CPAD 2026

FABRICATION DEVELOPMENT AND RESULTS FOR SPT-SLIM, AN ON-CHIP SUPERCONDUCTING SPECTROMETER FOR LINE-INTENSITY MAPPING

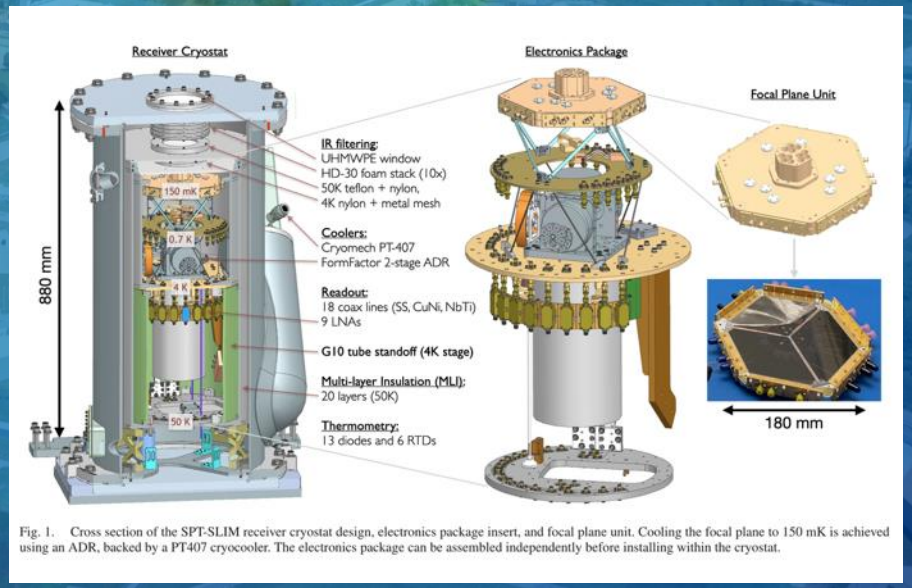


Fig. 1. Cross section of the SPT-SLIM receiver cryostat design, electronics package insert, and focal plane unit. Cooling the focal plane to 150 mK is achieved using an ADR, backed by a PT407 cryocooler. The electronics package can be assembled independently before installing within the cryostat.

Young et al., IEEE Trans. Appl. Supercond., 2026, Fig. 1

PRESENTER

Thomas Cecil
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COLLABORATION

SPT-SLIM Collaboration

FUNDING

NSF AST-2108763, OPP-1852617, OPP-2332483; DOE DE-AC02-06CH11357

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THE SPT-SHIROKOFF LINE INTENSITY MAPPER

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WHY LINE-INTENSITY MAPPING?

- Maps large-scale structure via the aggregate line emission (e.g., CO) of all galaxies in a voxel — no need to resolve individual sources
- Efficient access to high-redshift ($0.5 < z < 2$) structure vs. galaxy-by-galaxy spectroscopy
- mm/sub-mm lines are observable from the ground and well matched to large-format superconducting arrays
- Motivates compact, on-chip spectrometers packing many spectral channels per pixel

