Developing Cryotron Switches for TES Array Multiplexing

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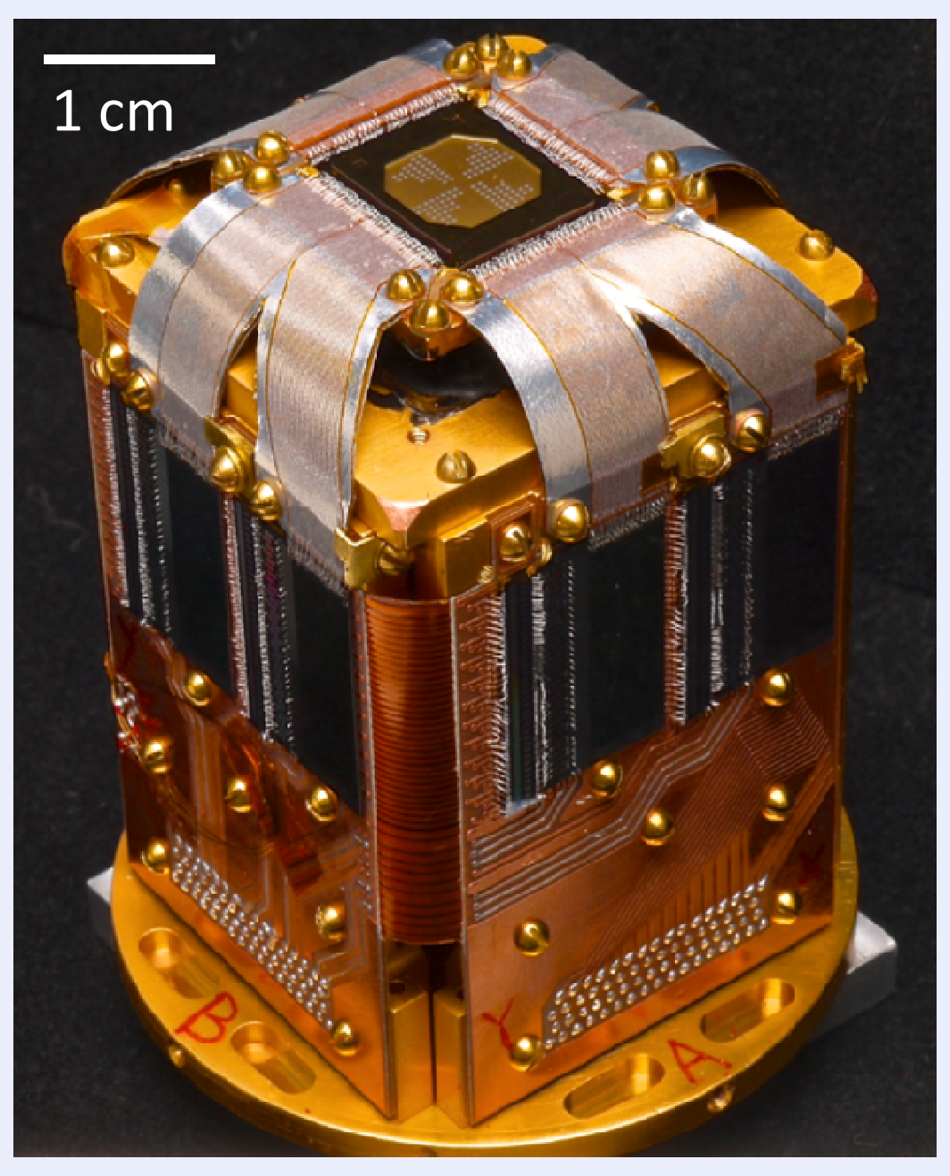
Limitations in Both Current and Future Applications

- Next-generation TES arrays will require 10^5 to 10^6 pixels
  - Improve imaging resolution
  - Reduce measurement time
  - Expand source capability
- Improvements on existing multiplexing strategies are needed
  - Reduce # of wirebond pads
  - Minimize power dissipation
  - Reduce # of leads to mK stage



