Design and Performance of the SPT3G First-year Focal Plane

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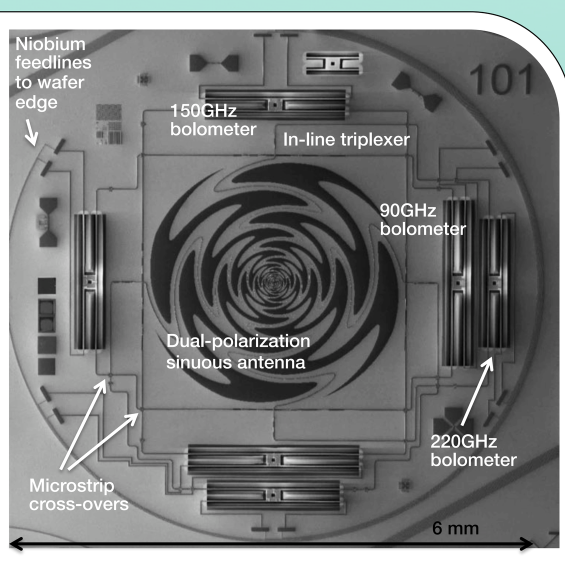
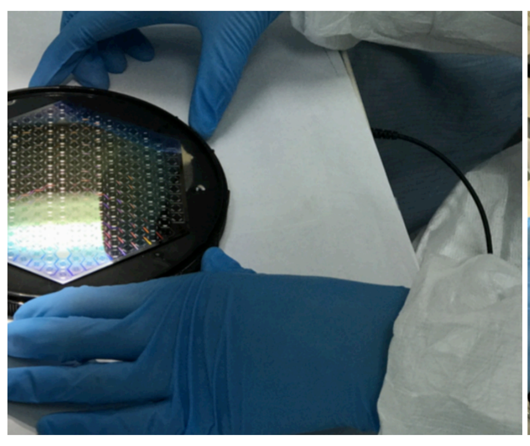
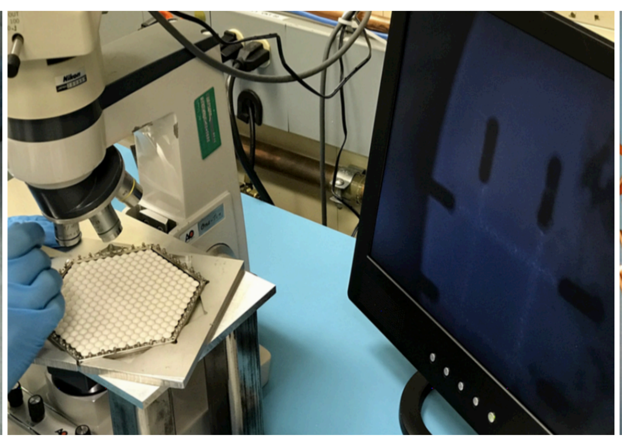
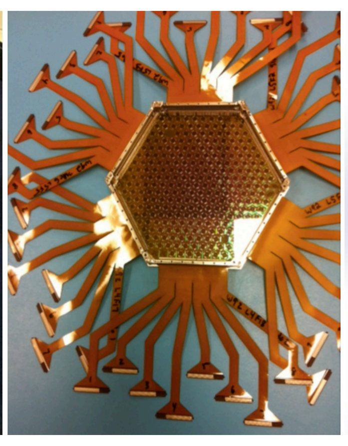
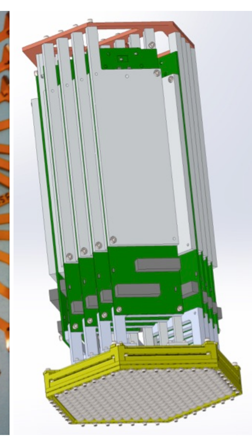
SPT3G detector overview

- The South Pole Telescope third-generation camera (SPT3G) is designed to map polarization of the Cosmic Microwave Background with ~16,000 detectors, an order of magnitude increase relative to the previous generation instrument.
- SPT3G camera contains ten 6"-hexagonal modules, each with 271 pixels.
- Each pixel includes a broad-band, polarization-sensitive sinuous antenna coupled to the sky via a hemispherical AR-coated alumina lenslet and six transition-edge-sensor (TES) bolometers which measure two linear polarizations in three frequency bands centered around 95, 150, and 220 GHz.
- Nb microstrip feedlines couple the antenna to the bolometers with in-line quasi-lumped-element triplexer filters to define the bandpasses.
- Sky signal from each antenna is terminated on a thermally-isolated island of low-stress silicon nitride suspended by four thin legs.
- Sky radiation is converted to heat in a Ti-Au load resistor and the rise in temperature is measured by a voltage-biased Ti-Au bi- or quadlayer TES detector.
- The bath temperature of the millikelvin stage is maintained at ~300mK, below the superconducting transition temperature of the bolometers.
- Response from each detector is traced to bond pads at the edge of the wafer via 5μm-wide niobium microstrip.
- Wirebonds to kapton and niobium flex cables link each wafer to the cold readout electronics mounted on the backside of each module.



