Understanding and Addressing Challenges in Superconducting Qubit Scale

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University of California, Santa Barbara
Wednesday October 25th, 2023

DARPA · CAS · UCSB · Maybell

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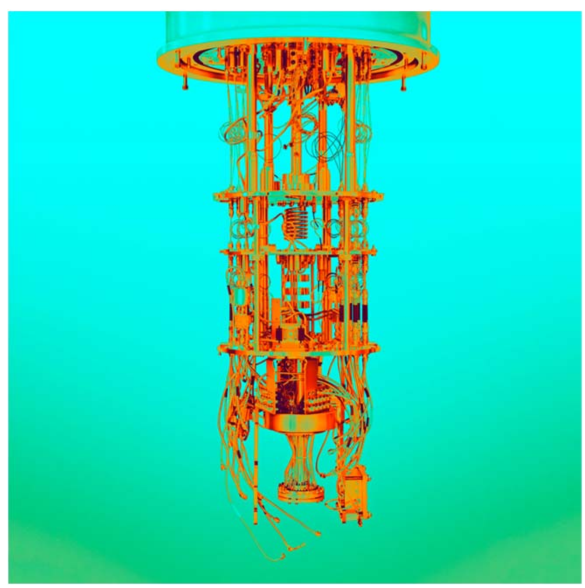
Outline

1. Challenges in Quantum Computing
1. Superconducting Qubit Environment
1. Engineering Constraints
1. Case Study: Wiring
1. Multiplexing in Control Electronics
1. Summary & Conclusion



Rigetti Computing Photo by Justin Fantl 2

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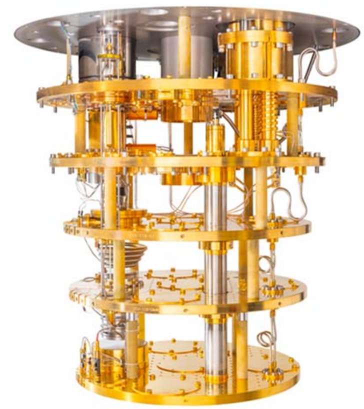
Challenges in Quantum Computing

Quantum computing relies on quantized objects which are isolated from their environment.

Qubits should live in an environment which is:

- Dark
- Cold
- High Vacuum



Leiden Cryogenics

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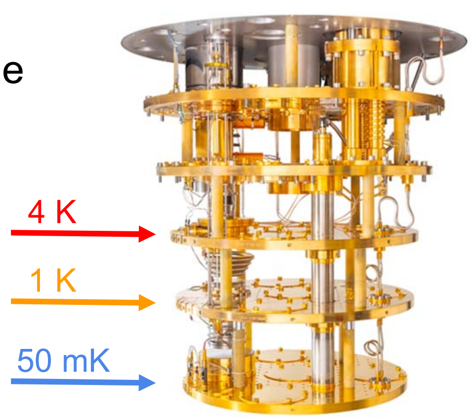
Designing with Dilution Fridges

Facts of Nature:

- Hard to cool large volumes of metal
- Hard to maintain vacuum over big volume

→ Space is limited

→ Cooling power is limited



Leiden Cryogenics

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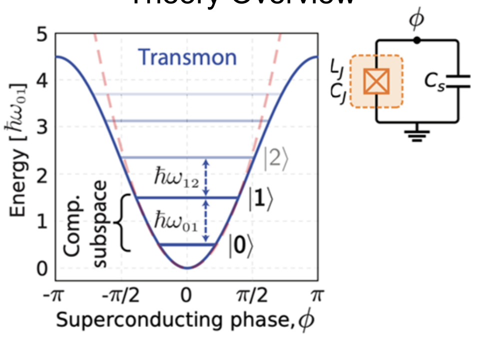
Superconducting Qubits

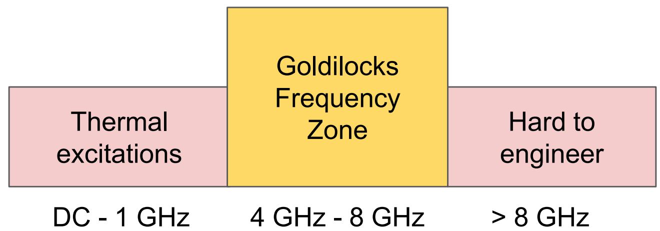
Superconducting Qubits are Promising*

Theory Overview



P. Krantz, M. Kjaergaard et al. *APR, 021318*, 2019

Tend to work in microwave frequencies



* Arute, F., Arya, K., *et al. Nature* 574, 505–510 (2019).
Kim, Y., Eddins, *et al. Nature* 618, 500–505 (2023).
Google Quantum AI. *Nature* 614, 676–681 (2023).

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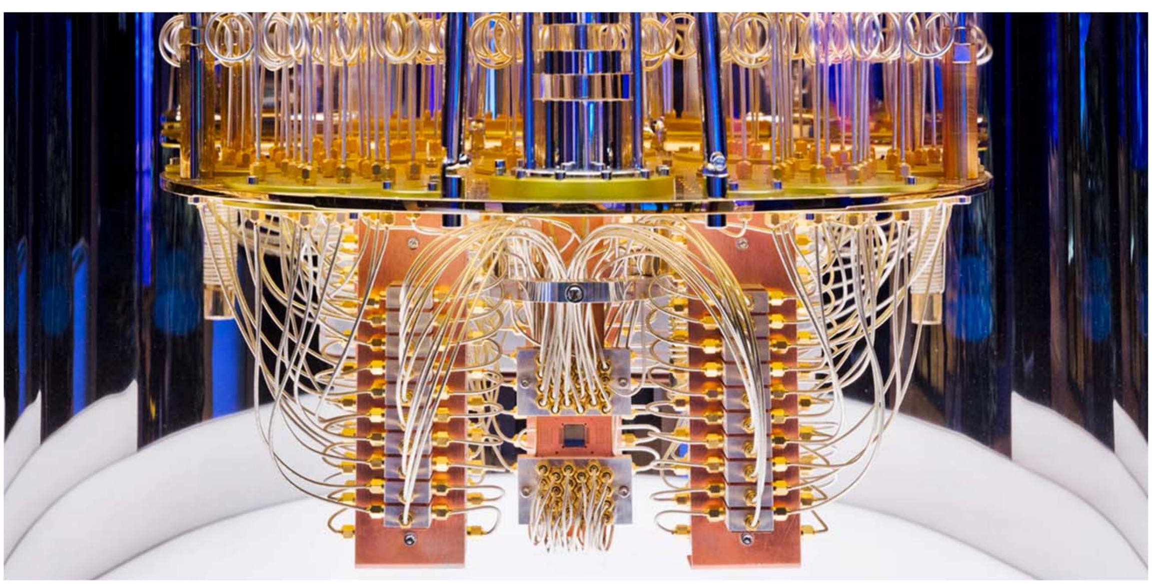
Challenges in Quantum Computing