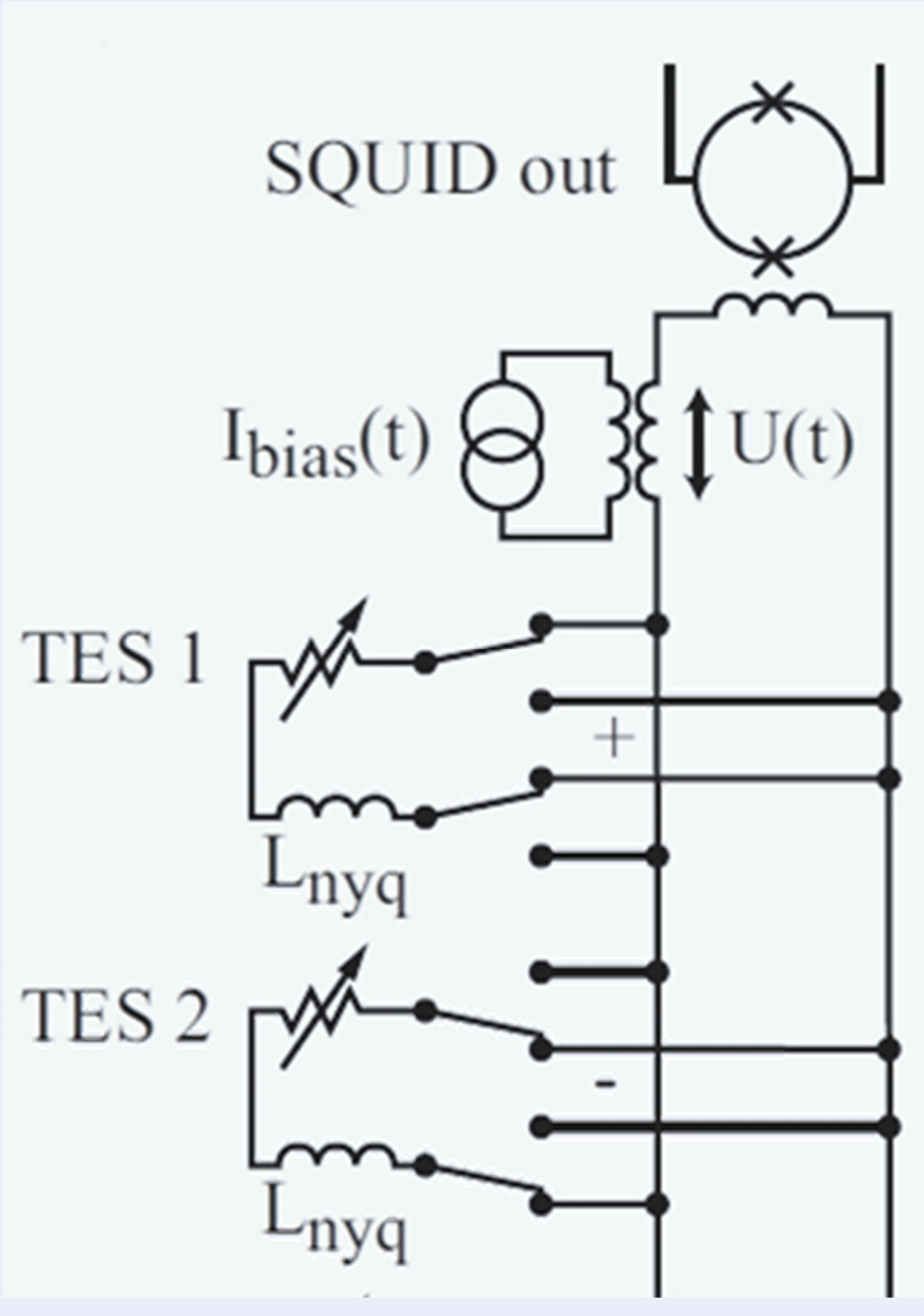
NIST 240 pixel 6 keV x-ray array

Binary Addressing

- # of pixels = 2^(# of bond pads)
  - Significantly reduce bond pad area for large arrays
  - Compatible with time division multiplexing (TDM) & Φ-CDM
  - **Requires in-plane switching**

