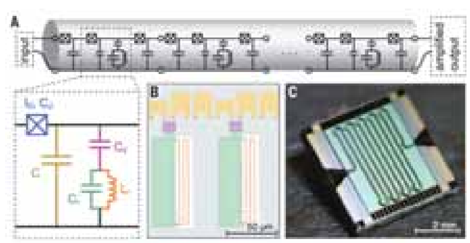
Saturation power: -100 dBm
Bandwidth: 2 GHz
Gain: 20 dB



Macklin, Sci. 350, 307 (2015)

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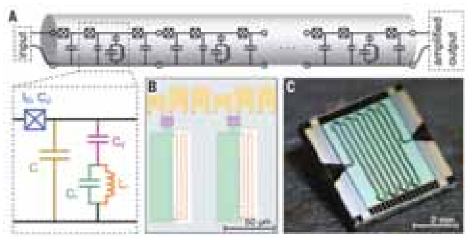
Saturation power: -100 dBm
Bandwidth: 2 GHz
Gain: 20 dB



Macklin, Sci. 350, 307 (2015)

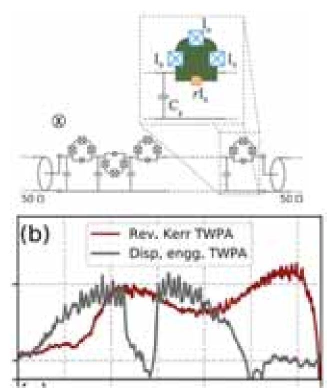
Want to reduce the total number of amplifiers

- Require large pump powers that add significant heat load to MXC
- Also readout chain currently uses large microwave components: circulators, isolators, directional couplers that use limited volume
- currently limited to 6-8 qubits per readout line

Amplifier Improvements

Improve on narrow and non-uniform amplification band with JJ-based devices

- Reserve-Kerr TWPA show broader, more uniform, amplification bands
- Utilizes third-order nonlinearity from asymmetric JJ-loop



Ranadive, Nat. Comm. 13, 1737 (2022)

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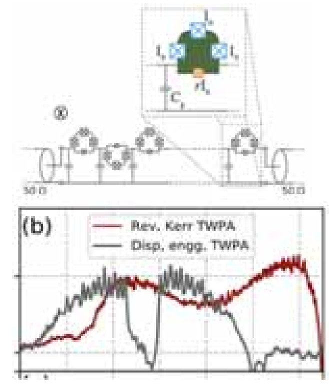
Still have saturation power issue for scaling

Move beyond Josephson Junctions



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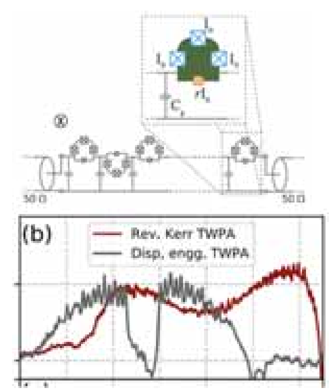

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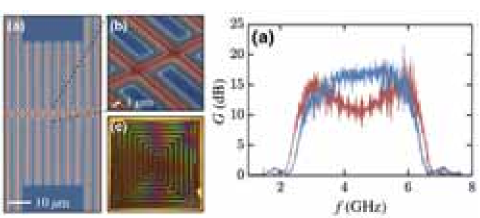

Malnou, PRXQ 2, 010302 (2021)

Kinetic Inductance TWPAs
- saturation power -60 - -50 dBm
- pump powers comparable to JJ-TWPAs
- T_{noise} ~ 0.6 K

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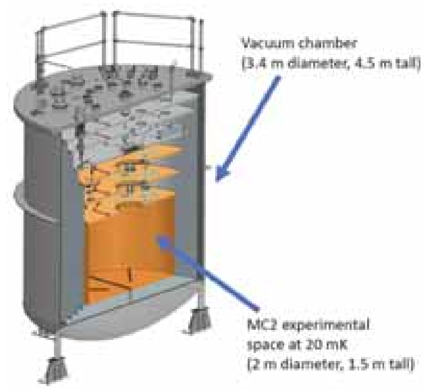
Scaling Dilution Refrigeration