IBM Quantum

P. Ball *Nature* 599, 542 (2021)

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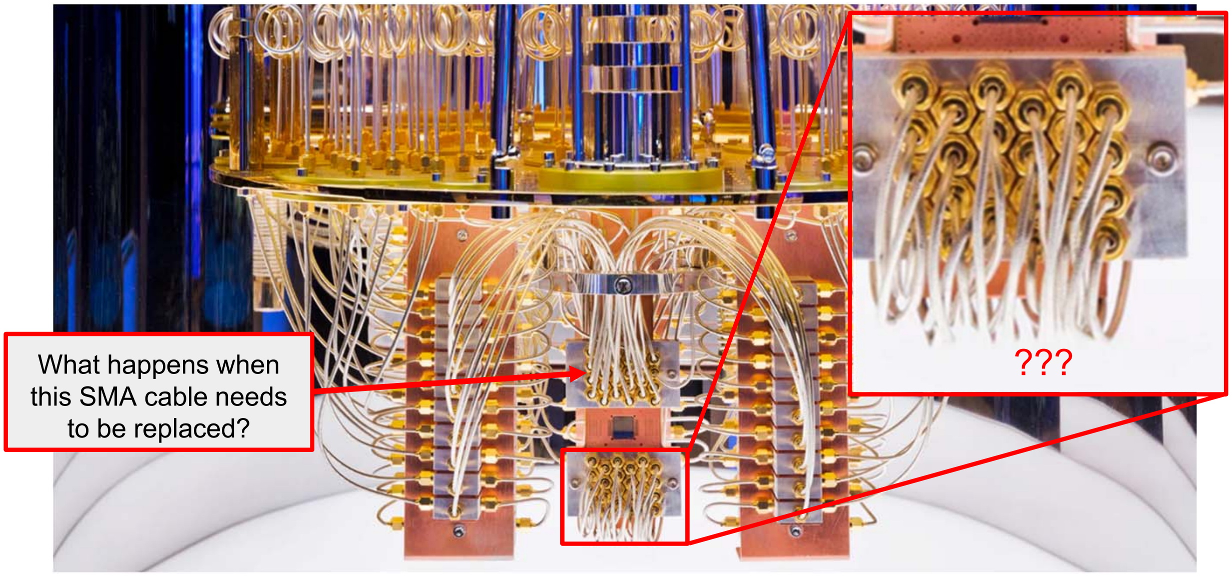
Challenges in Quantum Computing



IBM Quantum

P. Ball *Nature* 599, 542 (2021)

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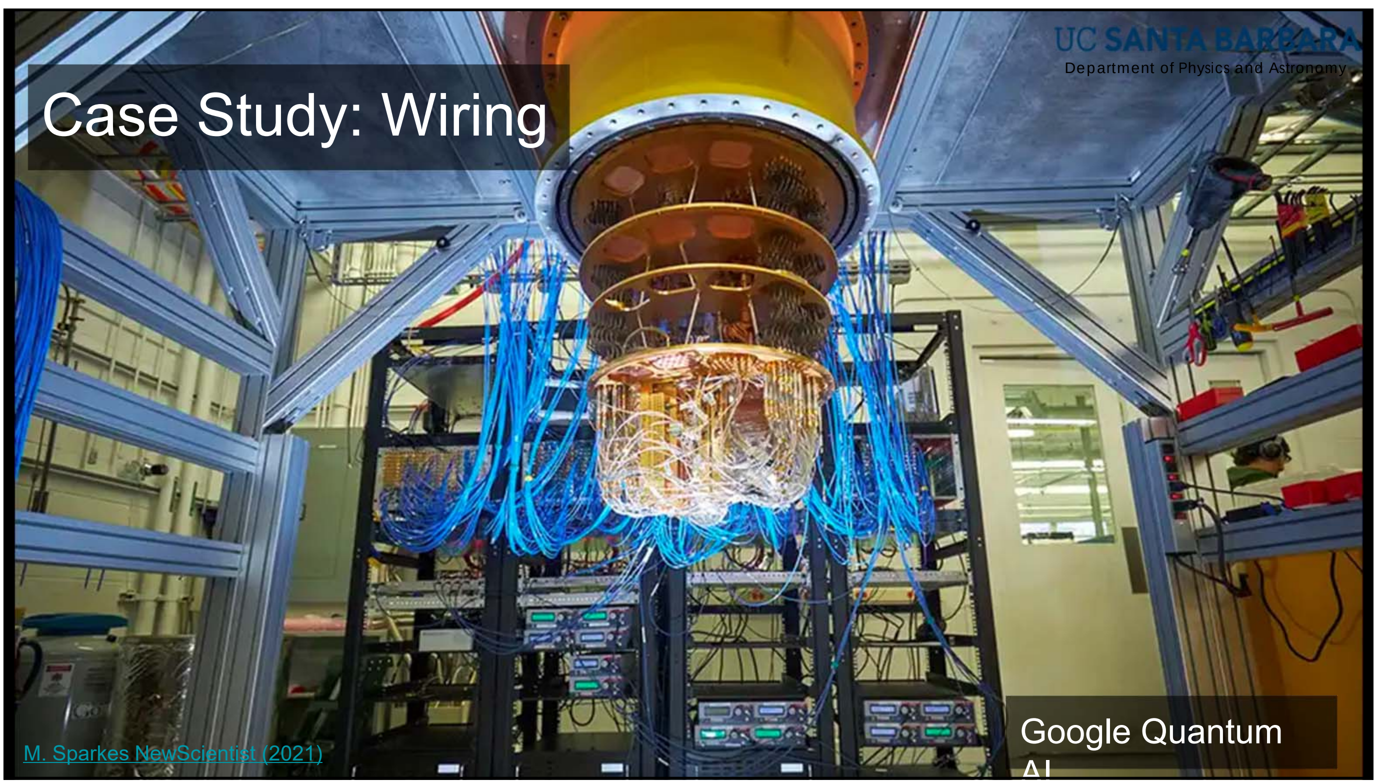

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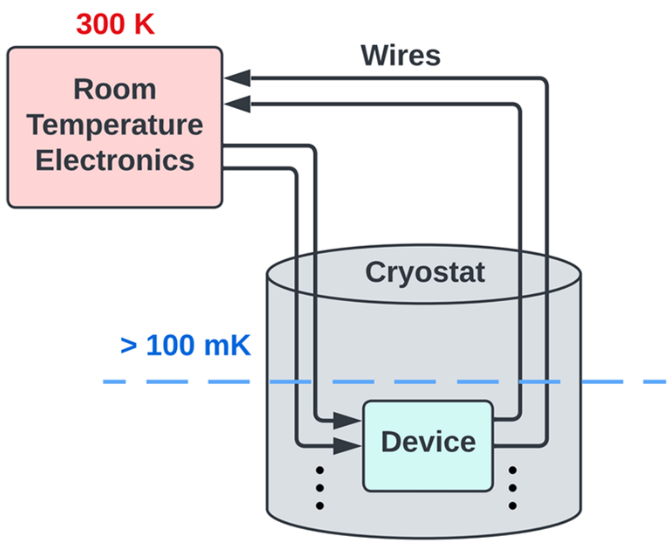
Cryogenic Wiring Overview



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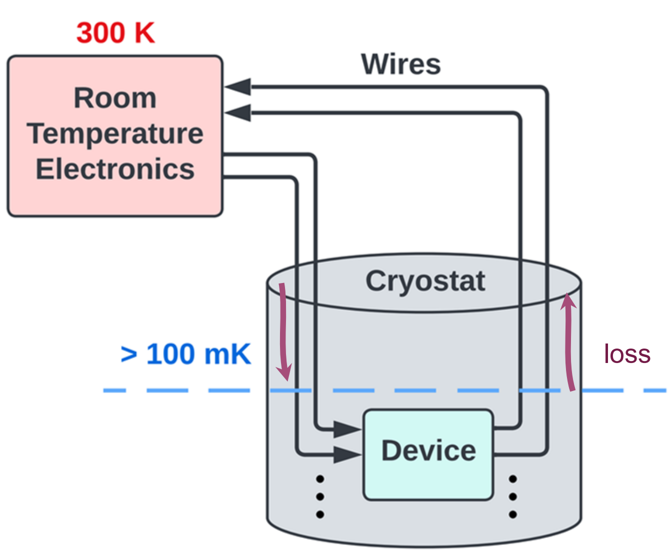
Cryogenic Wiring Overview