Current Steered-CDM

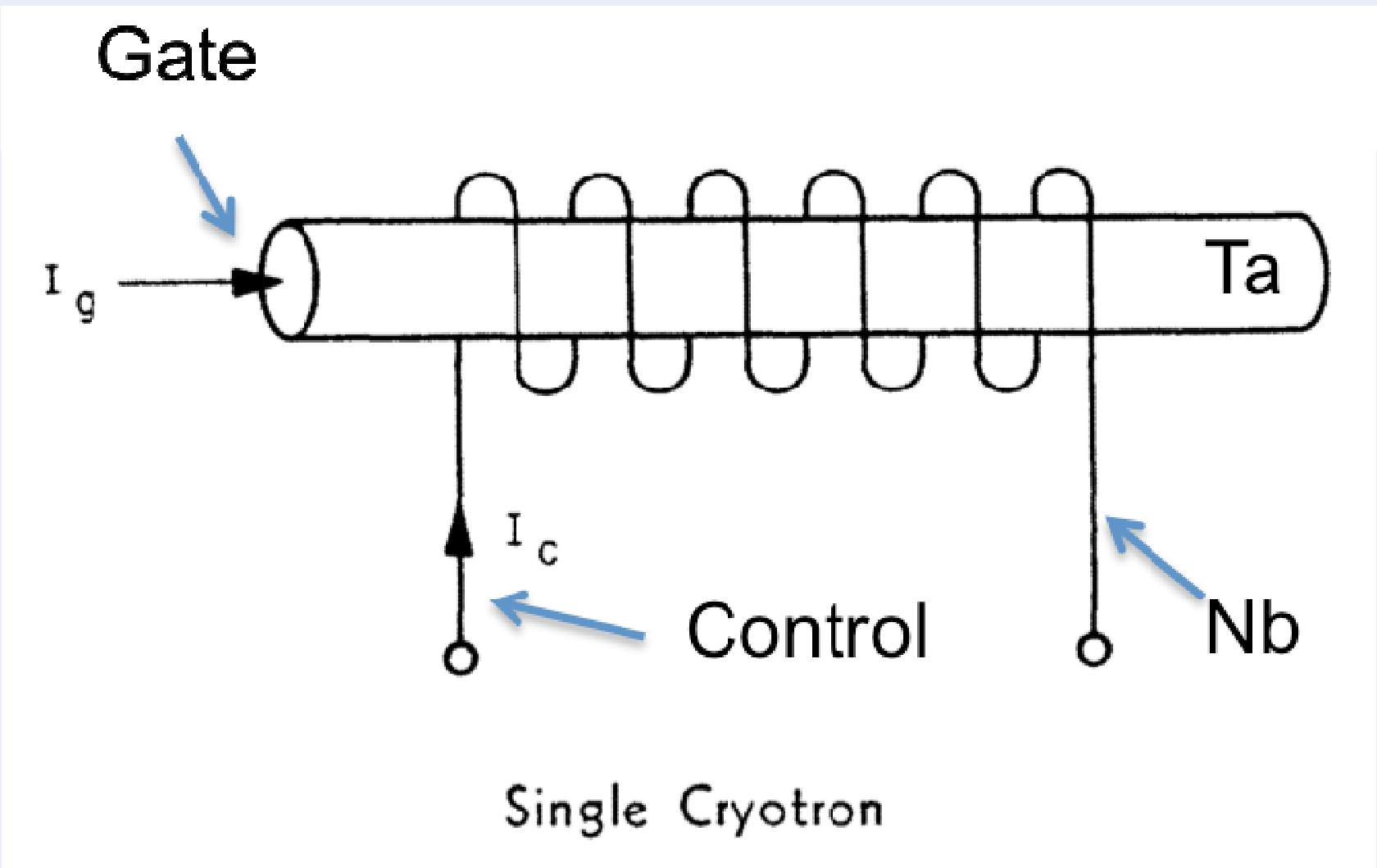
Irwin, K. D., et al. "Advanced code-division multiplexers for superconducting detector arrays." Journal of Low Temperature Physics 167.5-6 (2012): 588-594.



- Current steered – code division multiplexing (I-CDM)
- No power dissipation in shunts
- Can integrate into focal plane
  - Bolometers: long wavelengths arrays have room between pixels
  - Calorimeters: overhanging absorbers demonstrated
- Issues to navigate
  - TES bias variation
  - Cross-talk
- **Requires in-plane switching**

Please see Malcolm Durkin's poster (PB-31)