IBM Goldeneye
- 10 mW at 100 mK

https://research.ibm.com/blog/goldeneye-cryogenic-concept-system

Fermi Lab Colossus
- 300-500 uW

https://bluefors.com/products/kide-cryogenic-platform/



https://lss.fnal.gov/archive/2023/conf/fermilab-conf-23-037-sqms.pdf

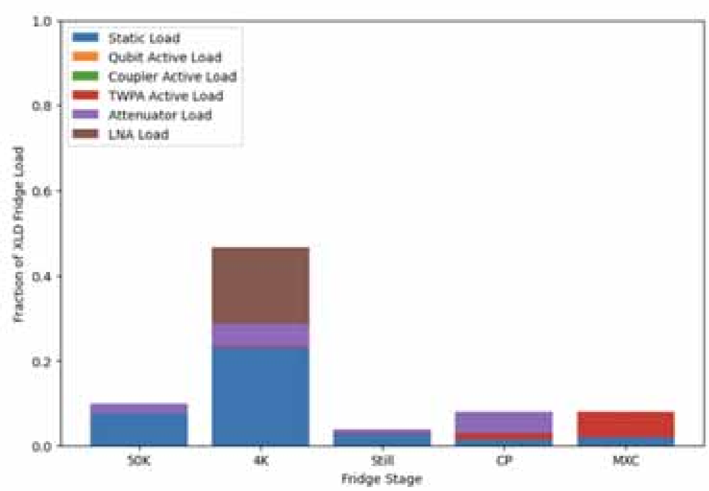
Bluefors KIDE
- 100 uW

Still only gets us to ~1000Q processor

Scaling from 1000 to 1M Qubits

- Superconducting Flex cabling

KIDE Heat Load for 1000Q

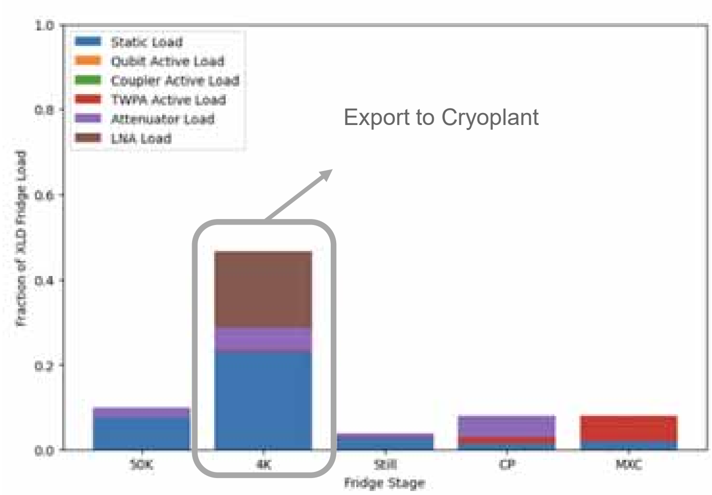


Courtesy of Josh Mutus

Scaling from 1000 to 1M Qubits

- Superconducting Flex cabling
- Export 4 K cooling power to external cryoplant

KIDE Heat Load for 1000Q



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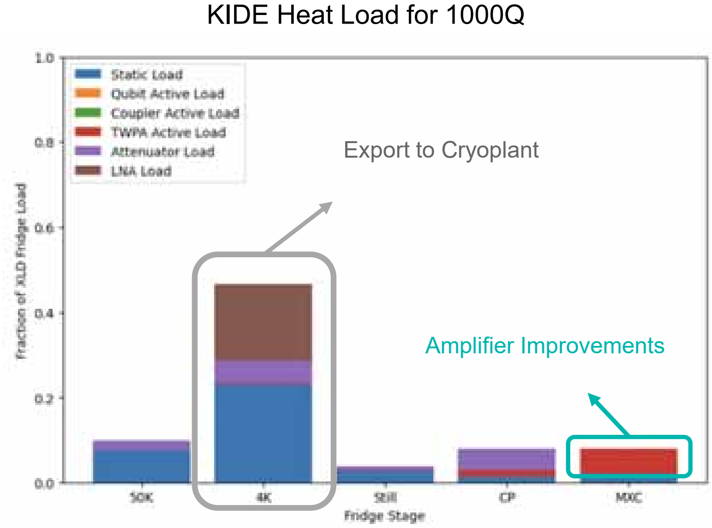

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→ 50-100,000 Qubits!

