Readout Preliminary Baseline Design Overview

Zeesh Ahmed (L2 scientist) for WBS 1.04

Plenary Session, Tuesday, March 9, 2021

Outline

- Readout Function and Scope
- Driving Requirements
- Architecture: Time-division multiplexing
- CMB-S4 implementation
- Design highlights
  - 100mK
  - 4K
  - 300K
- Optimization
- Workflow: Production/ Screening/ QA

12:30 → 14:00 **Readout: Parallel**

Conveners: Edward Young (SLAC; Stanford) , Dr Riccardo Gualtieri (Argonne National Laboratory)

Readout Notes

12:30 **Prototype design status**

Speaker: Dr Gunther Haller (SLAC)

Readout-System-De...

13:00 **Magnetic Shielding**

Speakers: Dr Alessandro Schillaci (Caltech) , Lorenzo Moncelsi (Caltech)

CMB-S4_March202... Magnetic Shielding

13:20 **SSA location (4K vs. 1K)**

Speaker: Darcy Barron (University of New Mexico)

13:40 **Warm electronics**

Speaker: Gunther Haller (SLAC)

Warm-Electronics-M...

Readout Functions and Scope

Functions:

1. Bias the Transition-Edge Sensor (TES) bolometers on their silicon wafers
2. Amplify measured signals
3. Sample/Digitize/Filter and hand off timestream to DAQ

Scope:

All the hardware and software elements that integrate/interface with the Modules, LAT, SAT and DAQ to provide above readout functionality

Driving Requirements

Requirement	Trace	Value	Origin	Validation
Supply electrical bias power appropriate to the TESs	MR 2.0, 3.0	Exact values are optimized for each observing frequency and telescope.	Flowdown from sensitivity requirements in each band.	1. Verify warm electronics DAC performance meets specifications. 2. Verify TES operation (with expected saturation powers) using prototype system.
Channel operability in operating instrument (readout-only)	MR 1.1, 1.2, 2.0, 3.0, 4.0	>=95%.	Flowdown from total instrument sensitivity requirements.	1. Screen components with interconnects. 2. Demonstration during prototyping that screening achieves yield requirement.
Noise equivalent current of readout at TES bolometer	MR 1.1, 1.2	<5% increase in total white noise level due to readout. 1/f shape & level TBD.	Flowdown from science requirements.	Measure noise power spectrum of integrated prototype readout system both open & with TES bolometers.
Crosstalk	MR 1.1, 1.2, 2.0	TBD from flowdown simulations.	Systematic error budget from instrument modeling and flowdown.	1. Measure inductor coupling in MUX chips (expected to be dominant) in prototypes. 2. Measure crosstalk in individual components. String test measurement in prototype system (no TESs).

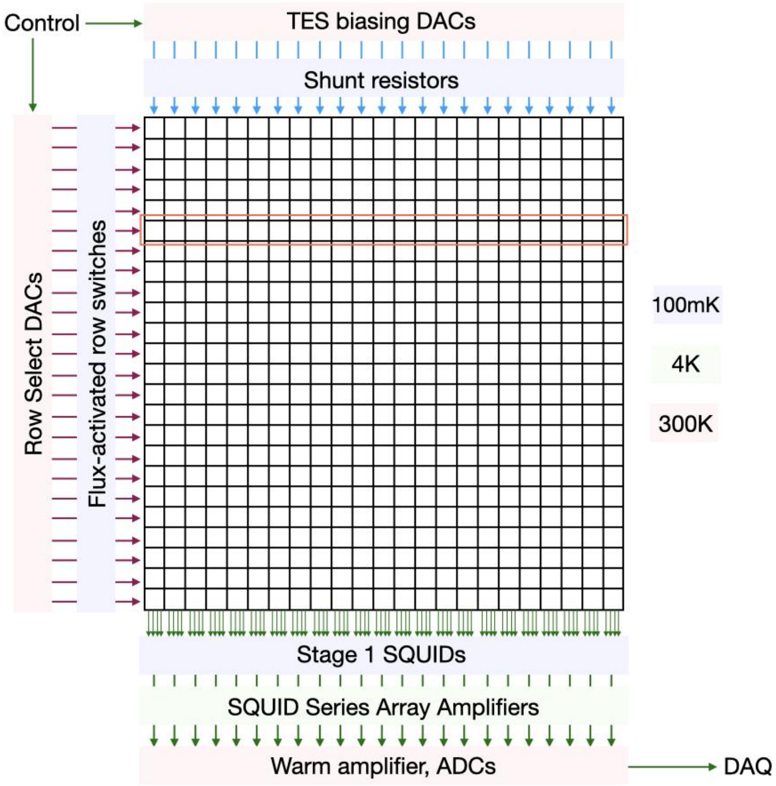
Architecture: Time-division multiplexing

- Arrange TESes of a detector wafer as a 2D logical grid
- Read one “row” at a time; switch at ~10s of kHz
- Connections to 300K scale as perimeter, not as area
- CMB-S4 will use ~64 “rows” (MUX64)

Uses *Superconducting Quantum Interference Devices* (SQUIDs) as cryogenic first- and second-stage amplifiers and as row switches. Microfabricated on silicon with superconducting materials.