Solution: The Cryotron

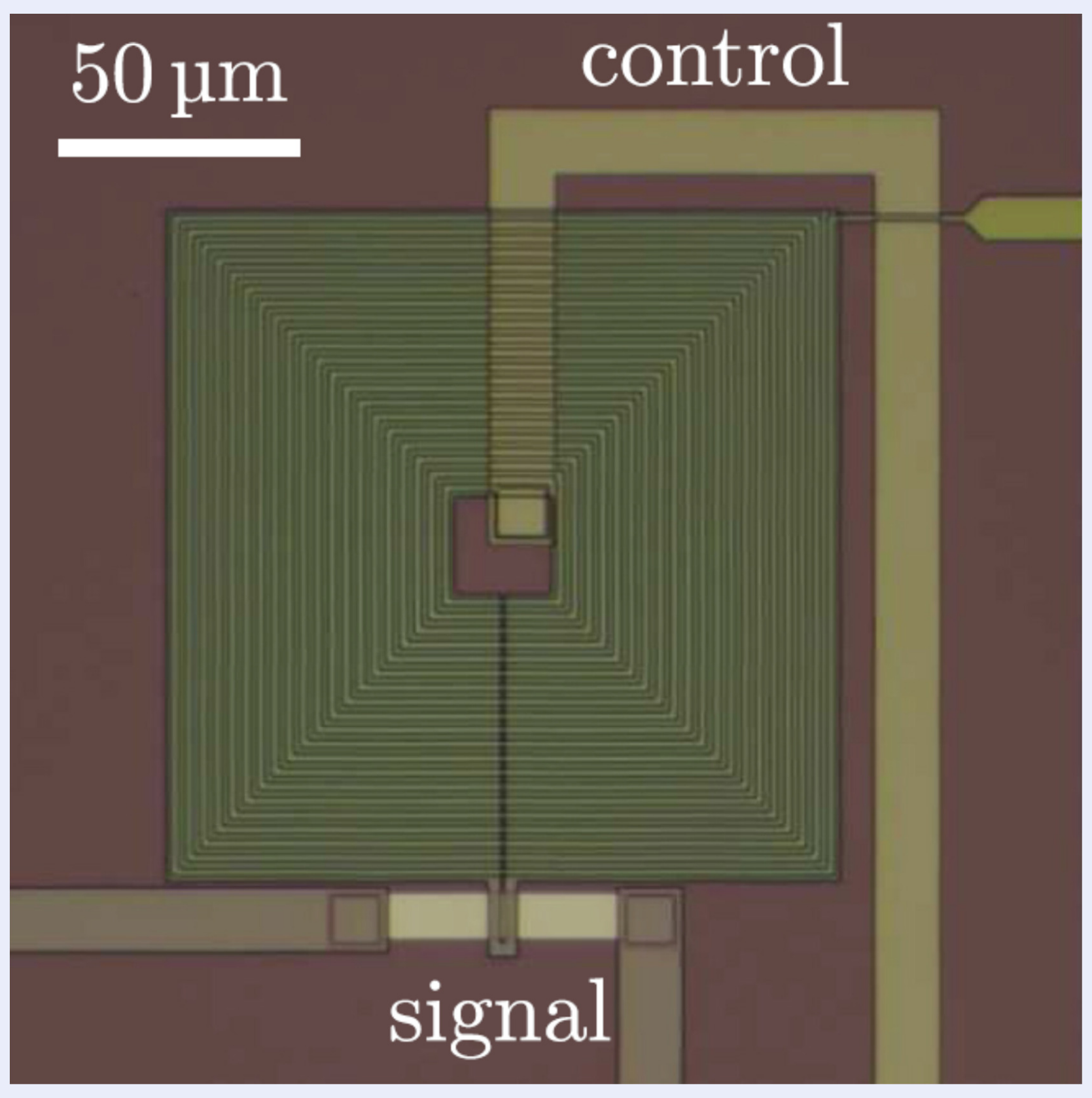


Buck, Dudley A. "The Cryotron-a superconductive computer component." Proceedings of the IRE 44, no. 4 (1956): 482-493.

- Proposed by Dudley Buck in 1950's
- Superconducting switch
  - Control line creates a magnetic field
  - Signal line switches from superconducting to normal

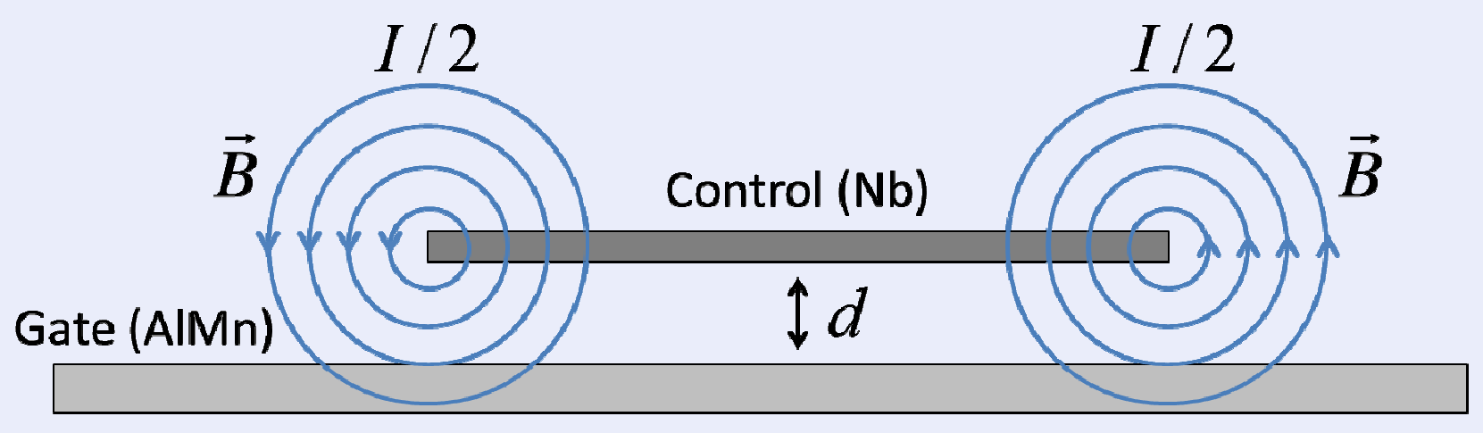
Initial Cryotron Design

Lowell, P. J., et al. "A thin-film cryotron suitable for use as an ultra-low-temperature switch." Applied Physics Letters 109 (2016): 142601.