Wires must be:

- Low loss

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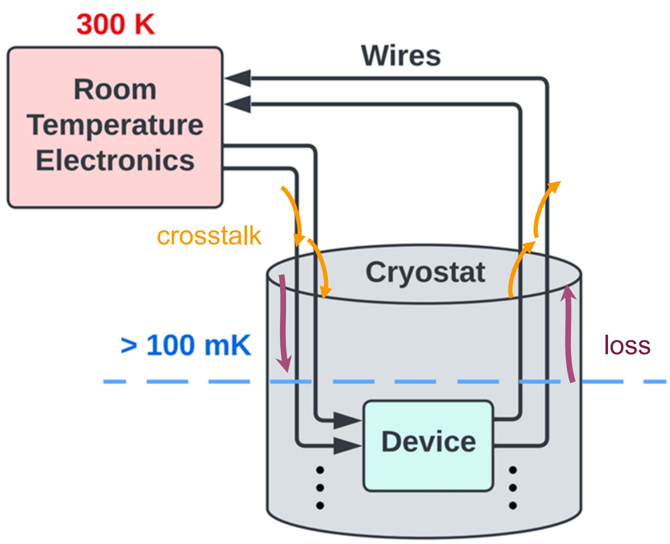
Cryogenic Wiring Overview



Wires must be:

- Low loss
- Low crosstalk

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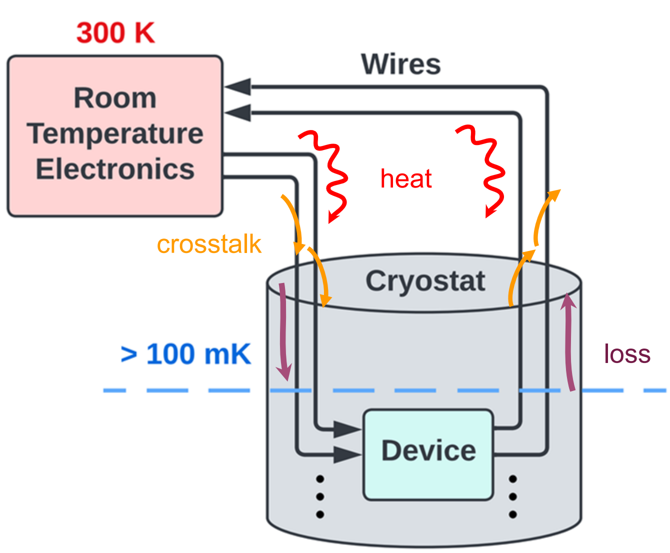
Cryogenic Wiring Overview



Wires must be:

- Low loss
- Low crosstalk
- Low thermal conductivity

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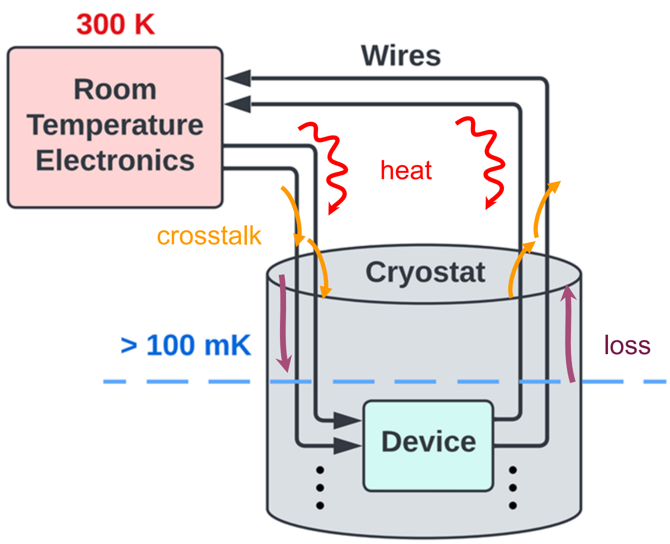
Cryogenic Wiring Overview



Wires must be:

- Low loss
- Low crosstalk
- Low thermal conductivity

Ideally also:

- Flexible
- Small form factor
- Cheap and easy to manufacture

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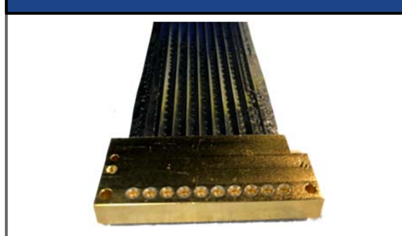
Current Solutions

Superconducting Coax (Cryo Coax)	Laminated Kapton (Delft Circuits)	Flexible Coaxial Cable (UCSB)*
		
Pros: • Excellent RF Performance Cons: • Ridged/Bulky • No integrated components • Heat Load	Pros: • Flexible • Potentially integrated RF components Cons: • Dielectric loss • Heat Load	Pros: • Flexible • Good Isolation • Low Heat Load Cons: • RF Performance • Not commercially available

* Commercial development underway by Maybell Quantum

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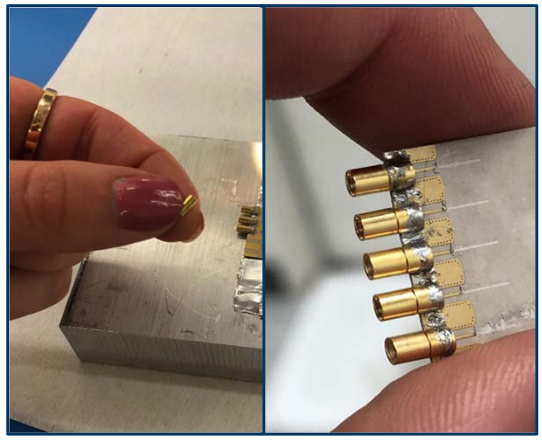
Coaxial Ribbon Cable Design

Function	Design Choice
Connect to MKID Device	G3PO
Transition to Connector	GCPW Board
Carry Microwave Signal	Coax Ribbon
Conductor + Dielectric	Nb-47Ti + PFA



- Very small allowing close trace pitch
- Easy push-on connection (no wrenches!)
- Used by existing MKID devices

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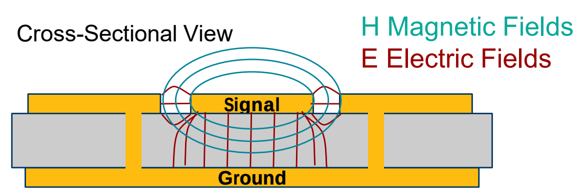