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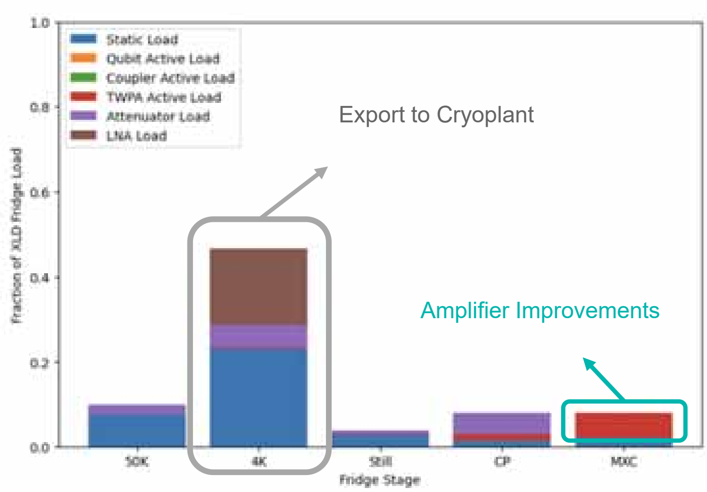

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Scaling from 1000 to 1M Qubits

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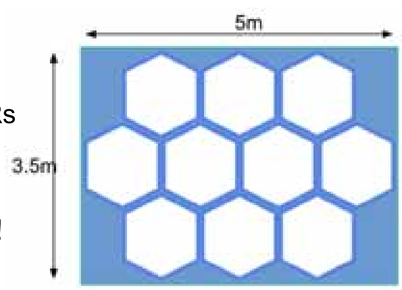
→ 50-100,000 Qubits!

High bandwidth Interconnects between KIDE DRs

→ ~ 1MQs!



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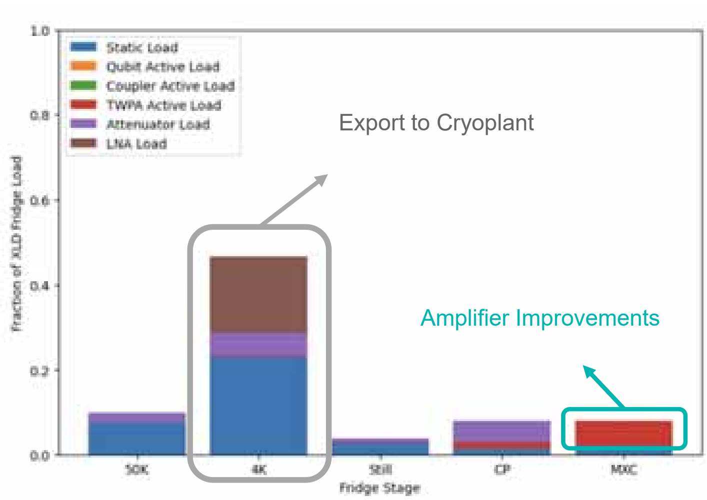

Courtesy of Josh Mutus

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Conclusion

- Shift in the industry to emphasize performance before scaling
  - other types of SC qubits
  - other candidate SC materials and substrates
- Once >99% 2-qubit gates and single-shot readout is demonstrated, there does seem to be a 'clear-ish' path to 100's of 1000s of qubits
  - improving dilution refrigeration technology
  - quantum interconnects
  - quantum-classic interface
  - readout chain improvements
- And conceivable possible in ~ 5 years

But other hardware platforms are promising! Remains to be seen whether, or for how long, superconducting qubits remain the most prominent hardware platform

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Thank you!

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