- Demonstrated with AlMn gate
- Transformer used to minimize control line current
  - 20-turn primary coil
  - Secondary coil in close proximity to signal line
- PECVD oxide used as insulator between Nb/AlMn layers

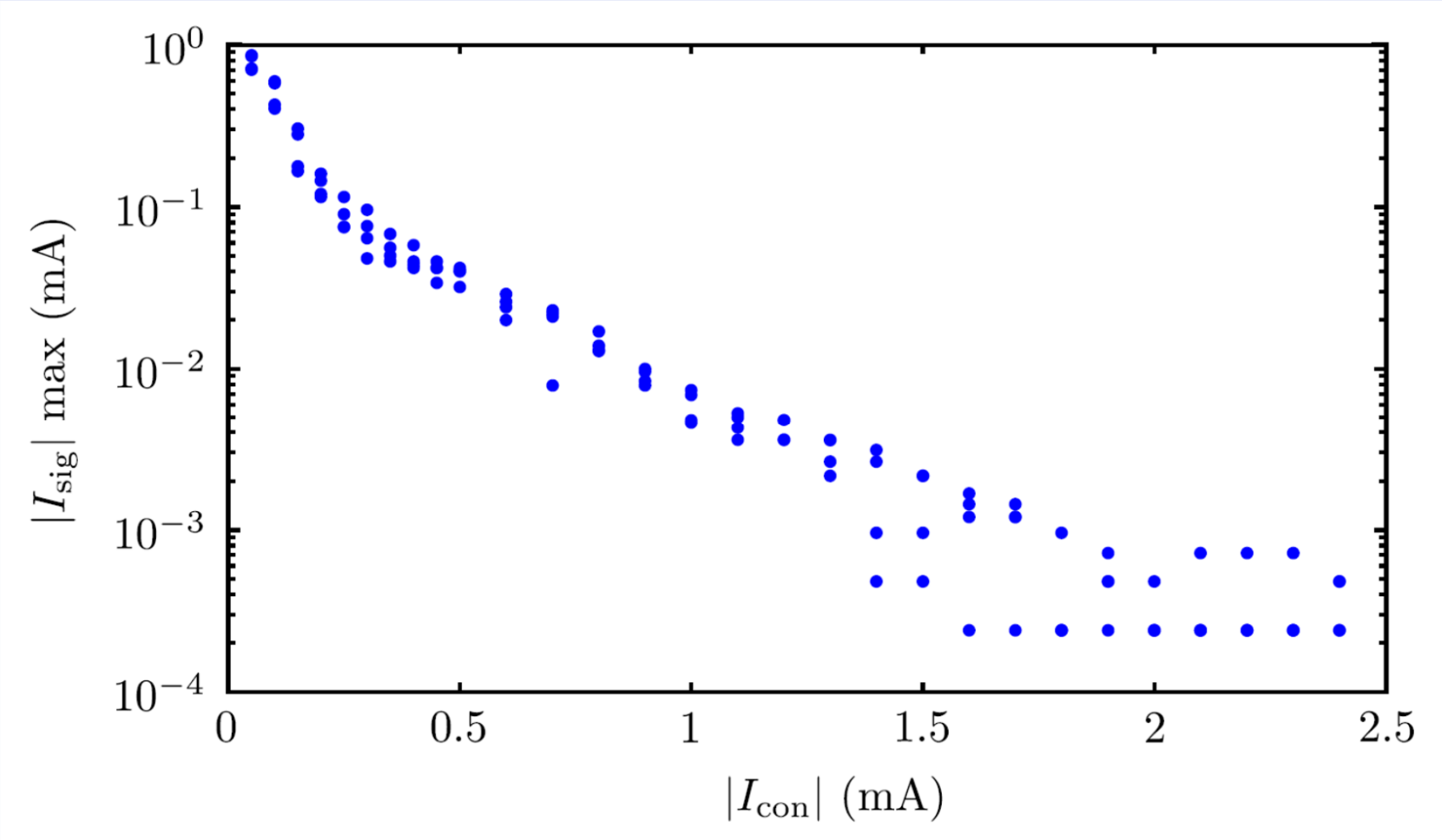
Cryotron Switching Field



- Maximum perpendicular magnetic field: $B_\perp = \frac{\mu_0 I_{con}}{8\pi d}$
- Requires T_c of control line >> T_c of gate
- T_c of AlMn can be tuned
- Simple model assumes current travels at edges of control line