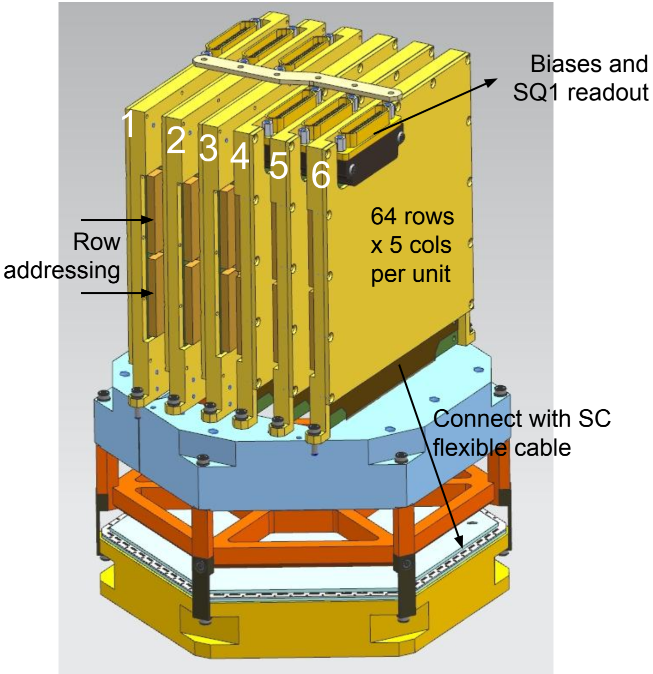
Room temperature electronics are simple, low-frequency boards with low-noise precision ADCs and DACs

TDM is a mature technology with heritage from Stage-2 and Stage-3 CMB experiments



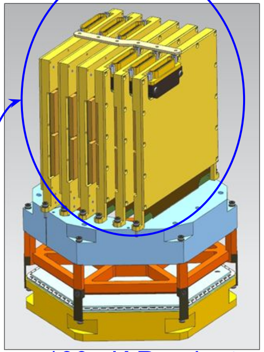
CMB-S4 implementation (1)

- Support up to 1920 TES readout per wafer
  - **1920 TES = 320 TES x 6 edges**
  - *Practical limit ~1872 TES (bonding interface)*
- One 100mK RO unit for each eafer edge
  - **320 TES = 5 columns x 64 rows**
  - 64 rows built using 6x 11-channel TDM SQUID multiplexer chips (6 usable for darks, diagnostics)
- *64 Row Addressing*
  - 64 row switches operated per module by row addressing pairs from *300K to 100mK*, daisy chained through 100mK RO units
- *5 Column Readout*
  - 5 columns' TES biases, SQUID bias and feedback carried from *300K to 100mK*
  - SQUID Array Amplifier per column at 1K or *4K*

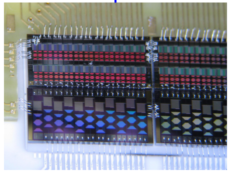


6x 100mK RO units attached to detector module. Each can service 300 TES in 64 row x 5 column configuration. *In development.*

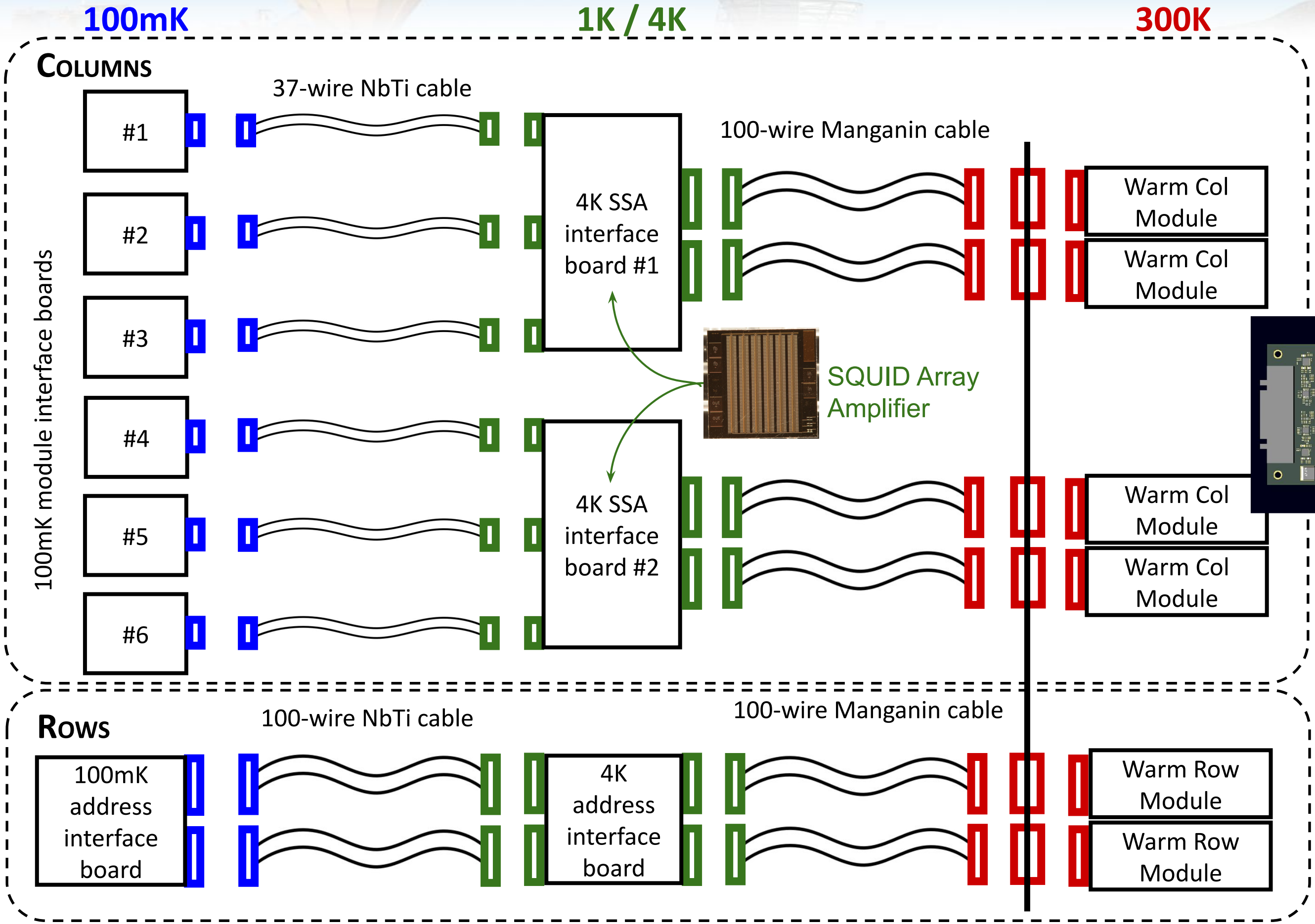
CMB-S4 implementation (2)