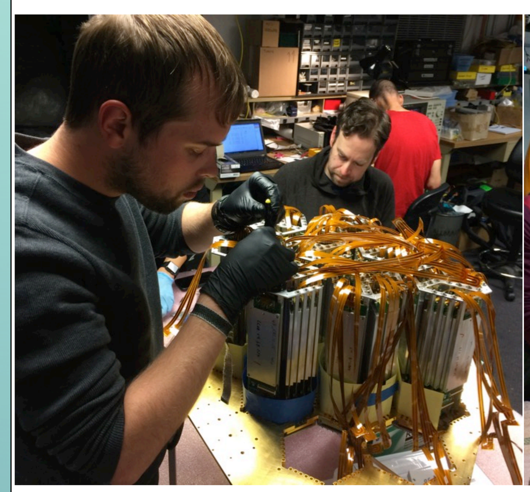
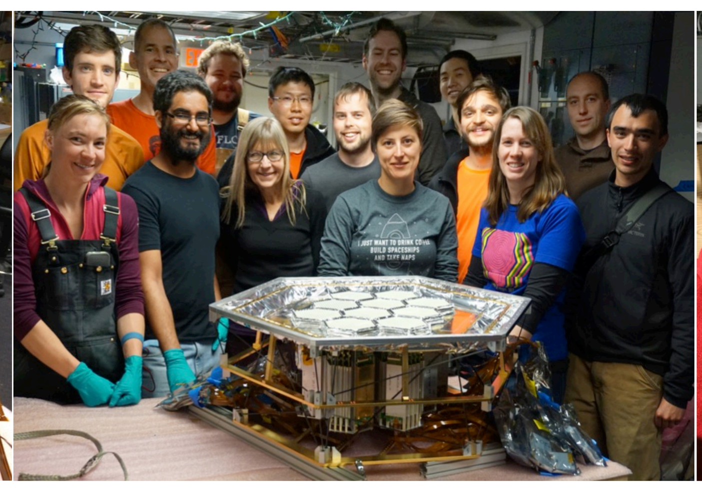
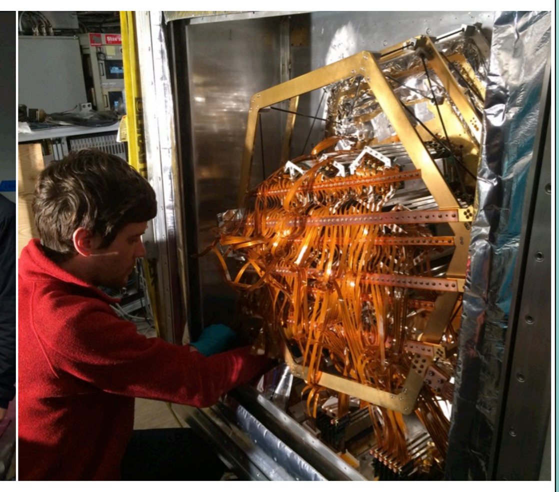
Module assembly

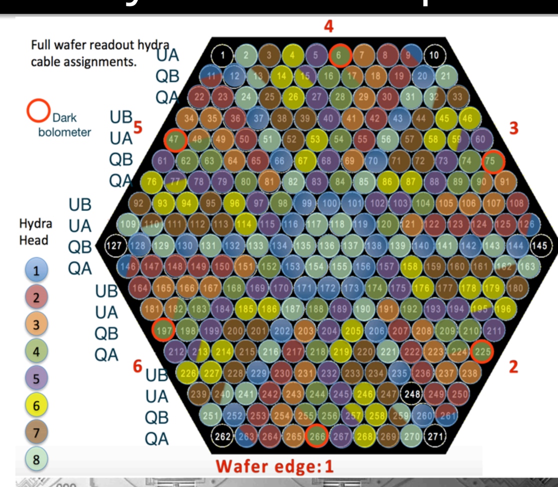
- Each of the ten modules is made up of a silicon detector wafer, a silicon lenslet wafer with one beam-defining alumina lenslet per pixel, an invar support frame to maintain alignment between the two wafers and mount each module in the millikelvin stage, 6 hydra-head flex cables, and 12 LC towers containing the cold readout electronics.
- To assemble each module:
  - An infrared microscope is used to match alignment marks between the detector and lenslet wafers
  - Flex cables are glued in place and deep-access automatic wire-bonding is used to electrically connect the detector wafer to the flex cables leading to the cold readout electronics
  - LC board towers are mounted to the back of each invar holder assembly

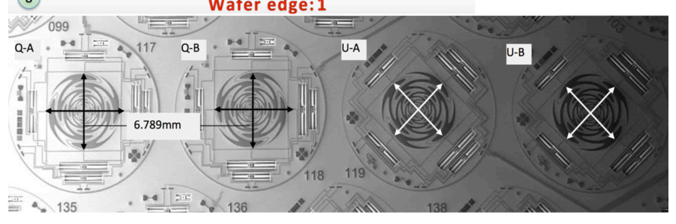
SPT3G focal plane assembly

During the austral summer of 2016-17, the SPT3G receiver was assembled and installed on the SPT. Below, (left) Daniel Dutcher works on attaching wafer modules to the gold-plated millikelvin stage, (middle) members of the detector team gather around the full-assembled focal plane, (right) Adam Anderson routes readout striplines from the modules to the readout amplifier SQUID cards mounted in the cryostat at 4K.