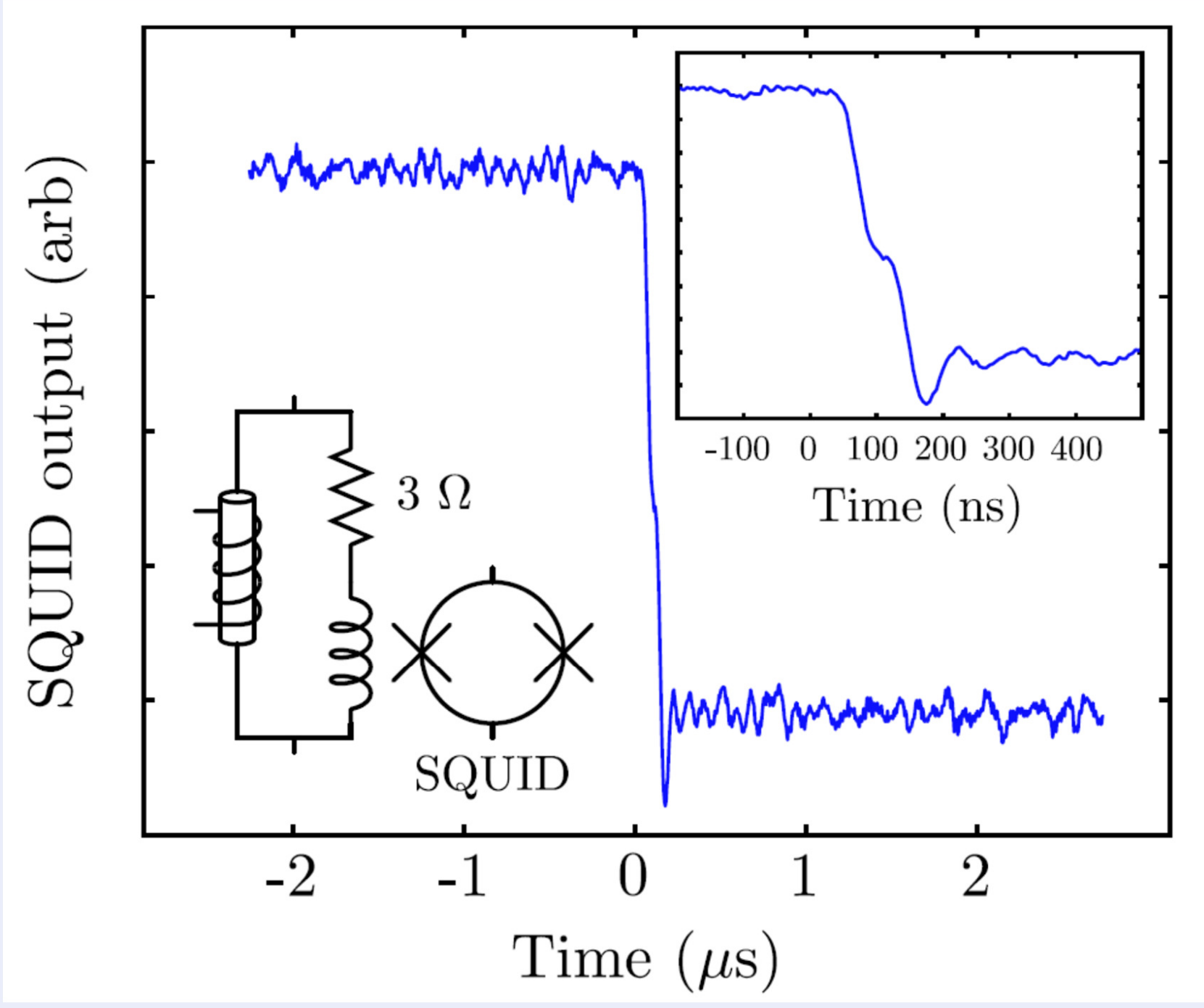
Control Current Actuation

- Maximum supercurrent I_{sig} versus control line current I_{con} at 70 mK
- Cryotron exhibits low-field regime with linear slope
  - Meissner state
- High-field regime with long decaying tail
  - Presence of vortices
- Required magnetic field is order of magnitude larger than predicted
  - Non-uniform magnetic field
  - Thin-film effects in AlMn



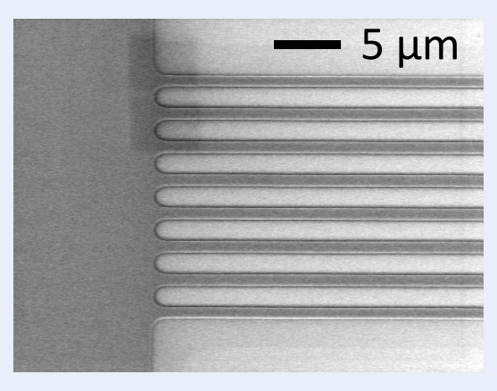
Switching Speed

- Cryotron in parallel circuit with SQUID
- Current is shunted to input coil
- Time constant τ ~ 30 ns
- Measurement restricted by readout electronics
  - Switching speed < 200 ns
  - Not limited by cryotron