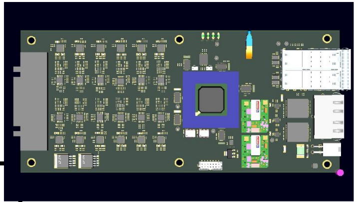
100mK Readout units on Detector module



SQUID multiplexer and TES bias chips



Cryogenic cabling

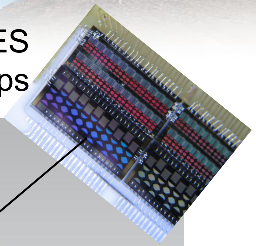


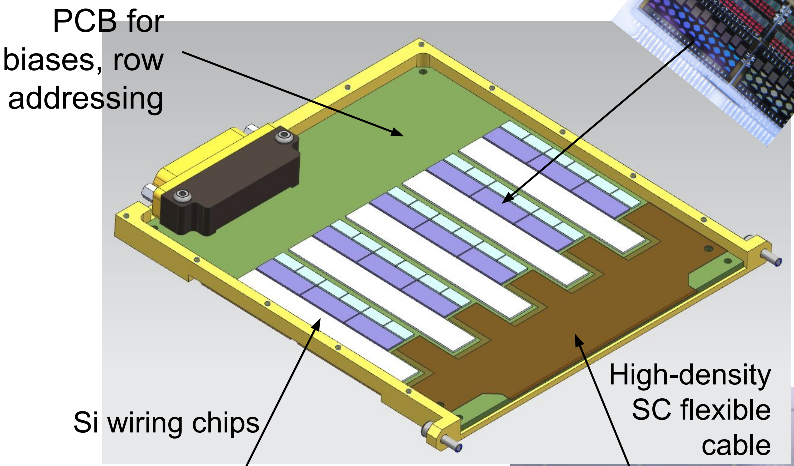
Warm electronics modules

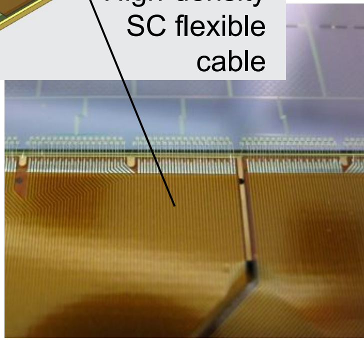
100mK: Technical Design (1)

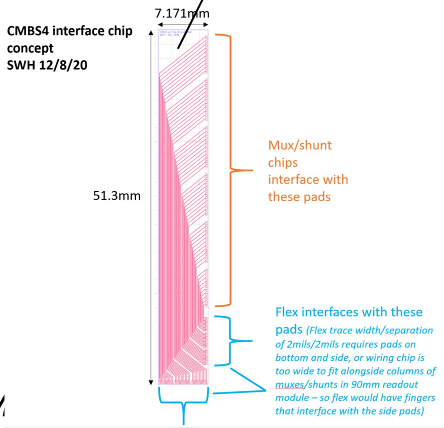
100mK Readout Units

- One per detector hex edge
  - 5 columns x 64 rows
- **Route signals** between detector wafers, 100mK silicon, cabling to 4K
- Provide **mechanical support** and **heat-sinking** for 100mK cryo silicon
- Shield 100mK readout hardware from **magnetic fields / EMI**
- Interface with **detector modules**, notably
  - Mechanical /thermal design
  - Bond pad pitch of readout -to-detector superconducting flex cable
- *Design status: In progress*









Anderson, Derylo, Haller, Henderson, Hilton, Moncelsi, Schillaci, Sapozhnikov, ...