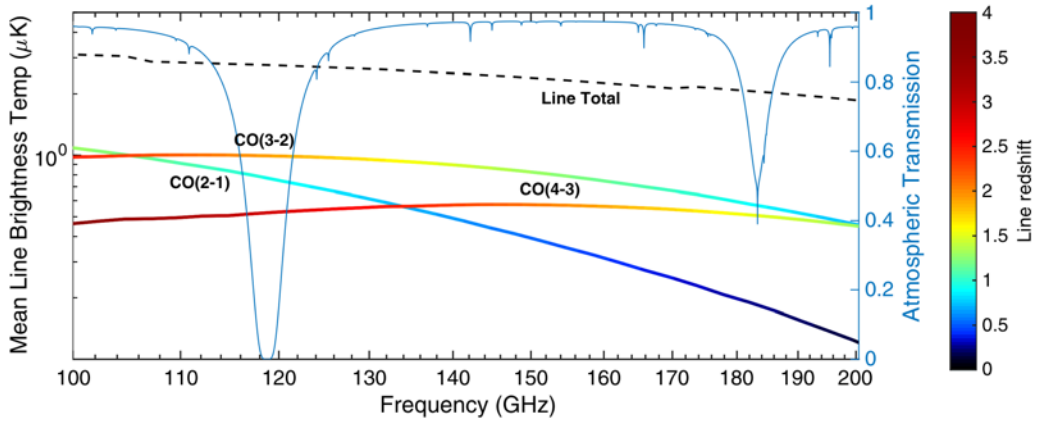


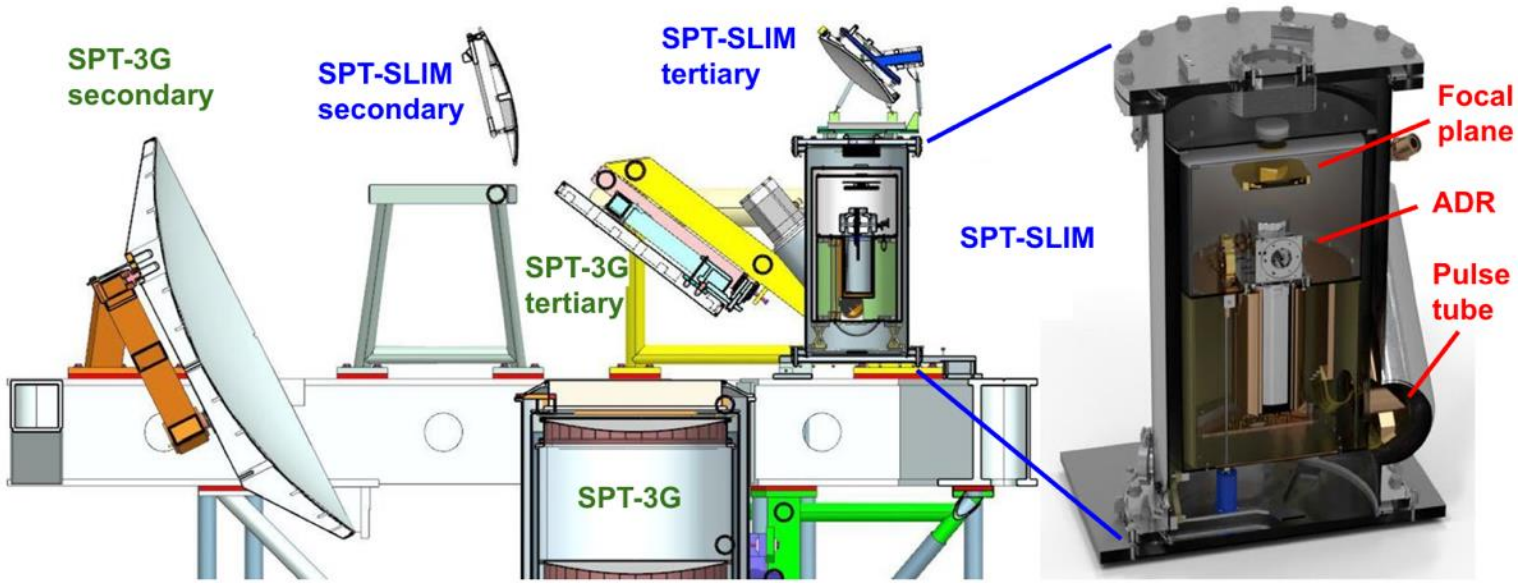
Fig. 1 Spectral lines targeted by SPT-SLIM, which will observe from 120–180 GHz. Shown are the model predictions for the brightness temperatures of CO(2-1), CO(3-2), and CO(4-3), their sum total (dashed black), and median atmospheric transmission during the South Pole summer (thin blue). The colors correspond to the observed redshifts of the lines (Color figure online)

Karkare et al., J. Low Temp. Phys., 2022, Fig. 1

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THE SPT-SLIM INSTRUMENT

- Pathfinder line-intensity mapping instrument riding on the South Pole Telescope
- 9 pixels / 18 spectrometers, >1000 detectors, R ≈ 300, 120–180 GHz
- Shares the SPT receiver cabin with SPT-3G; cooled to 150 mK with a 2-stage ADR + pulse tube
- First deployed during the 2024–2025 austral summer season

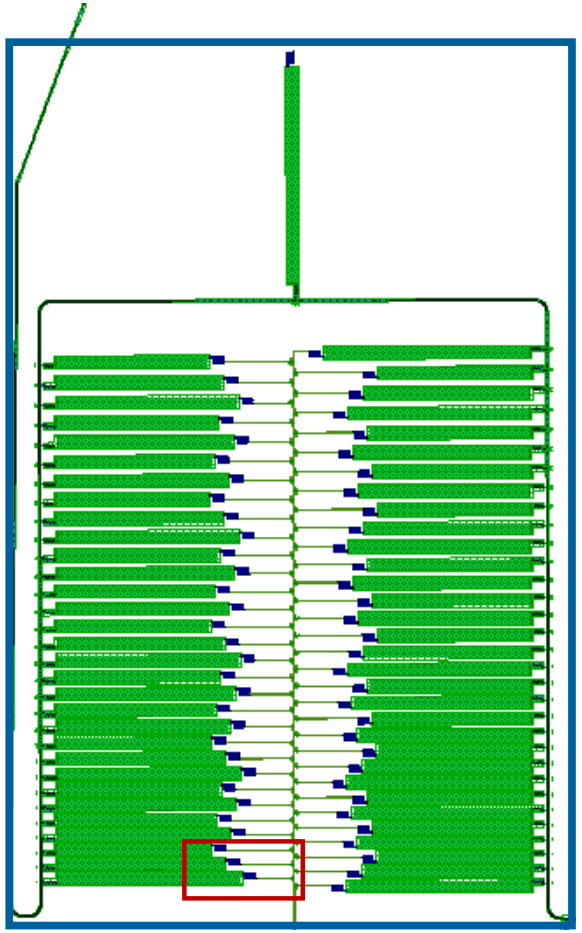


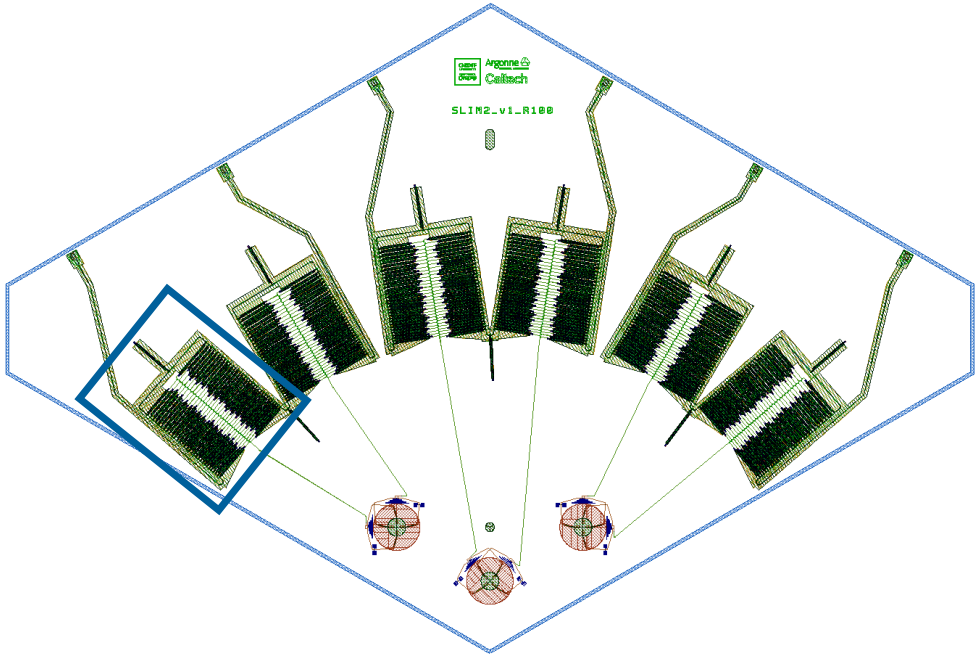
Karkare et al., J. Low Temp. Phys., 2022, Fig. 2