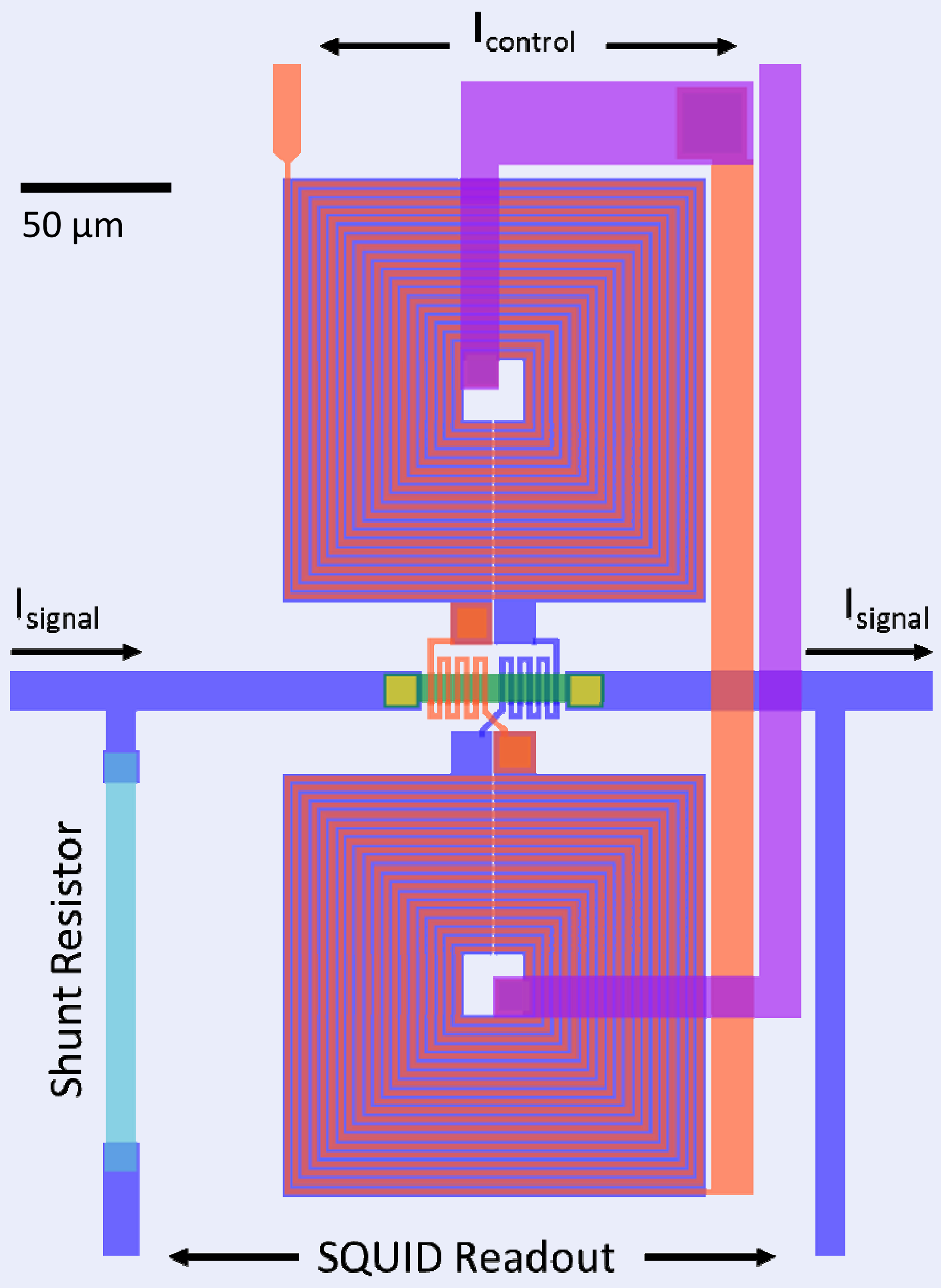
Increasing Signal Line I_c and R

- 4-probe measurements of AlMn signal traces
- Critical current (I_c) and normal resistance (R) vs. trace geometry