First-year focal plane layout

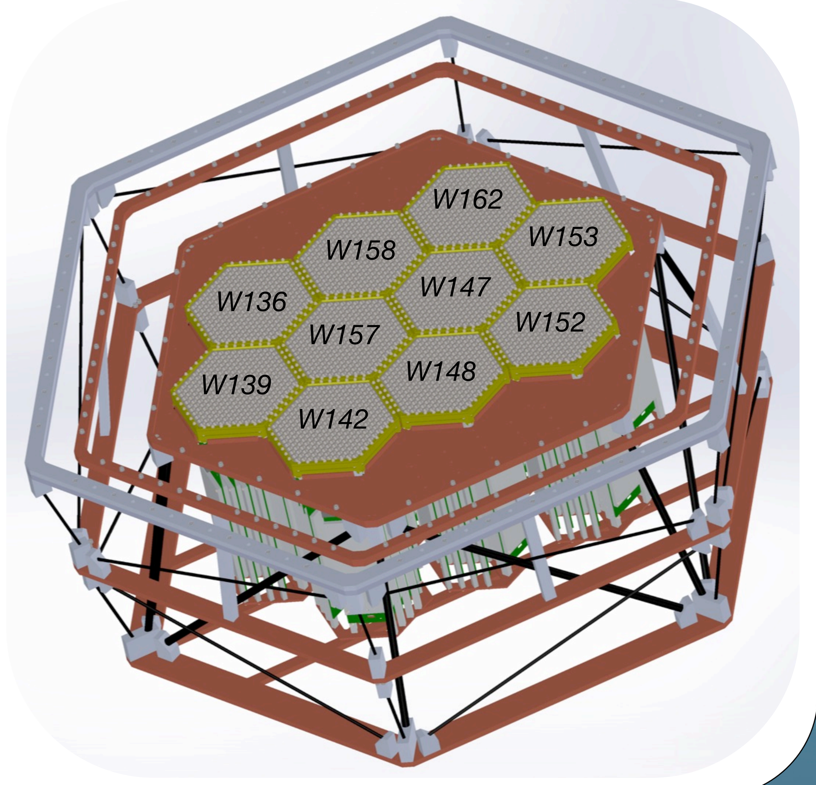




- Each detector wafer is made up of four distinct types of pixels: QA, QB, UA, UB.
- To evenly sample the linear polarization of the incoming CMB radiation, each detector wafer is populated with pairs of pixels where the sinuous antennae are clocked at 45° relative to each other, measuring Stokes Q and U parameters.
- Slight polarization wobble is accounted for by populating the wafer with left- and right-handed versions of the antenna[1,2].
- To disentangle the optical properties of the pixel from the non-optical electrothermal characteristics, six "dark" pixels are placed on each wafer, where the microstrip connection between the antenna and bolometer island is broken.

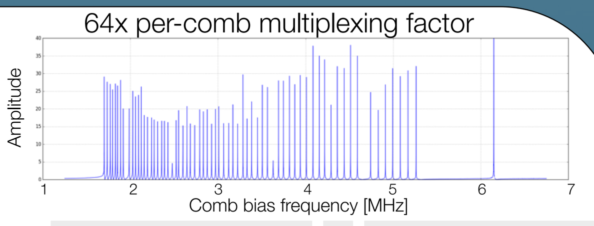
Wafer Characteristics Overview

Wafer	TES thickness Ti/Au [nm]	Wirebonding yield	Final hardware yield
136	200/30	0.88	0.54
139	200/30	0.89	0.77
142	5/5/200/20	0.89	0.84
147	5/5/200/20	0.89	0.75
148	5/5/200/20	0.91	0.79
152	5/5/160/20	0.91	0.79
153	5/5/160/20	0.88	0.81
157	5/5/175/20	0.88	0.87
158	5/5/175/20	0.88	0.82
162	5/5/160/20	0.83	0.77



Cold readout

- Frequency-domain multiplexing (fMUX) is used to read out the ~1600 detectors per module to avoid undue heat load on the mK stage.
- Each bolometer is connected in a series-resonant RLC circuit, C is varied to determine the resonant frequency, ω.
- A comb of sine-wave voltage bias carriers tuned to each bolometers' ω is supplied and all comb channels are summed along a single set of wires.
- Voltage oscillates much faster than TES response time, so the bolometer sees an integrated voltage bias.