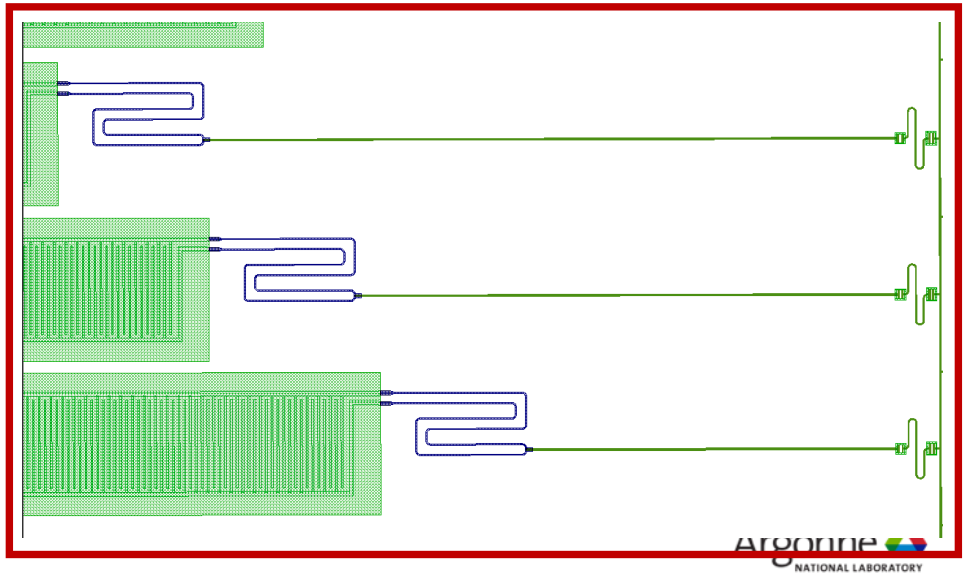
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ON-CHIP FILTERBANK SPECTROMETER CONCEPT

- Feedhorn-coupled orthomode transducer injects light into superconducting microstrip
- Signal routed to an on-chip filterbank of channelizing resonators
- Each spectral channel terminates in a lumped-element KID (leKID) — spectrometer and detector array in one chip
- This architecture is what makes a 1000+ channel array fabricable and scalable







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FABRICATION PROCESS

- Realizing this architecture at LIM-required resolution and sensitivity demands sustained fabrication R&D
- Key challenges
  - A robust hybrid (multi-material) leKID process
  - A microstrip dielectric that is low-loss AND compatible with low-temperature processing
  - A scalable wafer fabrication process

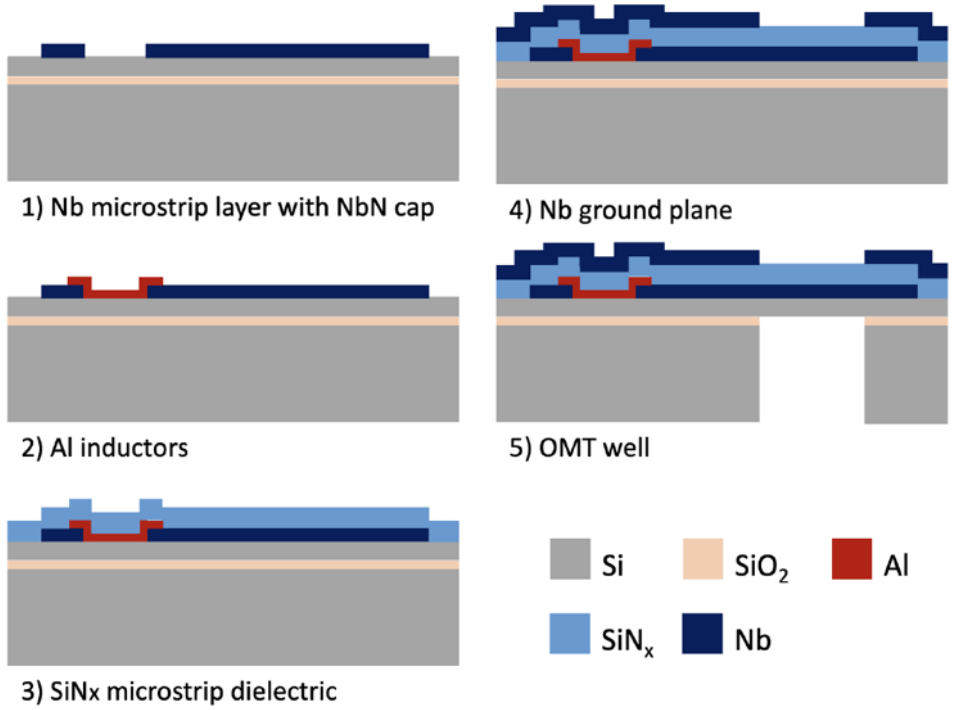


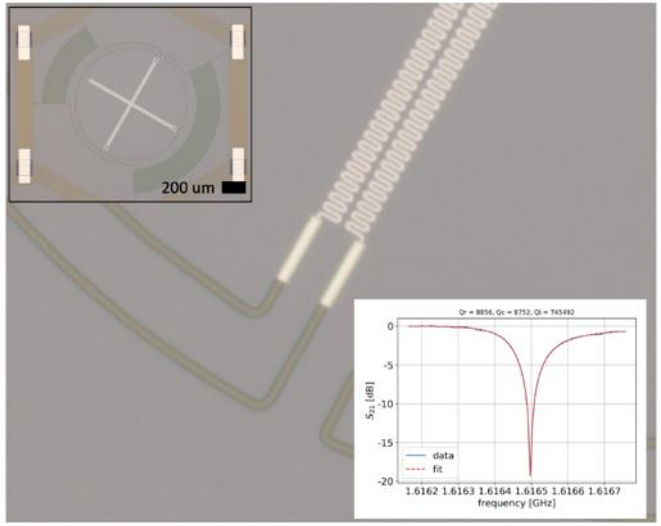
Fig. 2. Process flow for fabrication of a superconducting spectrometer with inverted microstrip on a SOI wafer.