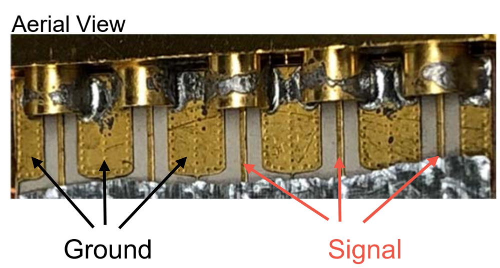

- Grounded coplanar waveguide structure minimizes cross talk

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Coaxial Ribbon Cable Design

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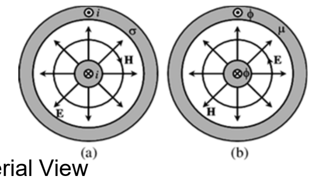
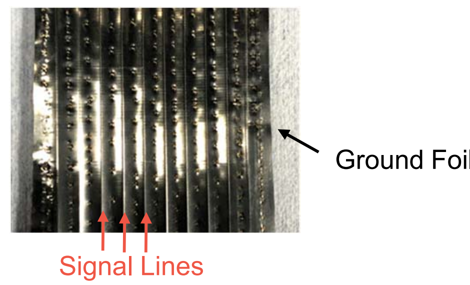
Connect to MKID Device	G3PO
Transition to Connector	GCPW Board
Carry Microwave Signal	Coax Ribbon
Conductor + Dielectric	Nb-47Ti + PFA

Cross-Sectional View



Aerial View



- Shared ground provides enhanced flexibility and mechanical support
- Coax structure minimized cross talk

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Coaxial Ribbon Cable Design

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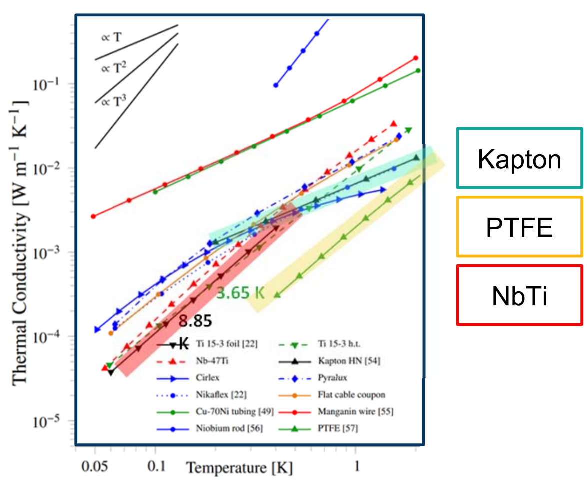

- Nb-47Ti has a high transition temperature (9 K) so will have good transmission at 4 K and has low thermal conductivity.
- PFA has low thermal conductivity and loss.

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M. Daal, N. Nobrist et al. *Cryogenics*, 98, 2 2019

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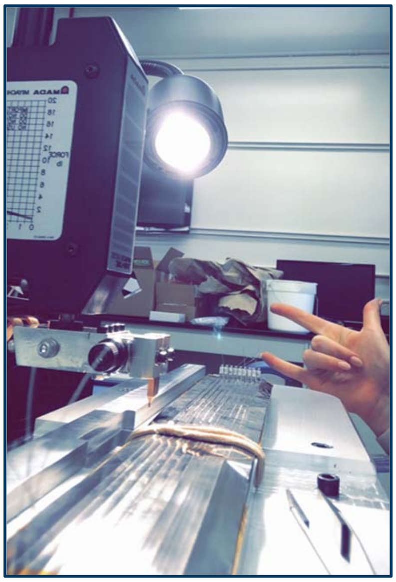
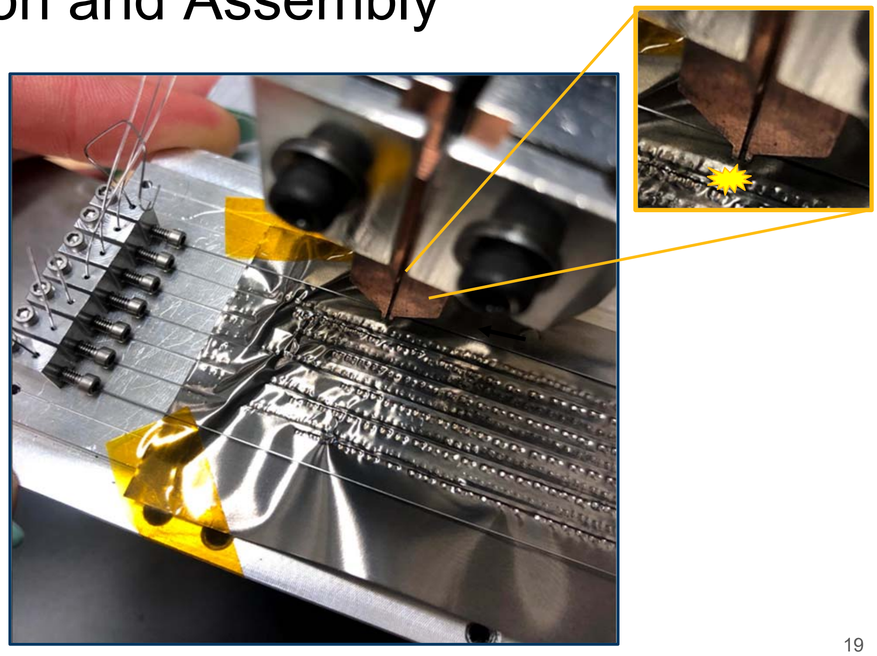
Cable Fabrication and Assembly





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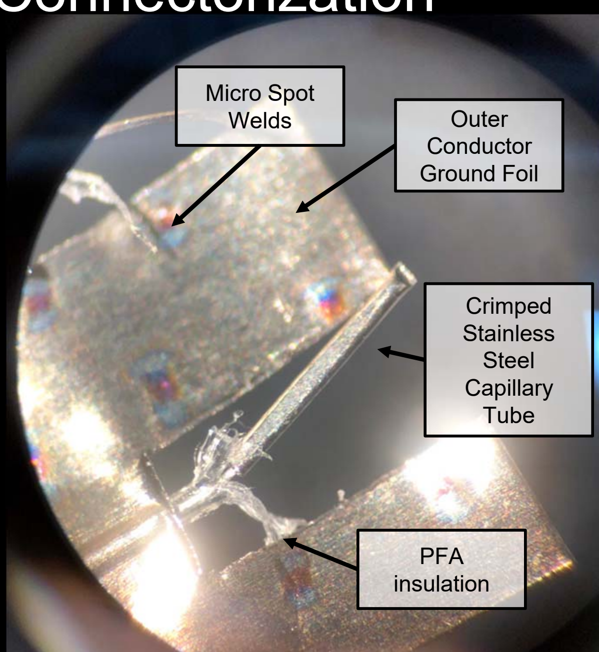
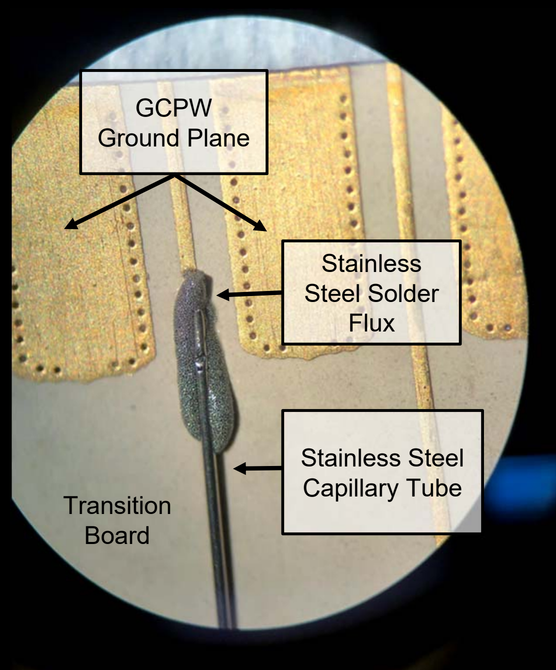
Connectorization