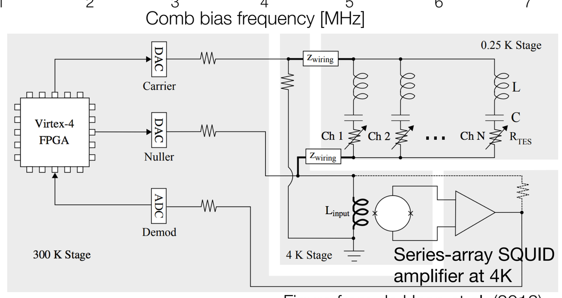
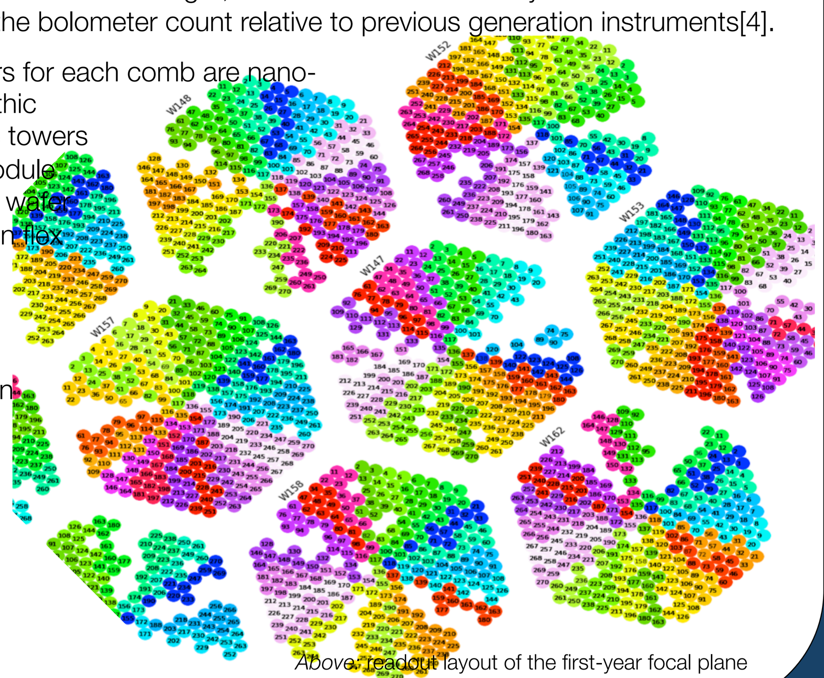


Figure from de Haan et al. (2012)

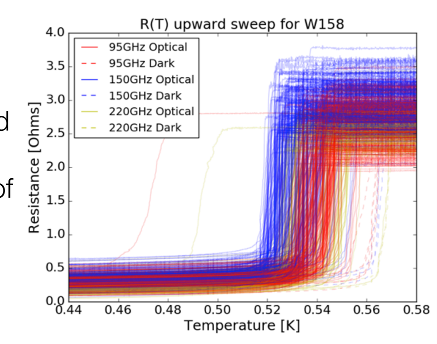
- To improve linearity and dynamic range of the SQUID, operate SQUIDs under feedback, supplied an identical but inverted sine wave "nuller" set relative to the carrier comb[3].
- For SPT3G we employ Digital Active Nulling (DAN), where the nuller signal actively cancels the current running through the SQUID in a bandwidth centered around each bolometers' resonance[4], a change from previous generations' static amplitude nulling.
- DAN allows for higher multiplexing factors, improved stability, and relaxed restrictions on stray inductance and therefore wire length, all of which are necessary for SPT3G's order-of-magnitude increase in the bolometer count relative to previous generation instruments[4].
- Inductors and capacitors for each comb are nano-lithographed on monolithic chips mounted on PCB towers on the back of each module and connected to each wafer with niobium and kapton flex cables.
- 24 individual LC chips are used to read out each module, resulting in 12 LC towers per module (one chip per side on each tower), allowing for the readout of 1536 bolometers per module.

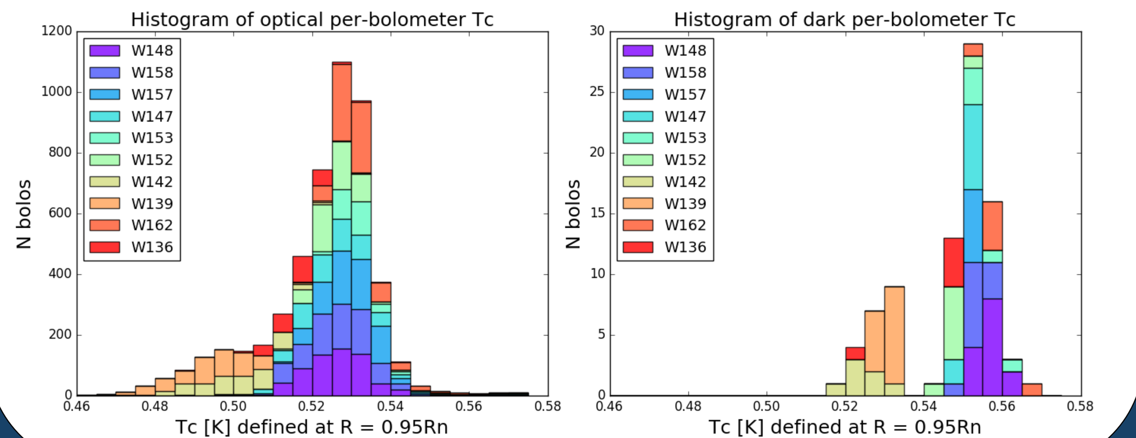


Above: readout layout of the first-year focal plane where color per-wafer shows comb assignment