Cecil et al., IEEE Trans. Appl. Supercond. 33(5), 2023, Fig. 2

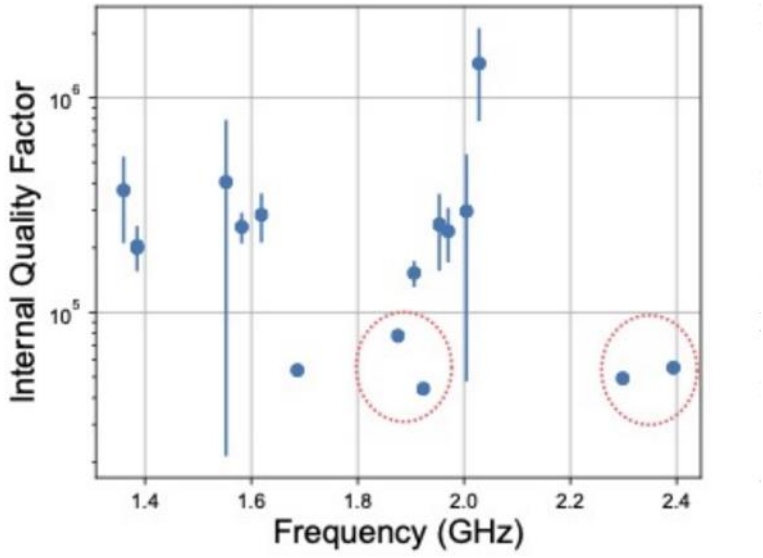
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HYBRID AL/NB LEKID FABRICATION

- leKIDs combine an Al inductor with a Nb capacitor
  - Smaller Al gap matches desired signal frequency
  - Larger Nb gap reduces thermal quasi-particle population
- Reliable galvanic Al–Nb contact achieved via a thin NbN capping layer, preventing native-oxide formation
- Validated on dedicated hybrid test chips: high internal Q (Qi) retained after the junction process



Cecil et al., IEEE Trans. Appl. Supercond. 33(5), 2023, Fig. 3

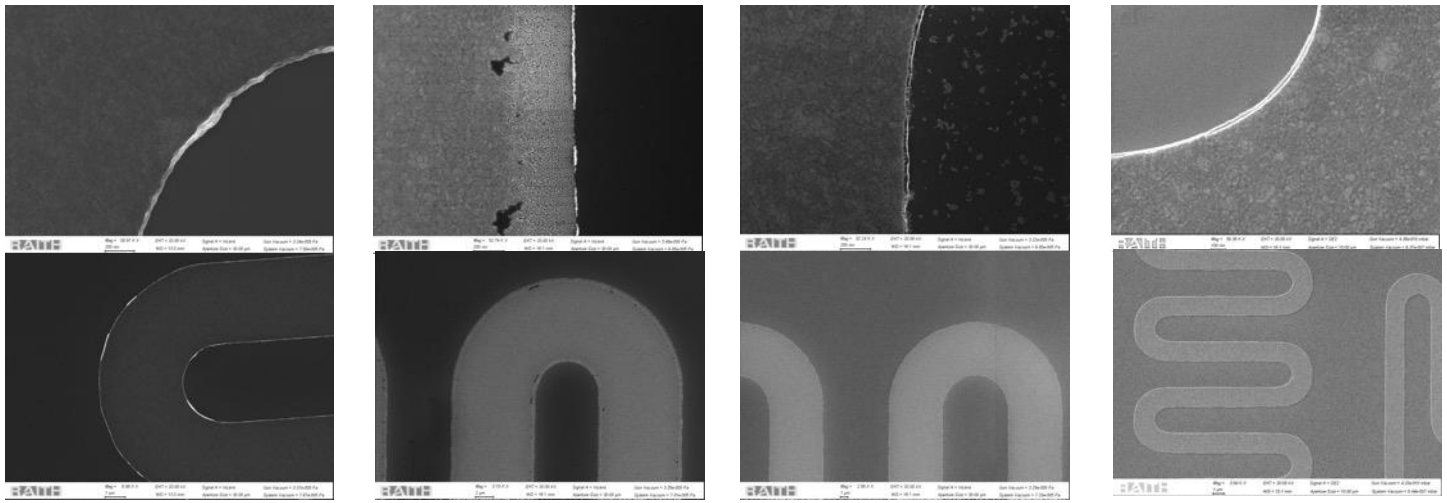


Cecil et al., IEEE Trans. Appl. Supercond. 33(5), 2023, Fig. 6

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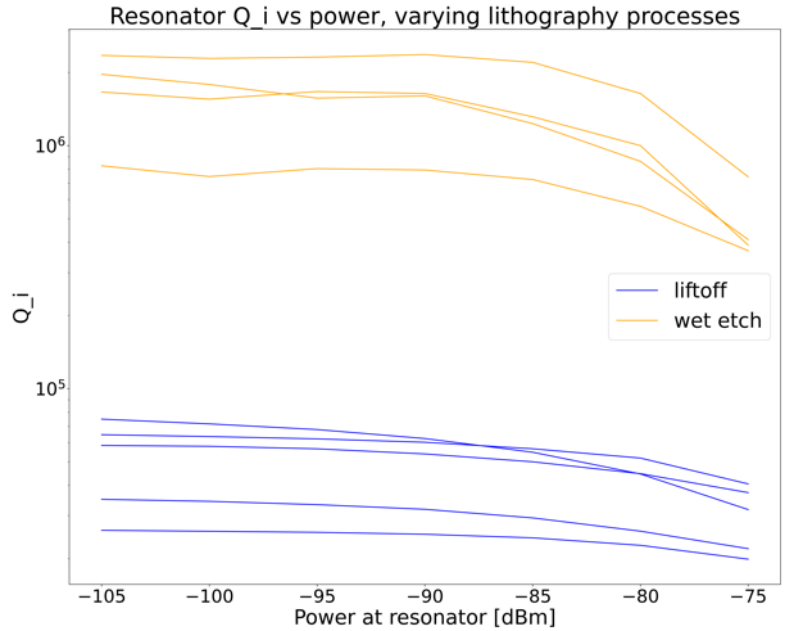
PROCESS OPTIMIZATION: PATTERNING

- Al patterning method strongly affects resonator Qi: liftoff vs. wet etch vs. plasma (dry) etch
- Wet-etched sputtered Al gives ~10× higher Qi than liftoff — now the baseline inductor process