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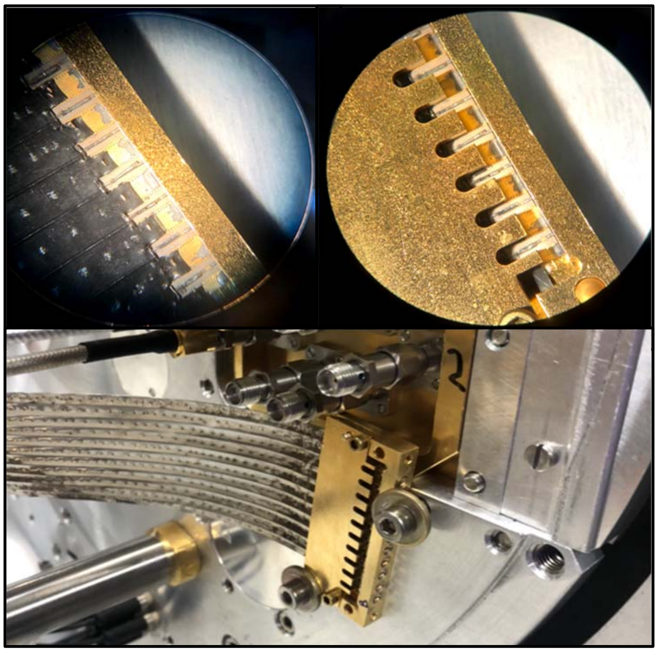
Finished Product



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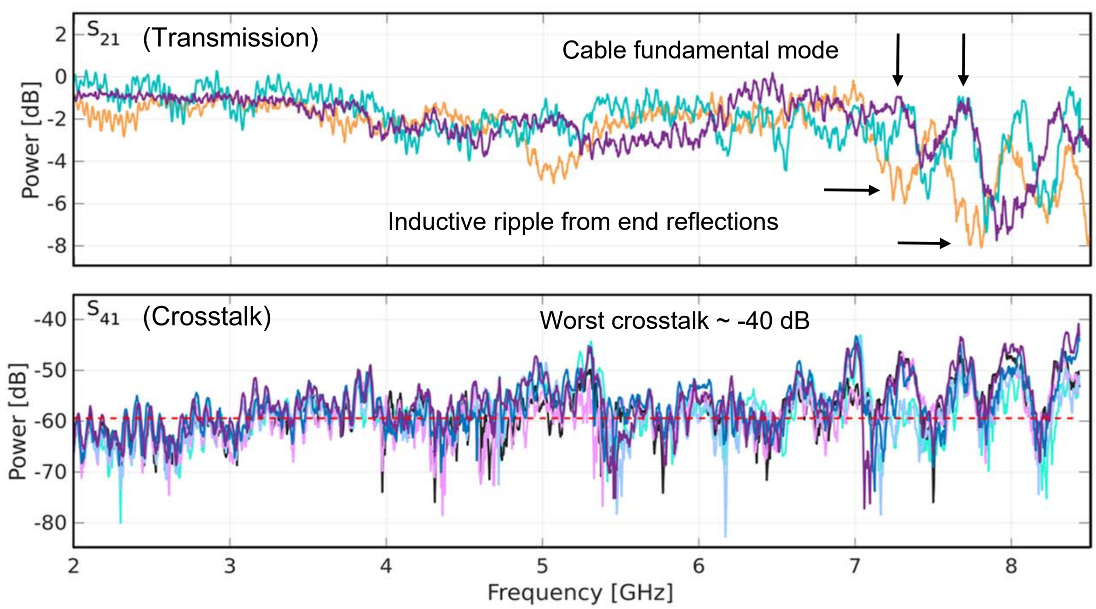
First Results



Smith et al. *IEEE Trans. Appl. Superconductivity,* 2020

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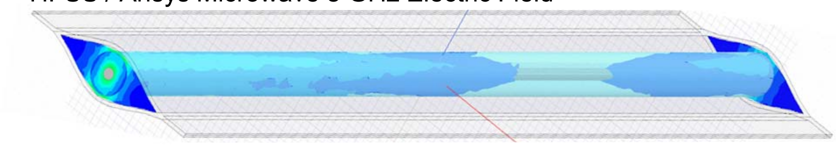
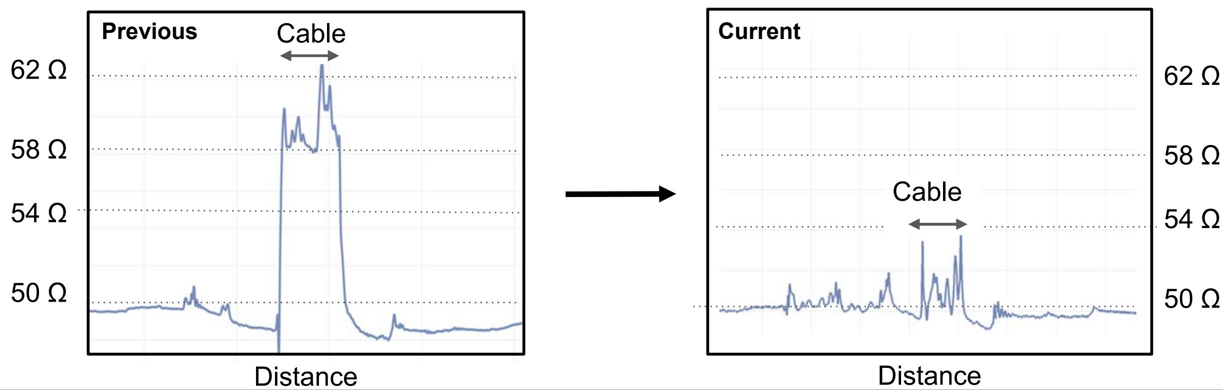
Improve Impedance Mismatch

HFSS / Ansys Microwave 8 GHz Electric Field



Eye-like geometry adds 10 Ohms
→ Increase wire diameter to compensate

Time Domain Reflectometry (TDR)



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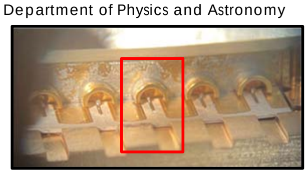
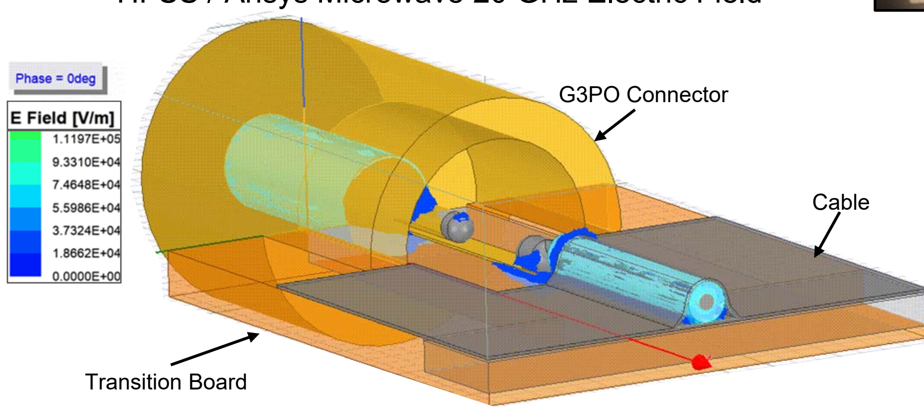
Simulated Transition