100mK: Technical Design (2)

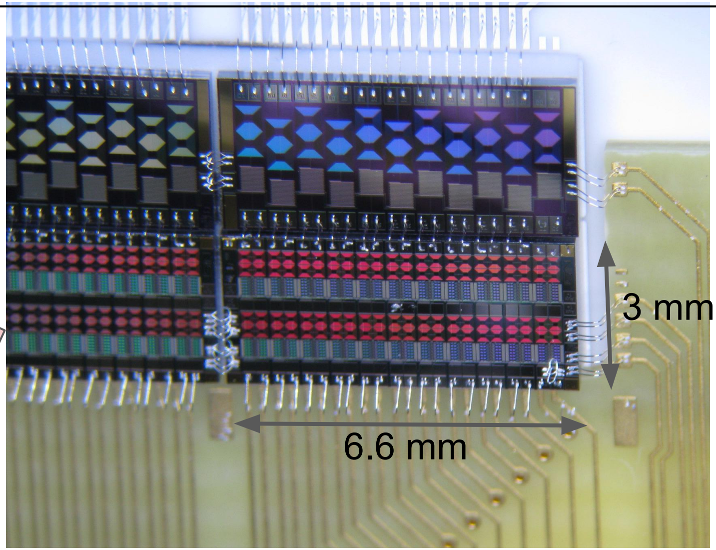
100mK TES Bias/interface/filter Chips

- Shunt resistors to voltage-bias TESs
- Nyquist inductors to control TES bandwidth
- Simple fabrication and tuning of components
- Efficient warm screening for continuity, witness cold screening for component tuning
- *Design status: Parameters need to be set, but but a mature design exists for protos*

100mK Multiplexer Chips

- First-stage SQUIDs to amplify TES currents
- Superconducting flux-activated switches to address rows
- *Design status: Parameters need to be set, but a mature design exists for protos*
- *Challenges include throughput for production*

***to TES wafer** via <u>superconducting</u> flex cable*



***Routing PCB**: Readout/biases per column, row-selects between columns*

Photo: BICEP / H. Hui, L. Moncelsi, A. Schillaci

4K: Technical Design

Photos: BICEP, ACT

4K SQUID Array Amplifier

- **Series array of SQUIDs** that amplifies signal for transmission to warm electronics. **One per column**
- Requires **magnetic shielding** to suppress environmental fields and gradients at chip location
- *Design status: Parameters need to be set, but a mature design exists for protos*

4K SAA Board

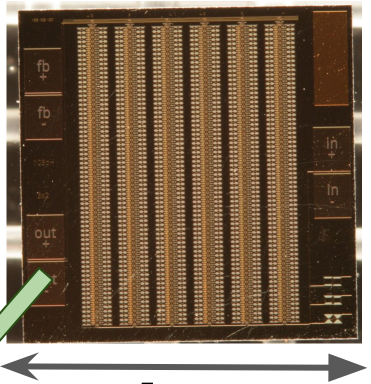
- Each set of 8 SAAs (on simple **carrier boards**) packaged in a single compact **shielded module.**
- Each **4K board** contains **16 SAAs**
- *Design status: In progress*

4K Mechanical Components

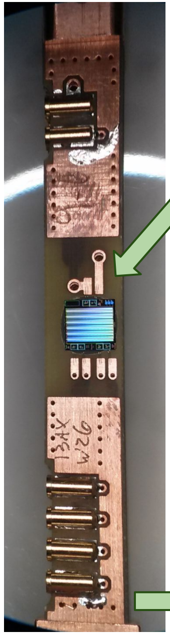
- Provides **shielding**, **mechanical** / **thermal** interfaces
- *Design status: In progress*

Open: 4K vs 1K. Some advantages to moving to 1K

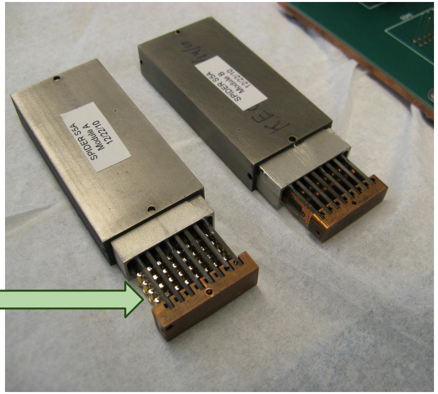
SQUID Array Amplifier



5 mm



SQUID Carrier Board



Example Magnetic Shielding

100mK & 4K Cables: Technical Design

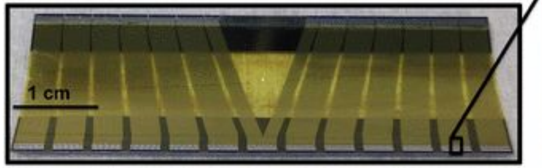
100mK Mux-to-Detector Flex Cable

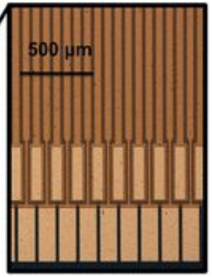
- **Superconducting** connection between detector wafer and Nyquist / Mux chips
- Dense **bond pad pitch** (interface to detector wafer). Currently set at 100um
- *Design status: Not started*
- *Challenges include yield at desired signal trace pitch*