Single-layer liftoff **Bi-layer liftoff** **Wet etch** **Plasma etch**

Cecil et al., "Impacts of Common Fabrication Processes on Al Resonator Performance," LTD2025 poster, 2025

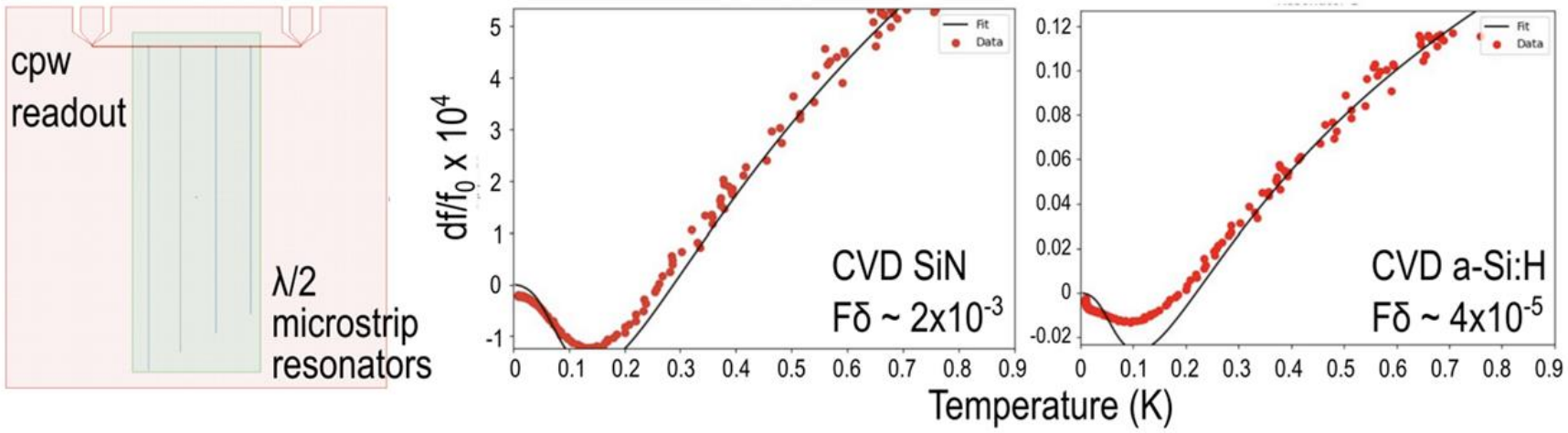


Cecil et al., LTD2025 poster, 2025

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LOW-LOSS, LOW-TEMPERATURE DIELECTRICS

- Dielectric loss sets the achievable spectral resolution and optical efficiency
- Standard CVD SiNx: loss tangent too high for R = 300 performance
- Hydrogenated a-Si (a-Si:H) is promising, but typically requires high-temperature (> 250°C) deposition
  - Al inductors have a low thermal budget (< 150°C) due to hillock formation



Barry et al., J. Low Temp. Phys. 209, 2022, Fig. 2(b)

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SPUTTERED SI-RICH SILICON NITRIDE DIELECTRICS

- Study low-temperature (e.g., sputtering / IBAS, <150°C) and screening loss with microwave test resonators
  - Compared SiO_2, a-Si, Si-rich SiN_x, and SiN_x films grown by IBAS (room temperature) and PECVD (100°C)
- Key results:
  - PECVD SiN_x at 100°C had a good loss tangent, but the lower deposition temperature caused significant flaking of the film — not usable as-is
  - Loss tangent decreases monotonically with increasing Si content across the film series — motivates moving to a Si-rich film as the low-loss compromise

TABLE I
DIELECTRICS DEPOSITION PARAMETERS AND PROPERTIES

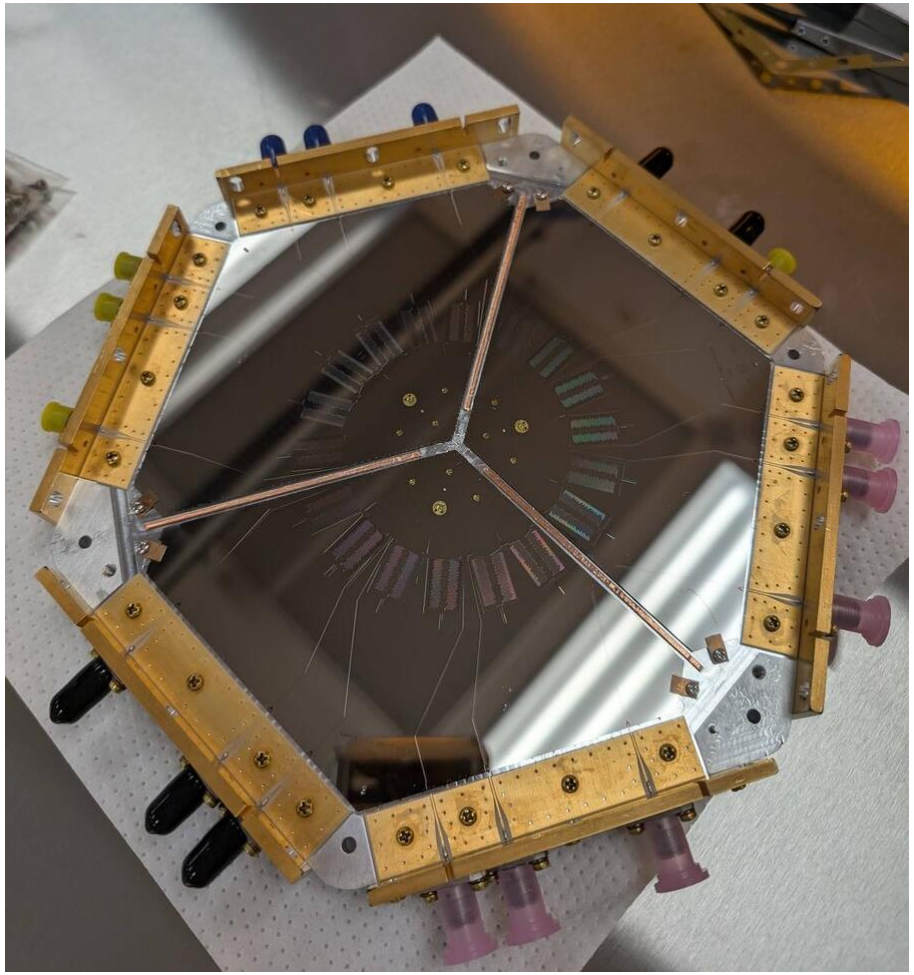
Material	Method	Deposition parameters	Ref. index	Stress	Tan delta
SiO2	MS	250°C 4h, 4.6sccm O_2 25sccm Ar	1.46	-314 MPa	$1x10^{-3}$
SiO2	IBAS	RT 1h, 8 sccm O_2, 20sccm Ar	1.58	-311 MPa	$8x10^{-4}$
a-Si	IBAS	RT 1h, 20 sccm Ar	4.5	-705 MPa	$5x10^{-4}$
(Si-rich)Nx	IBAS	RT 1h, 6 sccm N_2, 20sccm Ar	2.4	-1575 MPa	$8x10^{-4}$
SiNx	IBAS	RT 1h, 17 sccm N_2, 20sccm Ar	1.98	-1702 MPa	10^{-3}
(Si-rich)Nx	PECVD	100°C 1h, 33 sccm SiH_4, 24 sccm N_2	2.38	-792 MPa	$2x10^{-4}$
SiNx	PECVD	100°C 1h, 30 sccm SiH_4, 27 sccm N_2	2.4		$1.1x10^{-3}$