HFSS / Ansys Microwave 20 GHz Electric Field



Simulated connector transition to probe manufacturing tolerances and search for ways to improve design

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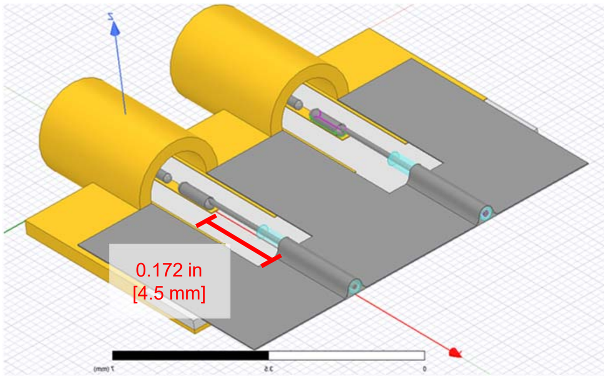
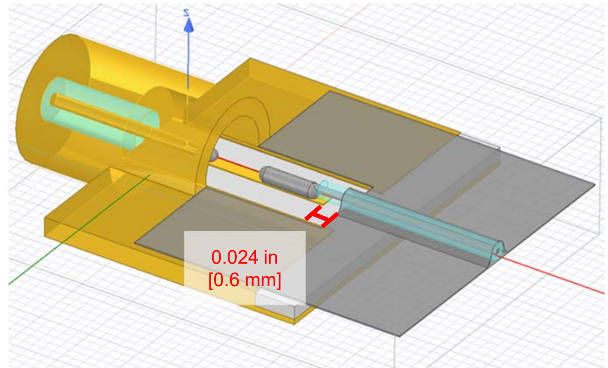
Key Connectorization Parameter

Bad Connectorization



Good Connectorization



Transmission loss is very sensitive to distance between ground foil and center strip

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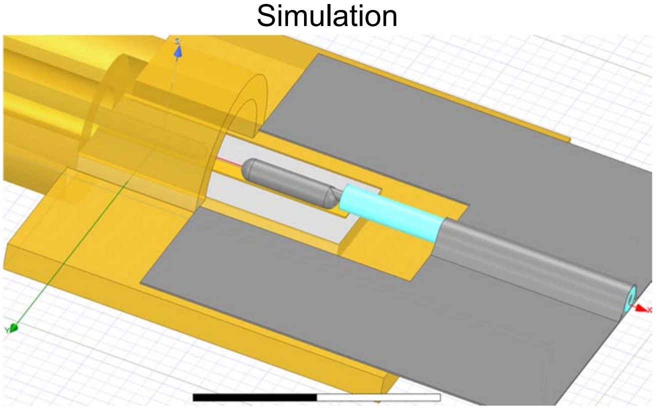
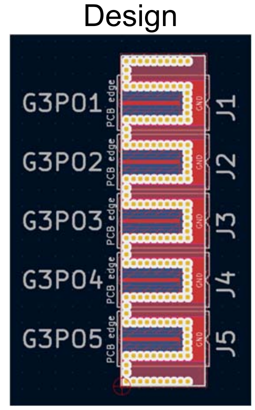
Transition Board Redesign

Simulation



Design



Manufacture

New transition board eases manufacturing tolerances and provides extra capacitance to help mitigate inductive transition

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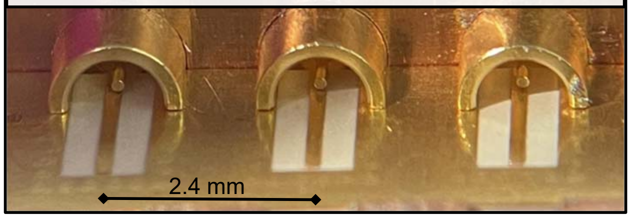
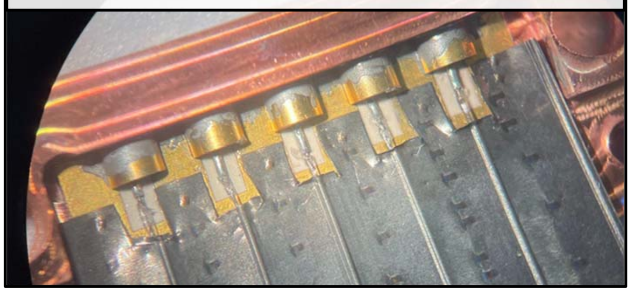
Cable Prototype

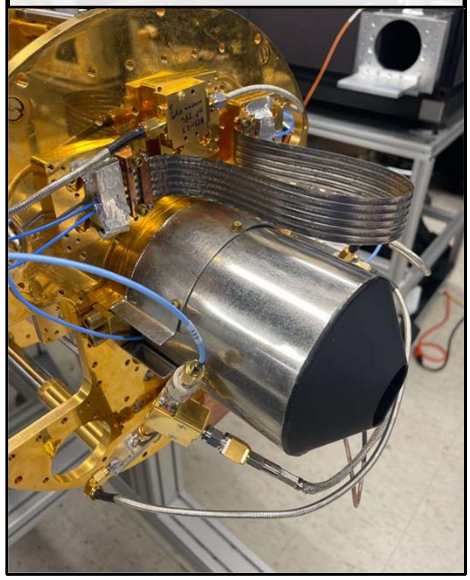
G3PO Connector Transition Board Interface



Cable End Connectorization



Cable Mounted in Fridge



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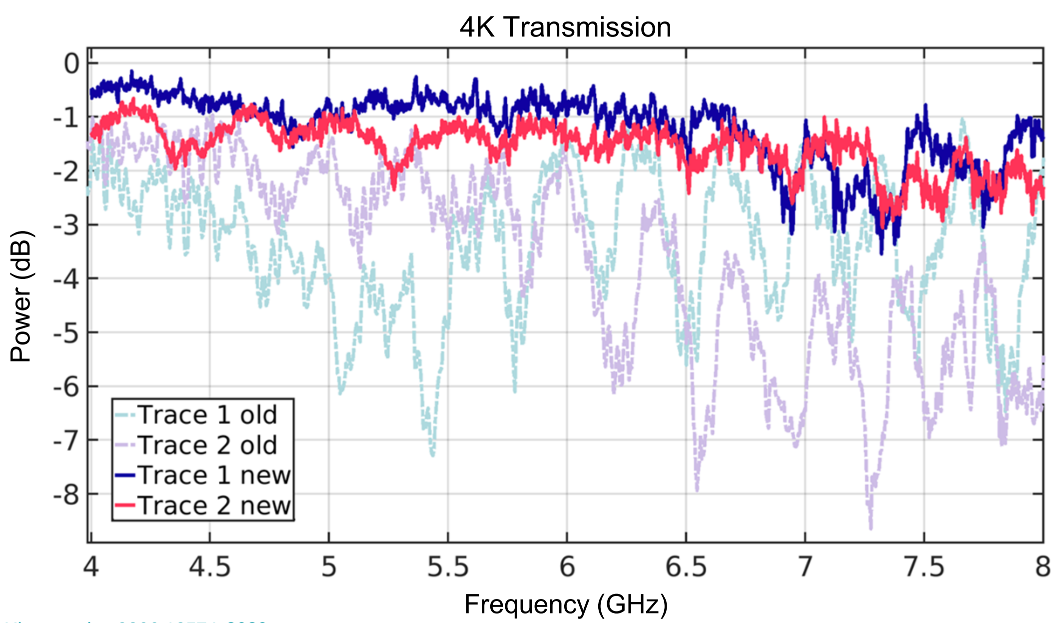
Results S21



Smith et al. *arXiv pre-print, 2306.13574*, 2023.