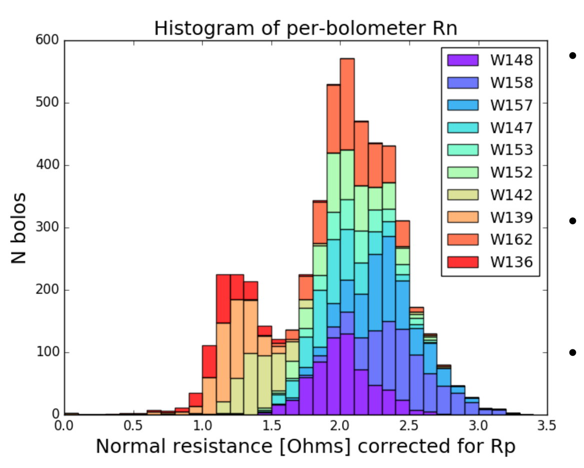
TES critical temperature

- Tc measured in situ on the SPT3G instrument to characterize uniformity and yield.
- Millikelvin stage temperature is swept slowly from above the bolometer critical temperature to below and back, while applying a very small voltage to the detectors and measuring the current response.
- Hysteresis of ~20mK is seen in the measured transitions between downward and upward sweeps due to thermal mass of the mK stage. We define the critical temperature as the temperature where each detector reaches a depth of 0.95*Rn in the transition, where Rn is the detector's normal resistance.
- Averaging the results for the downward and upward sweeps per bolometer, histograms of Tc measurements are shown below for optical and dark bolometers grouped by wafer.
- Tc is determined in fabrication by the TES geometry and design, the addition of Pd normal metal on the TES island, as well as other effects such as heat-treatment of the wafers during fabrication.
- Tc across the focal plane are quite uniform in the range 490-540mK. Due to differences in TES geometry and fabrication processes for SPT3G wafers, we expect some variation in Tc across wafers in the first-year focal plane.
- Optical power on the detectors will drive the measured Tc to lower values, consistent with the differences in average Tc for optically-coupled bolometers relative to dark, as shown below.



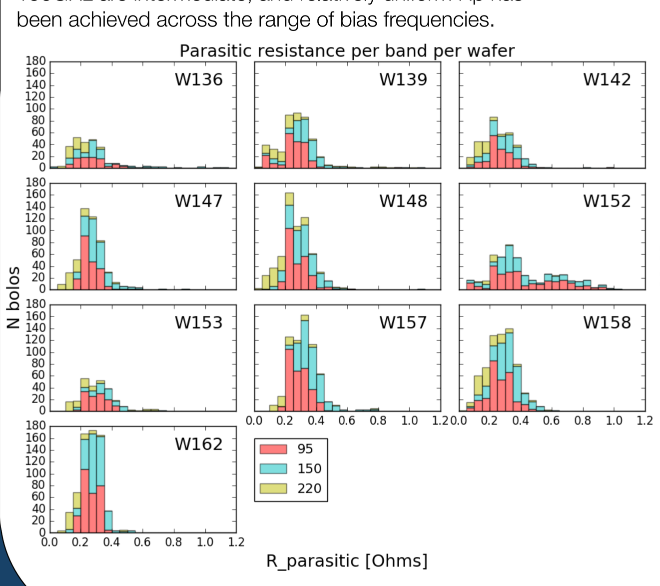


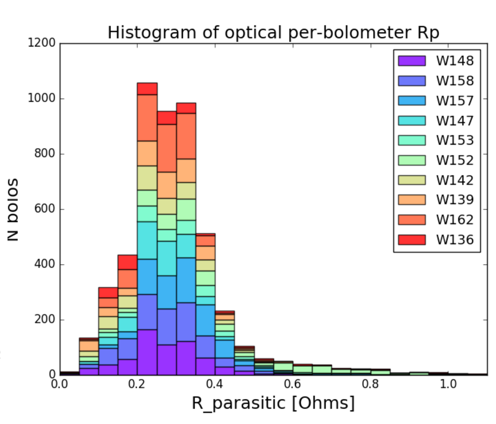
TES normal resistance



- From R(T) sweeps, bolometer resistance above the transition (Rn) can be measured.
- Rn is determined by the TES geometry and design and affects the response time constant for each detector in its readout circuit, and therefore the bolometer readout stability.
- Target values are Rn ~ 2 Ohms to provide appropriate in-transition resistance to the bolometer circuit.
- Parasitic resistance of the bolometer circuit, the residual resistance measured when the bolometer is below Tc can also be extracted for R(T) measurements.
- The parasitic resistance results from any non-superconducting elements in the bolometer circuit, which could be on the bolometer island or elsewhere in circuit, such as in the readout electronics.
- Measurements of Rp are used to correct measured saturation powers and Rn