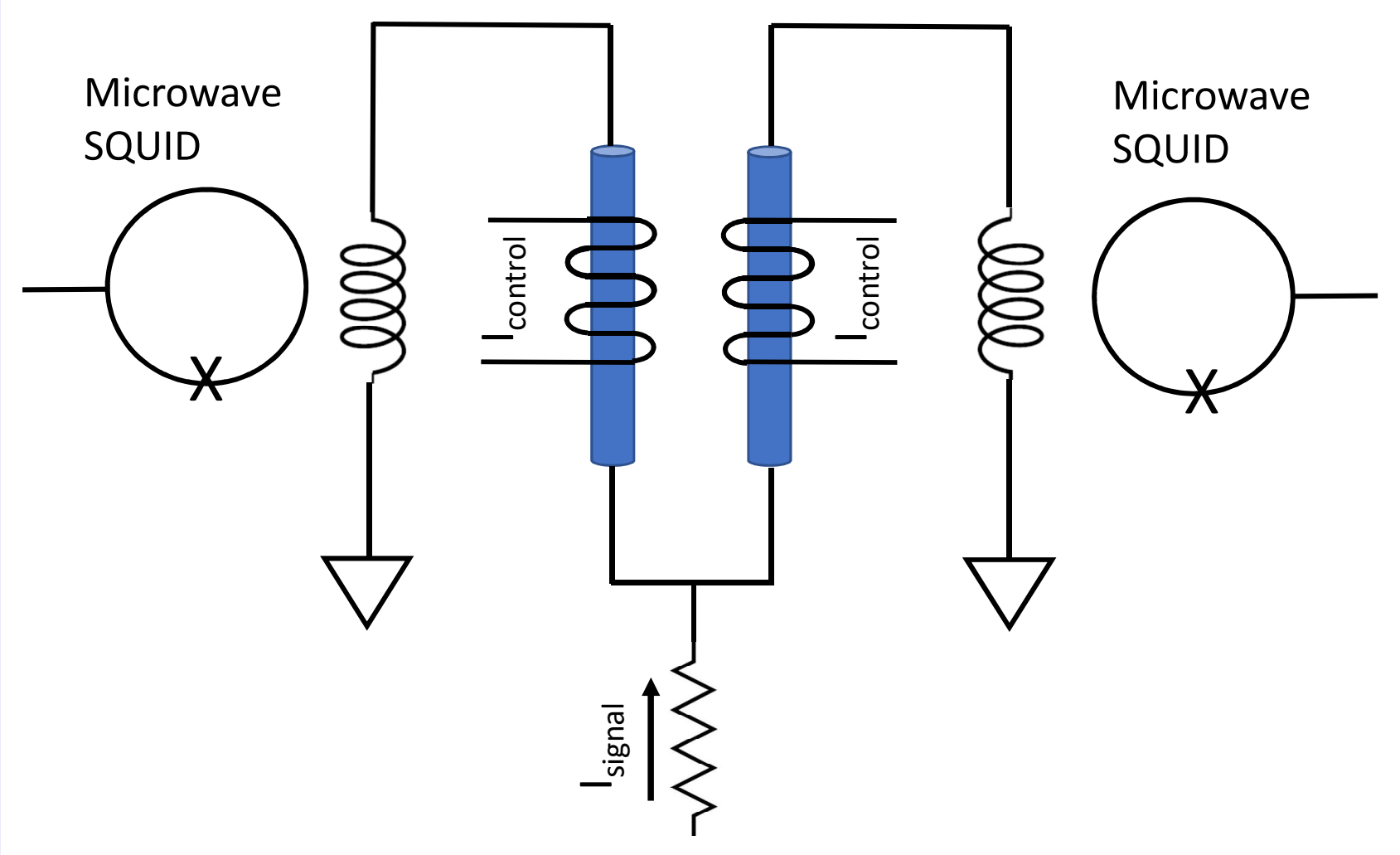
Trace Width (µm)	2	2	6	6
# of Traces	1	6	1	2
Total Width (µm)	2	12	6	12
Normal Resistance (Ω)	113	20	30	15
Average Ic (µA)	15	313	199	290
I_c Standard Dev. (µA)	1	42	14	32

Ongoing Speed Testing



- Implement dipole gradiometer
  - Minimize sensitivity to external magnetic fields
- Optimize gate design
  - Increase I_{signal}/ decrease $I_{control}$
  - Increase open state resistance
- Incorporate shunt resistor on chip
  - Reduce circuit inductance and "ringing" during switching
- Microwave SQUID readout
  - Sensitive to tens of nanoseconds switching speed

Current Steering: Single-Pole, Double-Throw



- Ongoing work to demonstrate single-pole, double-throw switch
- Two cryotrons in parallel
- Current is steered to readout microwave SQUIDS
- Future applications
  - Binary addressing for TDM
  - Coded readout in I-CDM
  - Superconducting logic components

Acknowledgements

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Conclusions and Future Work

- Cryotron demonstrated with switching speeds faster than 200 ns
- Microfabrication compatible with calorimeter and bolometer arrays
- **Pathway to reduce bond pad requirements for large arrays**

Continued Improvement

- Signal line material and geometry
- Reduce gate insulating thickness
- Minimize readout inductance
- Measure switching speed limit
- Demonstrate current-steering
- Implement binary addressing