Table I: Lisovenko et al., IEEE Trans. Appl. Supercond., 2023

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SPT-SLIM DEPLOYED

- SPT-SLIM focal plane
  - 3 sub-modules
  - 9 OMTs
  - 18 spectrometers (one per polarization)
  - > 1,100 detectors
- Deployed to pole during 2024-2025 ‘summer’ season



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CHARACTERIZING THE DEPLOYED SPECTROMETER: SPECTRAL BANDPASSES

- On-site Fourier Transform Spectrometer (FTS) measures as-built channel bandpasses
- Native FTS resolution is coarser than the R = 100 design
- Custom spatial-domain (interferogram) fit recovers channel frequency/resolution beyond native FTS resolution

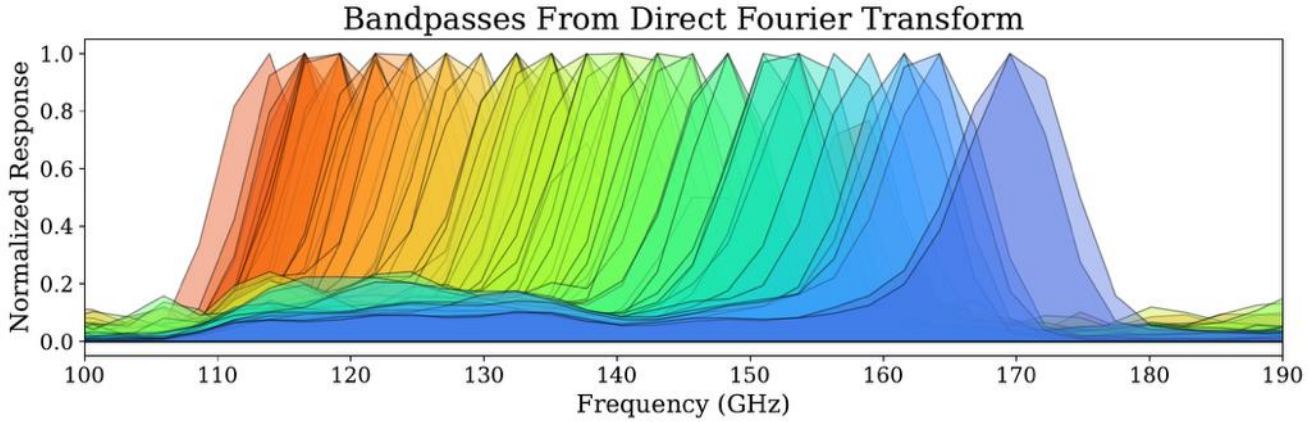


Fig. 2: The spectral channels of a polarization-pair of deployment SPT-SLIM filterbanks measured with the FTS. Note that the width of each filter profile has been broadened by the instrumental line shape of the lower-resolution $\Delta\nu \sim 6\,\mathrm{GHz}$ FTS.

Benson et al., IEEE Trans. Appl. Supercond., 2026, Fig. 2

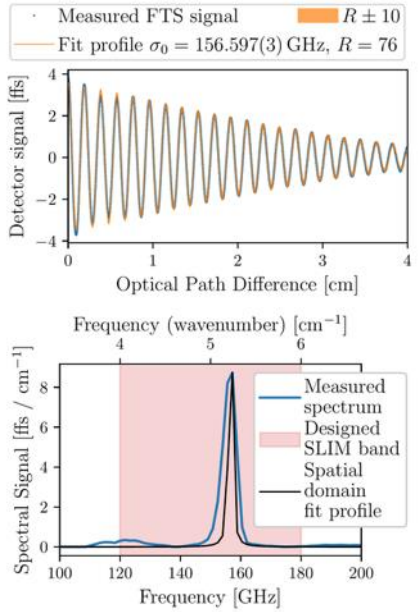


Fig. 4: A spatial-domain fit of the interference signal from one of the SLIM detectors (top). The spectrum of the corresponding spectrometer channel measured by the FTS and the spectral profile obtained from the spatial-domain fit are shown in the spectral (Fourier) domain (bottom). Note that the measured profile is smeared to a wider spectral bandpass due to the instrumental line shape of

Benson et al., IEEE Trans. Appl. Supercond., 2026, Fig. 4

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CHARACTERIZING THE DEPLOYED SPECTROMETER: ON-SKY RESOLUTION & DIAGNOSIS

- Measured average spectral resolution R ≈ 65–70, below the design target
- On-sky sensitivity can be improved by
  - Readout and magnetic shielding improvements (increase Qi)
  - Reduce inductor volume (increase responsivity)
  - Improve microstrip loss (measurements indicated loss is higher than assumed for design)
- Despite reduced resolution, the array survived deployment and produced a two-week science-quality dataset