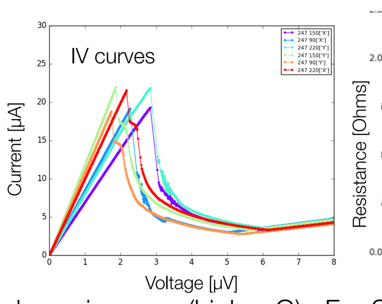
Below: Parasitic resistance colored by frequency band per wafer. Bolometers are ordered in readout bias frequency by observing band such that all 90GHz bolometers have the lowest bias frequencies, 220GHz have the highest and 150GHz are intermediate, and relatively uniform Rp has been achieved across the range of bias frequencies.

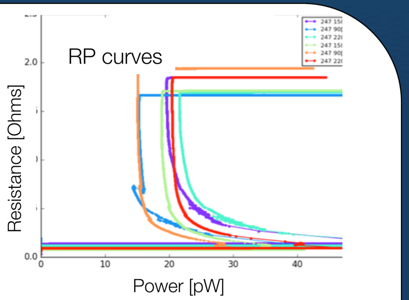




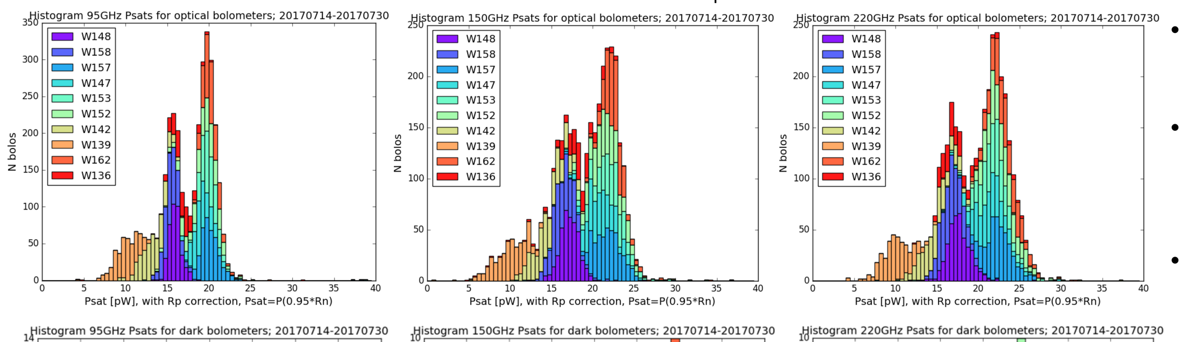
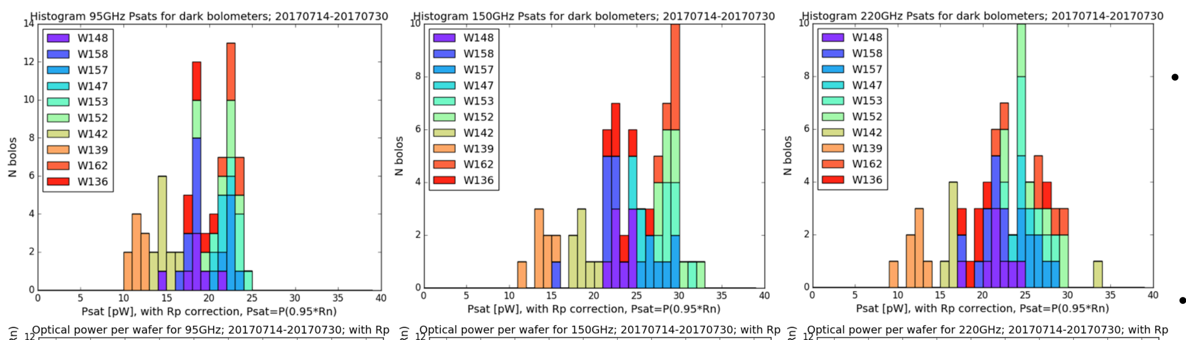
TES Saturation Power

- Bolometers are operated in an electrothermal circuit where power is provided by optical power from the sky and electrical voltage bias.
- The total power on the bolometer island flows to the bath via four thin silicon-nitride legs with thermal conductance G, such that $P_{tot} = P_{optical} + P_{elec} = \bar{G}(T_c - T_{bath})$.