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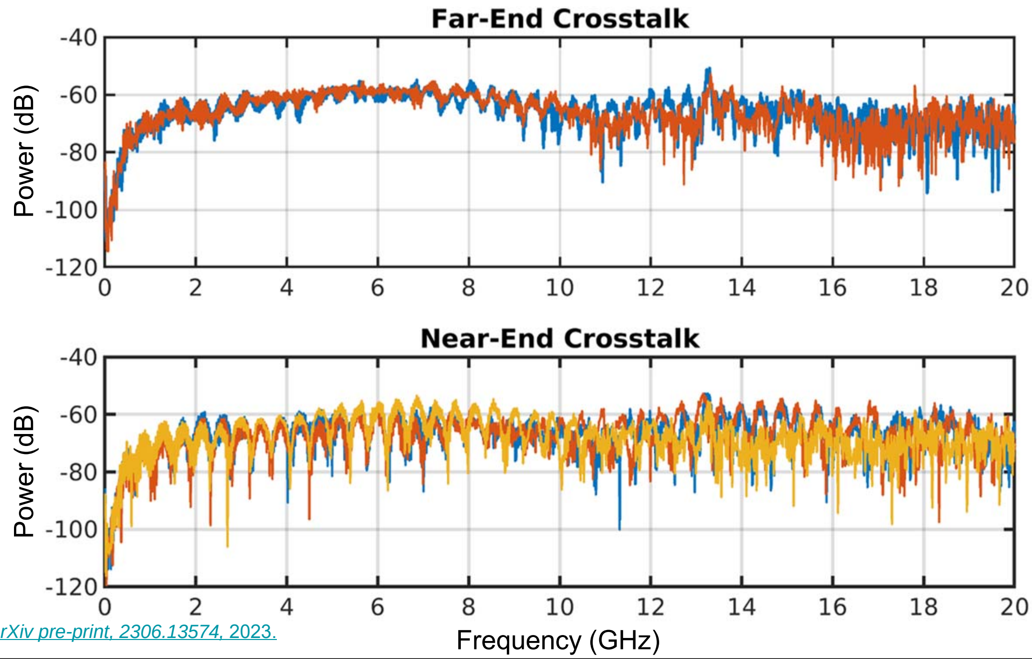
Results: Crosstalk



Smith et al. *arXiv pre-print, 2306.13574,* 2023.

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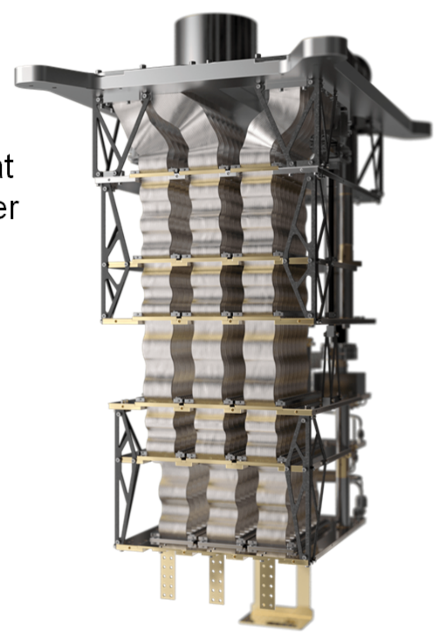
Overview & Next Steps

Improvement Overview

- Designed and fabricated NbTi ribbon cable with ½ heat load of commercial superconducting coax and 5x better trace pitch density.
- Loss is almost 7 dB better than commercial superconducting Kapton Flex at 8 GHz (~1ft).

Next Steps

- Maybell Quantum developing commercial solution.
- Integrate microwave components into transition board.
- Redesign clamp / end to increase isolation.



Maybell Icebox Prototype

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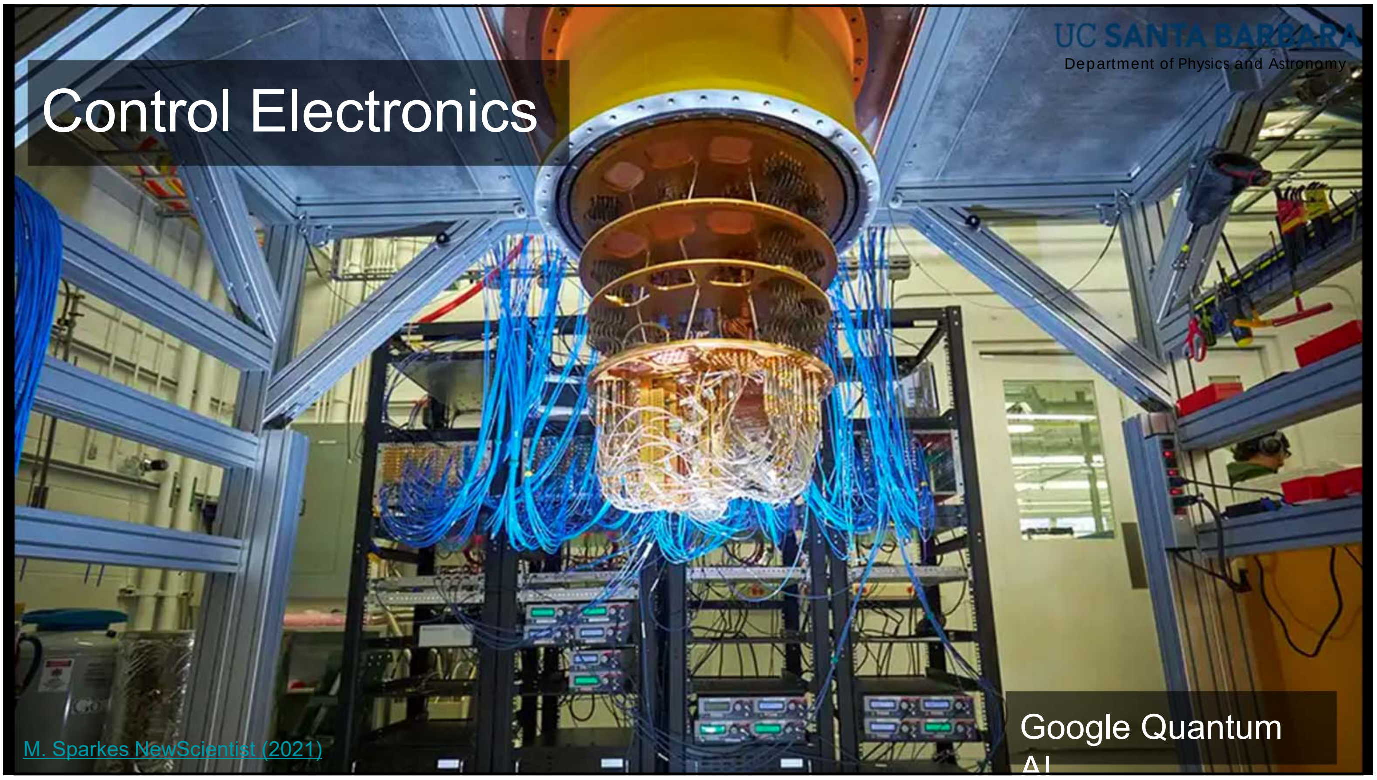
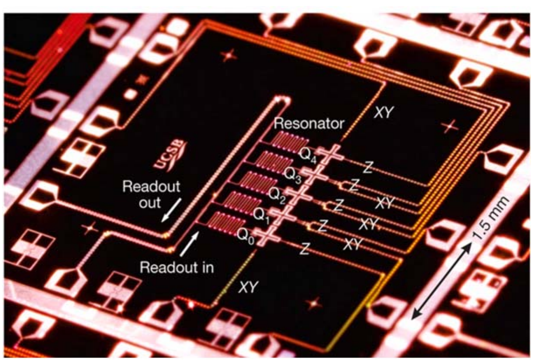
Control Electronics