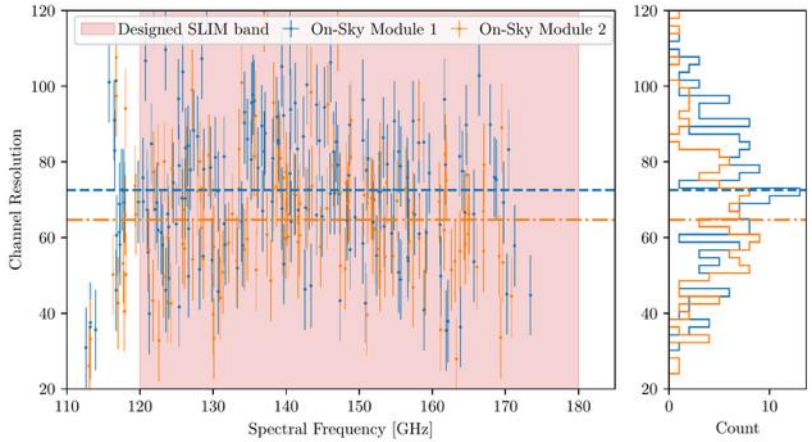


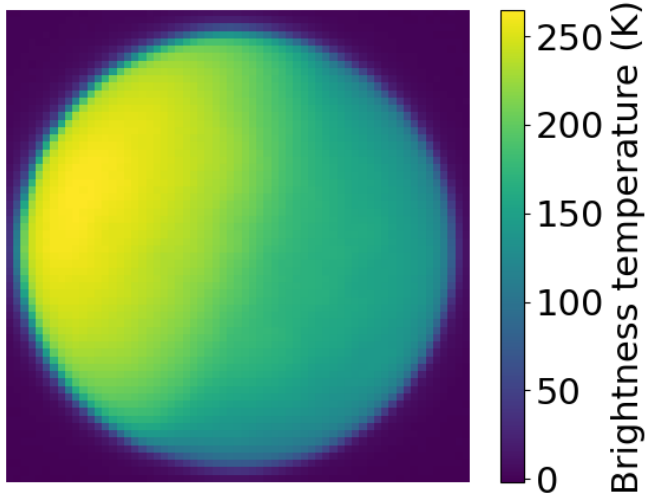
Fig. 6: The fitted resolution, R, of the on-sky submodules extracted from measurements with the South Pole FTS (see Eq. 4). Error bars represent the uncertainty determined from the simulated data shown in Fig. 5 at the corresponding SNR of the interferogram measured with the FTS.

Benson et al., IEEE Trans. Appl. Supercond., 2026, Fig. 6

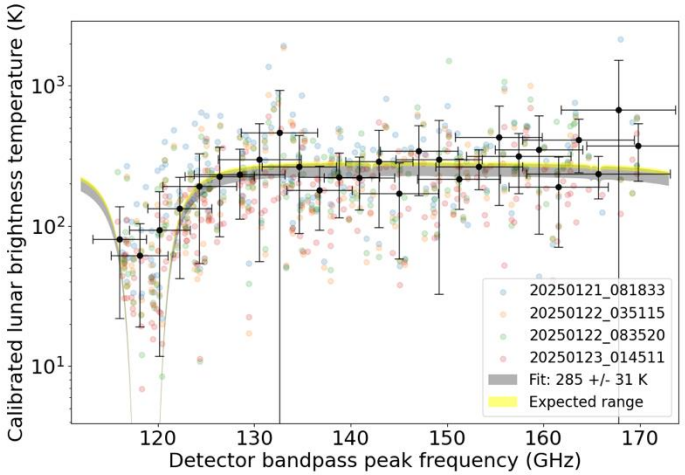
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CHARACTERIZING THE DEPLOYED SPECTROMETER: ON-SKY RESPONSIVITY CALIBRATION

- On-sky calibrations using bandpass measurements, elevation scans, and atmospheric opacity measurements
- Raw timestreams converted to fractional frequency shift; an atmospheric-loading model relates tuning frequency at each scan's elevation to incident power, recovering Moon power from the measured shift
- Observations corrected for differing Moon elevation and phase, then combined across all functional detectors into a single calibrated spectrum
- Blackbody fit (transmitted through the mean South Pole summer atmosphere) gives a Moon brightness temperature of 285 ± 31 K — consistent with expected lunar values, validating the responsivity model across the SLIM band



Dibert et al., IEEE Trans. Appl. Supercond., 2026, Fig. 6

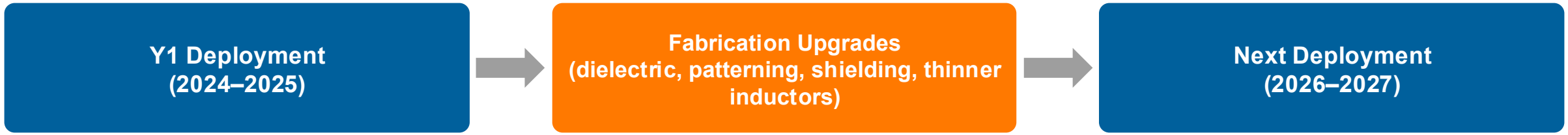


Dibert et al., IEEE Trans. Appl. Supercond., 2026, Fig. 7

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FABRICATION-DRIVEN UPGRADES FOR THE NEXT DEPLOYMENT

- Integrate the validated low-temperature a-Si:H dielectric into the full filterbank stack
- Adopt wet-etch Al patterning across all inductor layers to recover Qi lost to legacy liftoff processing
- Improve magnetic shielding of the focal plane
- Thinner Al inductors for reduced volume and increased responsivity