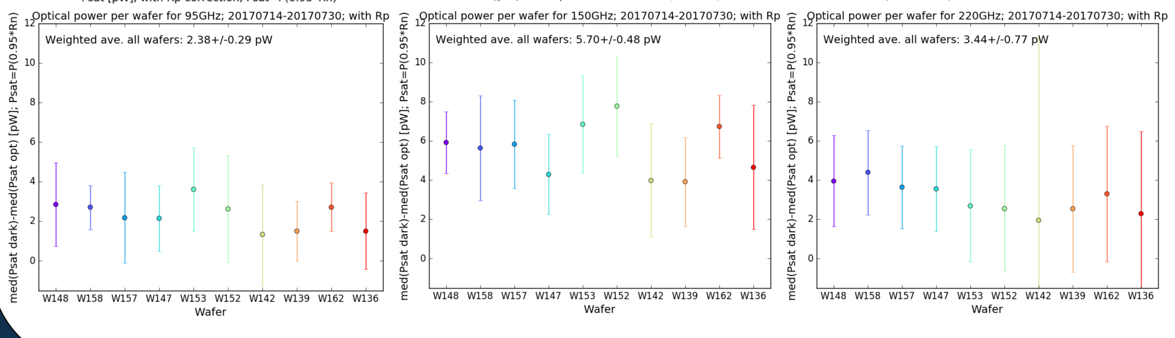




- G is chosen such as to balance lower noise (lower G) with high dynamic range (higher G). For SPT3G, we choose G such that $P_{tot} \gtrsim 2P_{optical}$ so that we can operate the circuit under high electrothermal feedback[3].
- Electrical voltage bias is supplied to the bolometer to hold it in the steep part of the R(T) transition, providing for strong electrothermal feedback (ETF): incoming radiation heats the bolometer, it's resistance increases, causing the electrical power $P_{elec} = V_{bias}^2/R_{bolo}$ to decrease, and the total power on the detector to remain constant[3].
- IV curves are measured to determine minimum electrical power needed to hold the bolometer normal, P_{sat}

- *Left:* P_{sat} data aggregated over full-array tunings in second-half of July 2017.
- Optical power contributes to the total power on the detector, reducing the measured P_{sat}.
- Target dark P_{sat}s are 10.2, 15.4, and 20.0 pW for 95, 150, and 220 GHz, respectively.
- Comparisons of P_{sat} for dark and optical detectors yields a measurement of the optical loading on the bolometers.



- *Left:* Optical loading calculated as median(dark P_{sat}) – median(optical P_{sat}).
- Agree moderately well but underestimate predictions of 4.4, 7.1, and 8.4 pW for 95, 150, and 220GHz, respectively.
- Places limits on internal loading modulo bolo optical efficiency

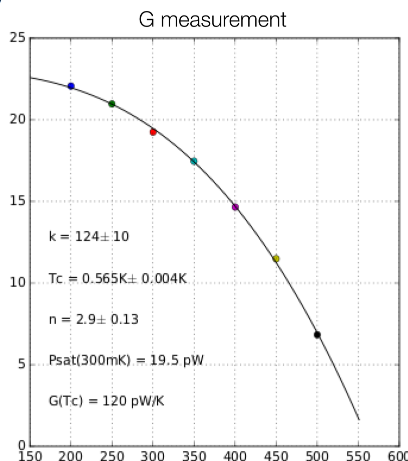
Loopgain

- Loopgain measures the strength of electrothermal feedback in the bolometer circuit:

$$L = \frac{\alpha P_{elec}}{G T_{bolo}}$$

where $\alpha = \frac{d\log(R_{bolo})}{d\log(T_{bolo})}$

- High loopgain is desirable for linearizing detector response and optimizing dynamic range, but must be coordinated with stability constraints on detector thermal time constants from each bolometer's electrical (readout) time constant.

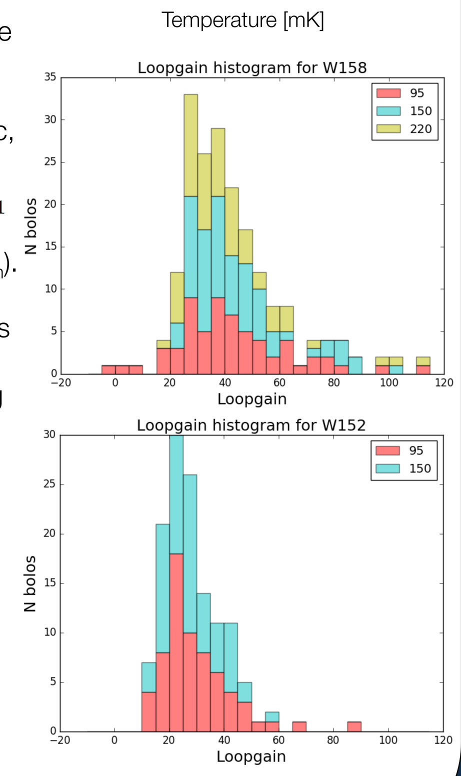


- To measure G, we take repeated IV curves at different thermal bath temperatures below Tc, and fit