100mK-4K Cable

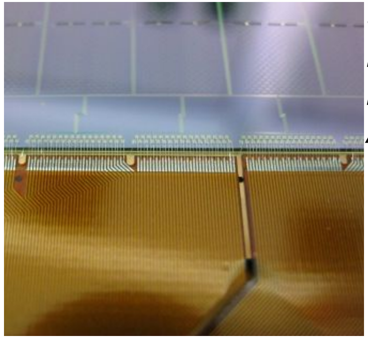
4K-300K Cable

- Route signals from detector wafer to warm electronics
- Commercial NbTi / Manganin twisted-pair loom cabling with standard connectors *(Tekdata, other vendors)*
- Strong **interface** constraints: lengths from LAT/SAT design, impedance limits from readout performance
- *Design status: Parameters need to be set, but but a mature design exists for protos*





AdvACT / C.G. Pappas+



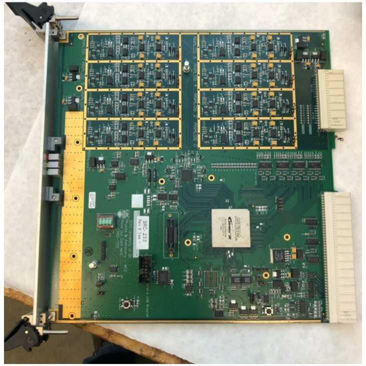
SPIDER / M.C. Runyan, L. Moncelsi A.D. Turner

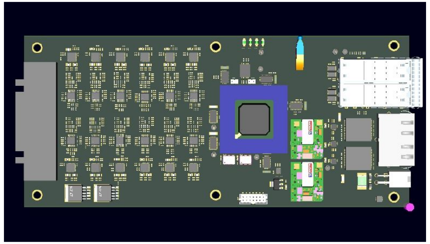
4K - 300K cable Manganin weave MDM-100 connector

300K: Technical Design

Legacy Readout Modules
UBC, Multi-Channel Electronics

~30cm





~12 x 25 cm CMB-S4 concept

Warm Readout Module Hardware & Firmware

- Row boards provide row addressing signals
- Column boards provide all other signal generation (SQUID and TES biases), filtering, preamplification, conditioning, and digitization.
- Firmware provides PID SQUID controller, data transmission, and a control interface for the hardware.
- *Design status: Not started*

Readout Software

- Software provides low- and high-level user control over the hardware and firmware, interfaces with DAQ and Control
- *Design status: Not started*

RO Parameter Optimization for CMB-S4

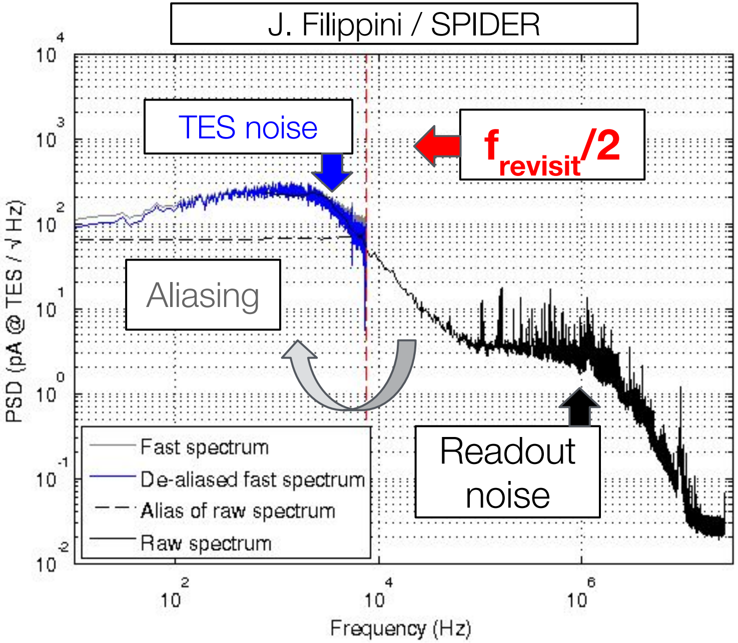
Optimization and **system engineering** across DRM (also SAT, LATR) can help ensure noise, bandwidth, stability reqs met

Readout noise equivalent power (**NEP**) set by:

- Detector resistance
- Mux chip SQUID design
- **Aliasing**, set by bandwidths below

TES noise bandwidth set by L/R time constant:

- Detector resistance
- Nyquist chip L, R
- Stray L, R from Detector, 100mK Readout, Module



Readout bandwidth set by impedances on two paths:

100mK SQUID - 4K SQUID

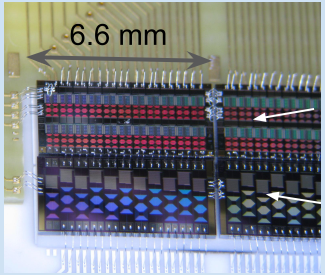
- Mux chip SQUID output impedance
- 4K SQUID amplifier input impedance
- Stray L, R from 100mK, 4K readout
- Cable lengths set by telescopes (LAT, SAT)

4K SQUID - Warm Electronics

- 4K SQUID amplifier output impedance
- Warm readout electronics
- Cable lengths set by telescopes (LAT, SAT)