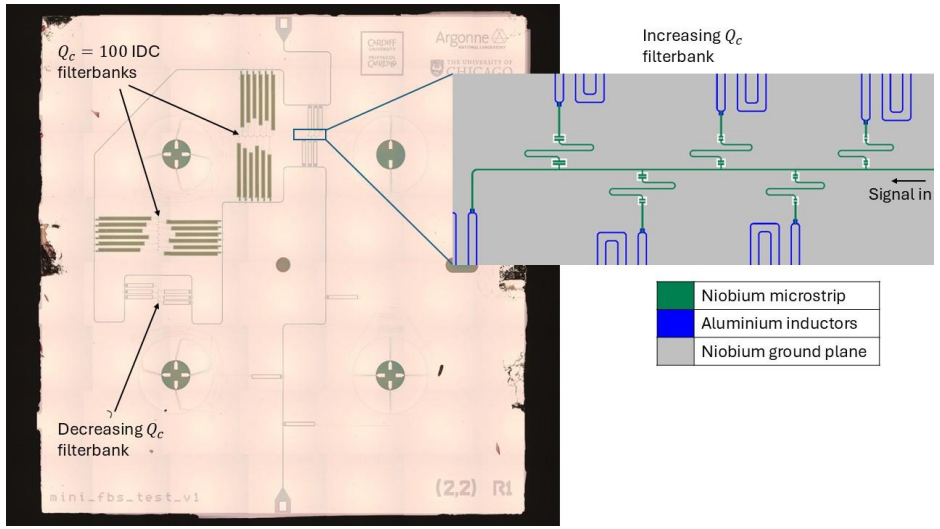


Goal: close the R ≈ 65–70 → design-target resolution gap

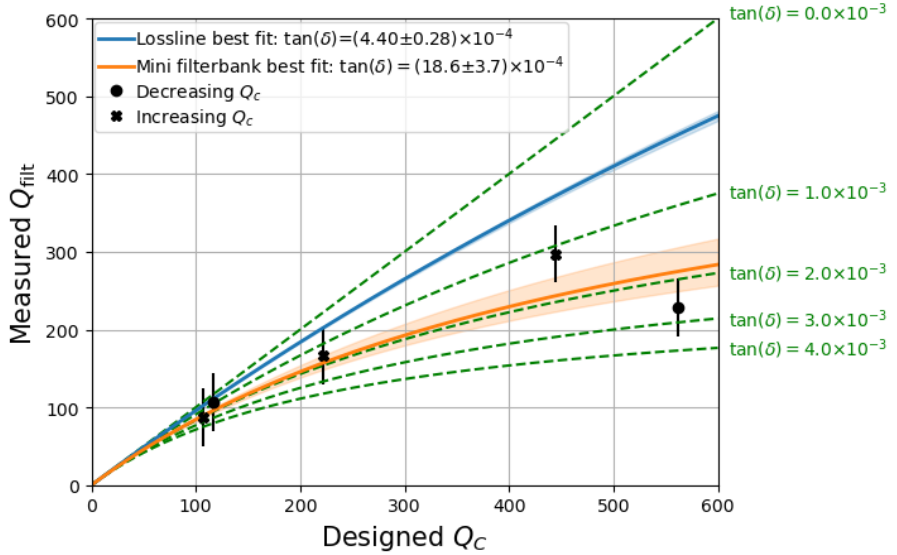
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IMPROVED MICROSTRIP AND LOSS CHARACTERIZATION

- Microstrip loss degrades channel efficiency and broadens linewidths relative to design
- Performance at ~ 100GHz may not be reflected in measurements made at ~ 1 GHz
- Two independent methods measure loss tangent of a new sputtered a-Si:H dielectric: “lossline” (response vs. microstrip length) and “mini-filterbank” (filter Q vs. designed coupling Q)
- Loss measurements of room temperature sputtered a-Si:H
  - Lossline: tanδ = (4.40±0.28)×10⁻⁴; mini-FBS: tanδ = (18.6±3.7)×10⁻⁴ — both confirm much lower loss than SiNx (~4×10⁻³)



Bapat et al., IEEE Trans. Appl. Supercond. (in press, 2026), Fig. 2

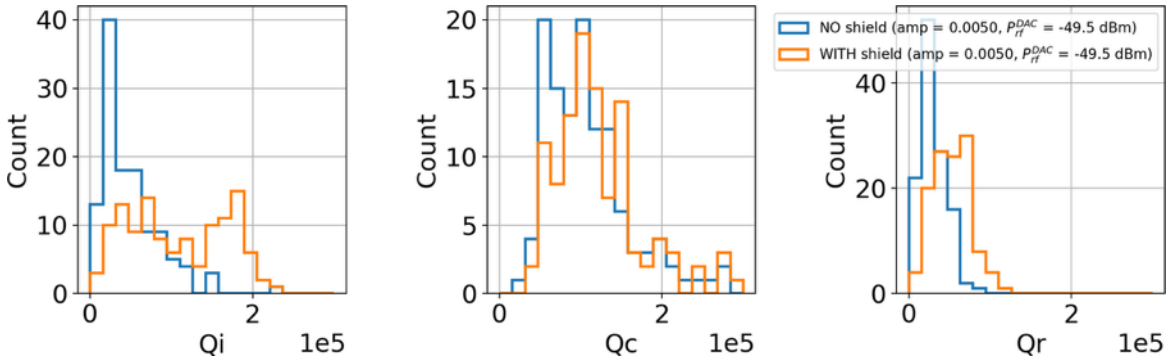


Bapat et al., IEEE Trans. Appl. Supercond. (in press, 2026), Fig. 4

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MAGNETIC SHIELDING FOR THE NEXT DEPLOYMENT

- Suspect lack of magnetic shielding reduced resonator quality factors, contributing to the measured resolution shortfall
- Tested a sub-module with a magnetic shield around cryostat: higher Qi with Qc largely unchanged
- New shield designed for the next deployment, with measured/design field-shielding factors:
  - Axial (+Y): 13 Transverse (+Z): 18 Transverse (+X): 29
- Shield has been manufactured and is ready for deployment



Sub-module quality factors with and without a magnetic shield placed around the cryostat



Manufactured shield designed to fit around the SPT-SLIM focal plan

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SUMMARY

- On-chip superconducting filterbank spectrometers enable large-format, high-channel-count LIM instruments like SPT-SLIM
- Fabrication R&D — low-loss dielectrics, hybrid Al/Nb leKIDs, process optimization — is directly traceable in on-sky spectral performance
- First deployment validated the architecture end-to-end; fabrication upgrades are already defined for the next deployment

2024–2025
first SPT-SLIM deployment at the South Pole

>1000
superconducting detectors in the SPT-SLIM array

R ≈ 100 → 65–70
design vs. measured on-sky spectral resolution

Thank you — questions?

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