$$G(T) \equiv \frac{\partial P}{\partial T} = nkT^{n-1}$$

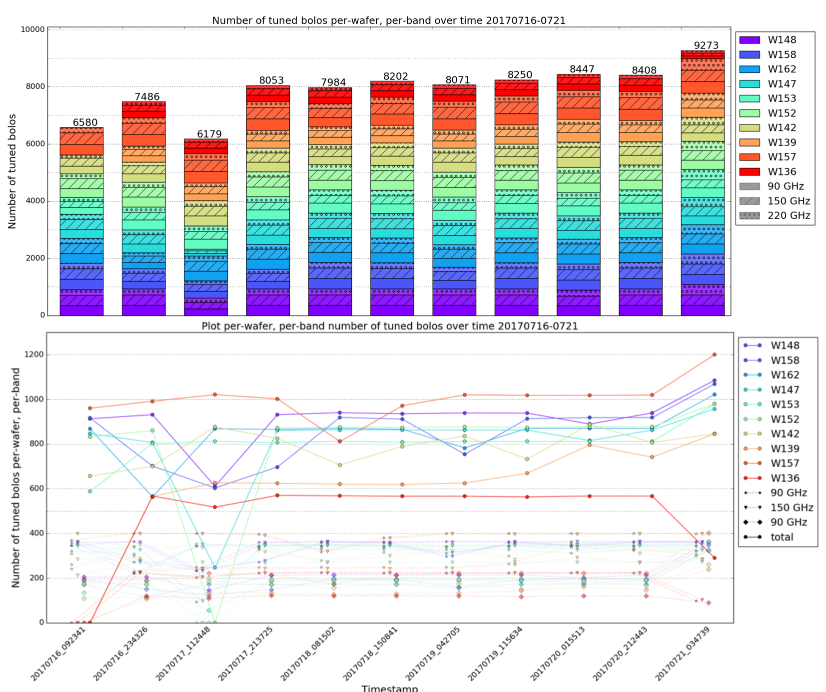
to the curve of $P_{sat}(T_{bath})$.

- *Right:* Loopgain results shown for two deployed wafers using testing data prior to deployment.
- Loopgain for SPT3G bolometers is higher relative to previous generations of SPT detectors owing to steep R(T) transition profiles.

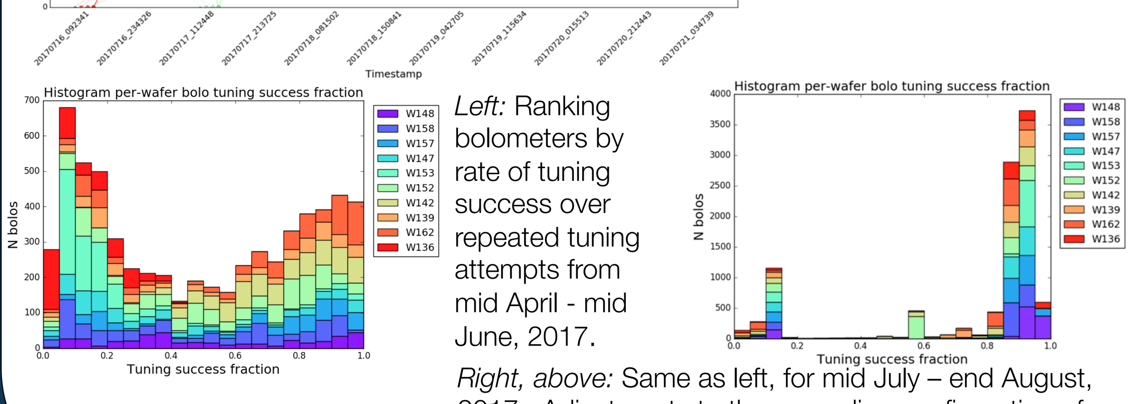


Yield

- 80% tuning yield has been demonstrated so far in 2017 and efforts at maintaining high daily yield are ongoing



Left: Per-band and per-wafer number of bolometers successfully tuned over repeated tuning attempts through July 2017.



Left: Ranking bolometers by rate of tuning success over repeated tuning attempts from mid April - mid June, 2017.

Right, above: Same as left, for mid July – end August, 2017. Adjustments to the grounding configuration of the warm readout electronics made substantial improvements in yield and tuning repeatability.

References and Acknowledgements

[1] C.M. Posada and S. Padin et al. (2015), Fabrication of Large Dual-polarized Multichroic TES Bolometer Arrays for CMB Measurements with the SPT-3G Camera. Superconductor Science and Technology, 28 (9) No. 094002
[2] A. Suzuki (2013), Multichroic Bolometric Detector Architecture for Cosmic Microwave Background Polarimetry Experiments. PhD thesis.
[3] M.A. Dobbs et al. (2012), Frequency multiplexed superconducting quantum interference device readout of large bolometer arrays for cosmic microwave background measurements. arXiv:1112.4215v2
[4] T. de Haan, G. Smecher, and M. Dobbs (2012), Improved Performance of TES Bolometers using Digital Feedback. arXiv:1210.4967

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