Readout Deliverables Highlights

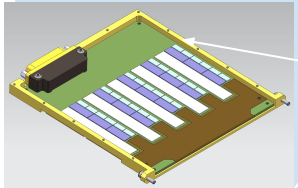
Cryo 100mK electronics

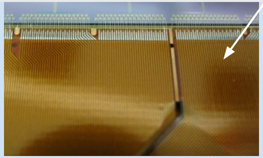


Si microfabrication, cryogenic testing

MUX chips (~55,000)

TES biasing chips (~55,000)

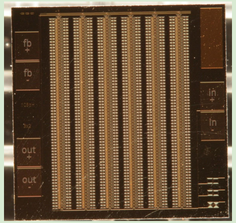




RO units and Superconducting flex cables (~3000 each)

Custom fabrication, commercial procurement

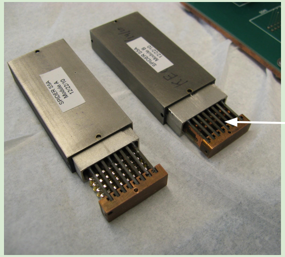
Cold 1K/4K electronics



5 mm

Si microfabrication, cryogenic testing

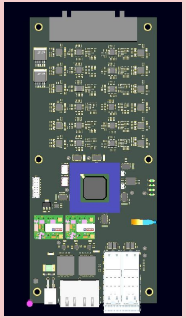
4K SQUID Array Amps (~8500)



Shielded modules

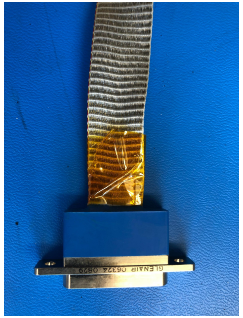
Carrier Board

Warm electronics



Custom fabrication, commercial procurement

Row boards (~1000)
Column boards (~1500)



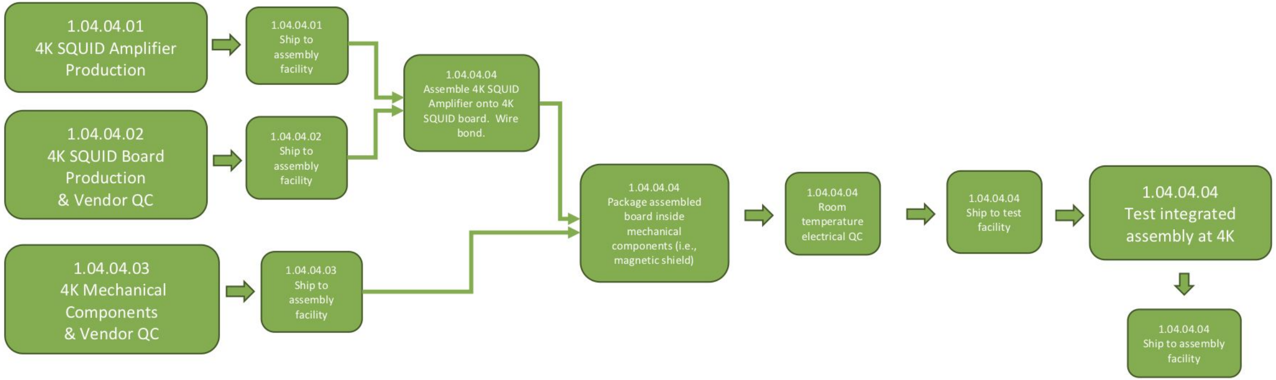
Custom fabrication, commercial procurement

100mK-to-4K cables,
4K-to-300K cables
(~1500 each)

Workflow: Production/ Screening/ QA

Although this TDM design has vast heritage in deployed instrumentation, much large number of parts to be fabricated, especially superconducting circuits on silicon. Design/planning involves:

- **Modular component designs to enable high-throughput workflow of fabrication, QA and delivery**
- Extensive in-process quality monitoring for microfab
- High-throughput screening of fabricated superconducting circuits at 4K in deployable packaging (100mK RO units, or 4K SAA modules)



CMB-S4

Summary/Conclusions

- CMB-S4 will implement DC voltage biasing and time-division multiplexed readout of its TES bolometers
- We have an implementation concept, some mature designs and preliminary parameters to use for prototyping based on Stage-2 and Stage-3 experience
- Engineering design for preliminary baseline has commenced where possible with limited resources, although mostly outstanding.
- Incorporating design features for ease of production, screening, QA
- DRM parameter optimization and system engineering can help avoid missed requirements. Ultimately, validation of design will come from testing the performance of prototypes.