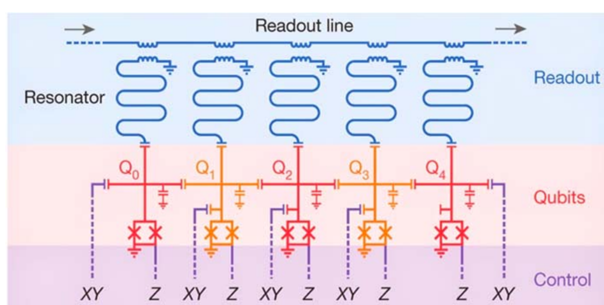


M. Sparkes NewScientist (2021)

Multiplexing

Multiplexing is key to reducing wire count.





R. Barends, J. Kelly, et al. *Nature* 508, (2014)

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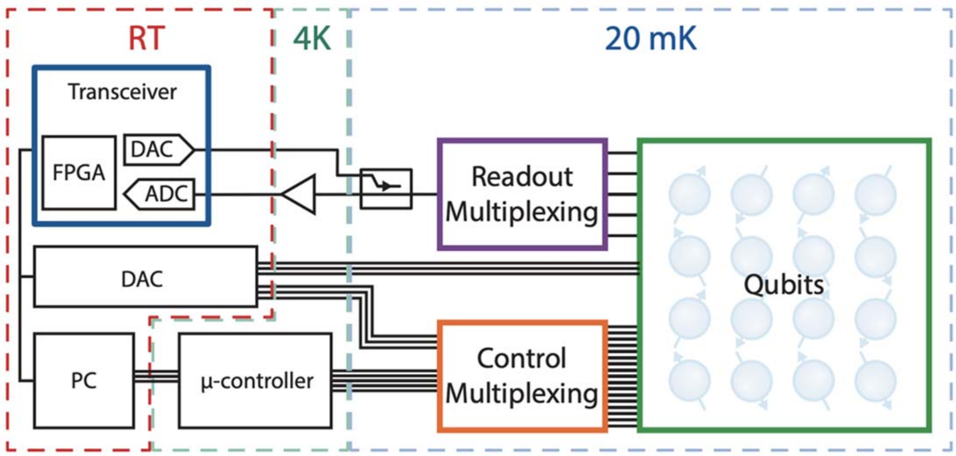
Multiplexing

Cryogenic multiplexing is an active area of research.



D. Reilly. *IEDM* (2019)

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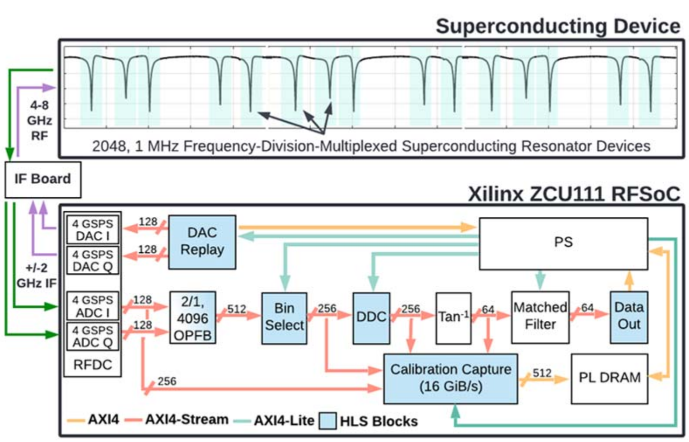
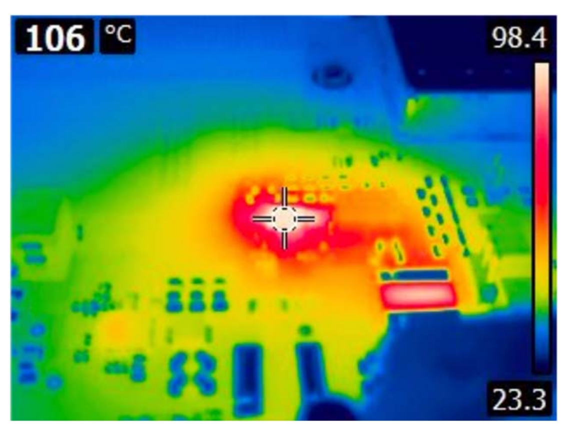
Multiplexing: Not a Free Lunch

Multiplexing demands real-time processing from RT electronics.



Cryo Multiplexing Demands DSP



RFSoC Voltage Controller

Smith et al., FCCM 30, 2022.

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FPGA Readout Systems

QICK

QICK: Quantum Instrumentation Control Kit

The QICK is a kit of firmware and software to use the Xilinx RFSoC to control quantum systems.

It consists of:

- Firmware for the ZCU111, ZCU216, and RFSoC4x2 evaluation boards. We generally recommend using the newer generation of RFSoCs (ZCU216 and RFSoC4x2) for better overall performance.
- The `qick` Python package
- A quick start guide for setting up your board and running a Jupyter notebook example
- Jupyter notebook examples demonstrating usage

Classical Control Systems

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Digital Object Identifier 10.1109/TQE.2021.3116540

QubiC: An Open-Source FPGA-Based Control and Measurement System for Superconducting Quantum Information Processors

YILUN XU[1], GANG HUANG[1], JAN BALEWSKI[1], RAVI NAIK[2], ALEXIS MORVAN[1], BRADLEY MITCHELL[2], KASRA NOWROUZI[1], DAVID I. SANTIAGO[1], AND IRFAN SIDDIQI[1,2]

[1]Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA
[2]University of California at Berkeley, Berkeley, CA 94720 USA

Corresponding author: Gang Huang (ghuang@lbl.gov).

L. Stefanazzi, *arXiv pre-print*, 2110.00557, 2021.

https://ieeexplore.ieee.org/document/9552516

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Summary and Conclusion

What we discussed:

- Superconducting qubits present an interesting and challenging design space at the intersection of cryogenics, physics, and microwave electronics.
- Wiring is a major roadblock in scaling up qubit number.
- Novel manufacturing pathways and enhanced materials research may help.
- More work will be needed in room temperature electronics to manage highly multiplexed systems.

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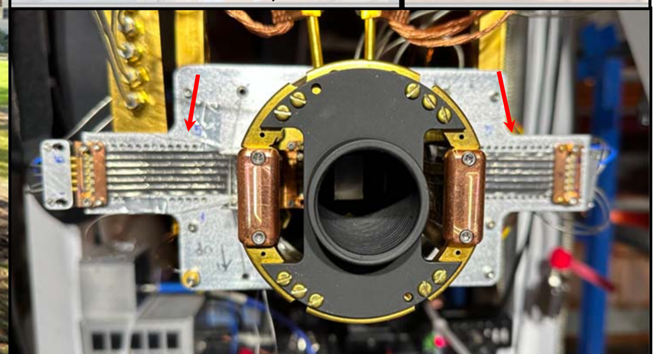
Thank You!

Mazin Lab

Atacama Desert, Chile

Viscacha



New Cables + Device Stage

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