Backup slides

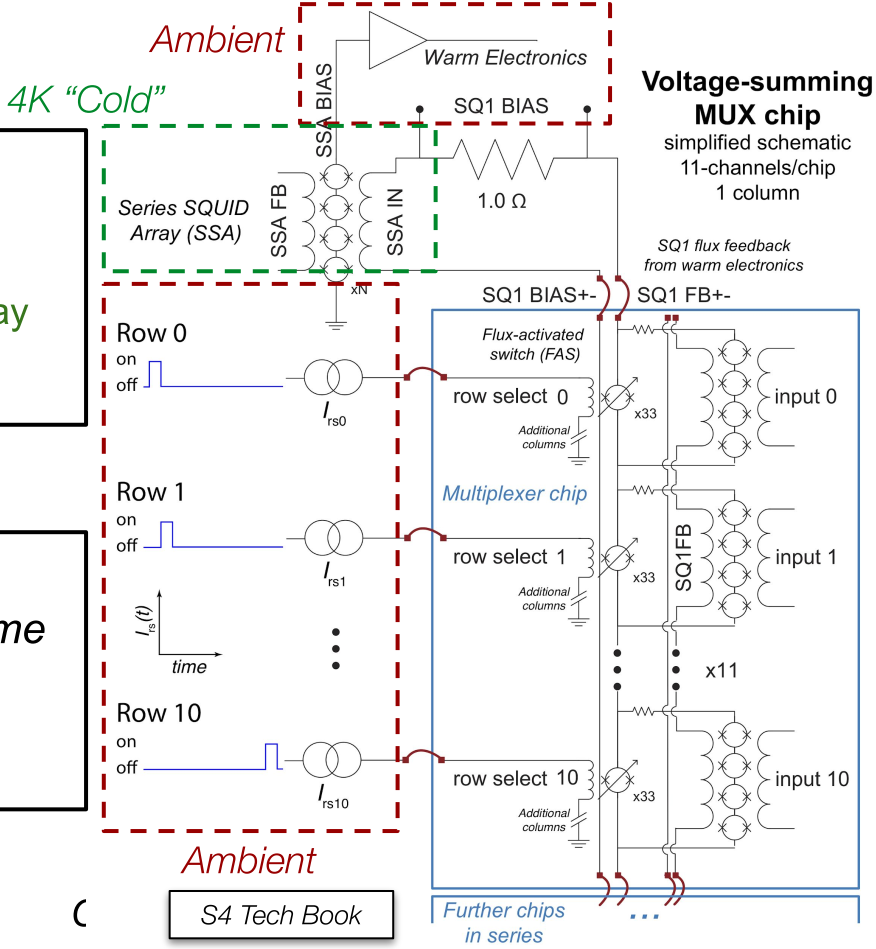
Amplify TES signals

- 100mK SQUID
  One per TES
- 4K Series SQUID Array
  One per column

Switch among TESs

Read rows one at a time

- Josephson junction switches
  One per TES



S4 Tech Book

Sample TES signals

Control readout system

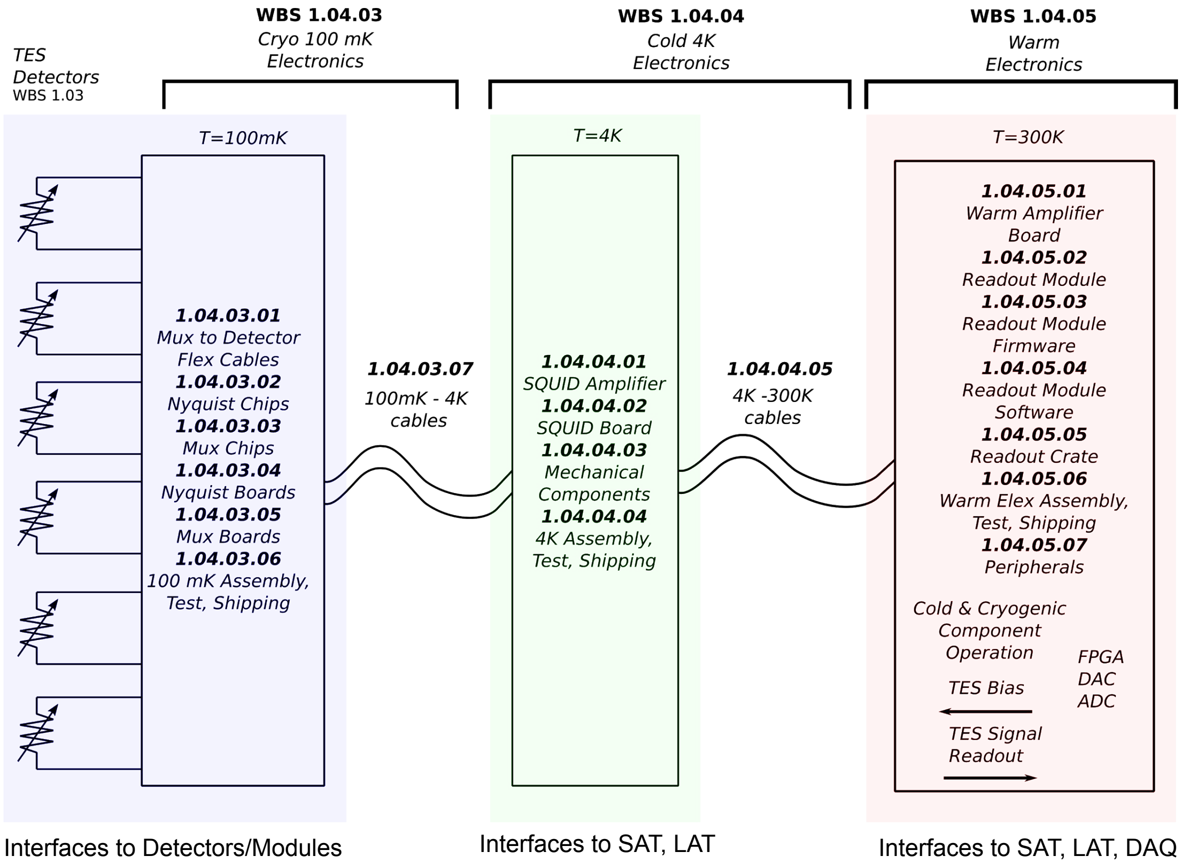
- ADCs, DACs
- Real-time filtering
- Interface to DAQ

Supply stable **voltage bias** to each TES

- Parallel shunt resistor
- Bandwidth-limiting inductor

More detail available in the CMB-S4 Readout Assessment materials and backup

CMB-S4: Time-division multiplexing



Interfaces to other L2

Driving Interface Highlights

- Detectors:
  - Electrical connection via wire-bonds
- Modules
  - Mechanical/shielding packaging of 100 mK Cryo into detector module
  - Thermal power dissipation
- LAT/SAT
  - Mechanical volumes for 4K Cold inside cryostats & 300K Warm outside
  - Electrical effects of cable run lengths
  - Thermal interfaces with cryogenic system
- DAQ
  - Electrical connections to DAQ data ethernet
  - Software/control/telemetry connection to observatory control system in DAQ

WBS 1.03 Detectors	WBS 1.04 Readout	WBS 1.05 Module Assembly & Testing	WBS 1.06 Large Aperture Telescopes	WBS 1.07 Small Aperture Telescopes	WBS 1.08 Data Acquisition and Control	WBS 1.09 Data Management	WBS 1.10 Chile Site Infrastructure	WBS 1.11 South Pole Site Infrastructure	WBS 1.12 Integration & Commissioning	L2 Element
	E, T (339)	M, E, T (463)								WBS 1.03 Detectors
		M, E, T (321)	M, E, T (318)	M, E, T (354)	E (324)					WBS 1.04 Readout
			M, T, O (345)	M, T, O (342)					M, E, T (447)	WBS 1.05 Module Assembly & Testing
					M, E, T (333)		M, E, T (336)	M, E, T (330)	M, E, T (435)	WBS 1.06 Large Aperture Telescopes
					M, E (351)			M, E, T (348)	M, E, T (411)	WBS 1.07 Small Aperture Telescopes
						E (327)	M, E, T (417)	M, E, T (423)	M, E, T (444)	WBS 1.08 Data Acquisition and Control
							M, E, T (426)	M, E, T (432)	M, E, T (441)	WBS 1.09 Data Management
									M, E, T (450)	WBS 1.10 Chile Site Infrastructure
									M, E, T (453)	WBS 1.11 South Pole Site Infrastructure
										WBS 1.12 Integration & Commissioning

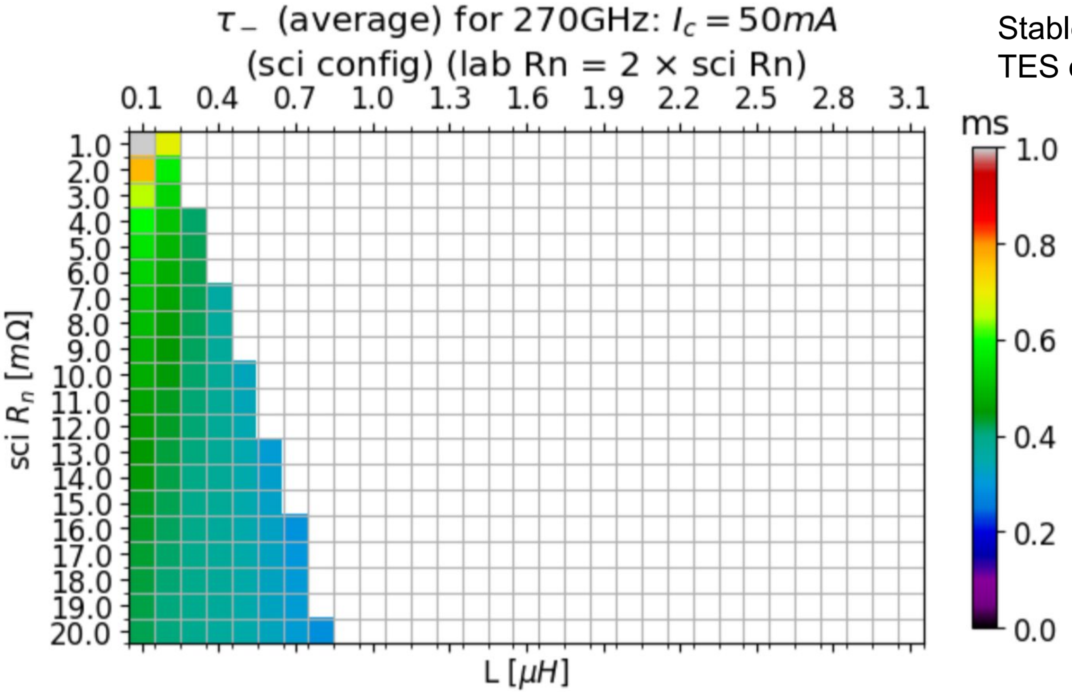
Interface type	
M	mechanical
E	electrical, data, control, telemetry
T	thermal
O	optical

(Number) in cell indicates docdb document number

Numbers in table above are **DocDB ids.**

Ongoing refinement of associated specifications/levels before CD1.

DRM parameter optimization example



Normal resistance

Total inductance in bias circuit

Stable, overdamped TES operation

Osherson, Filippini