Towards Photon Counting Kinetic Inductance Detectors for Far-IR Spectroscopy

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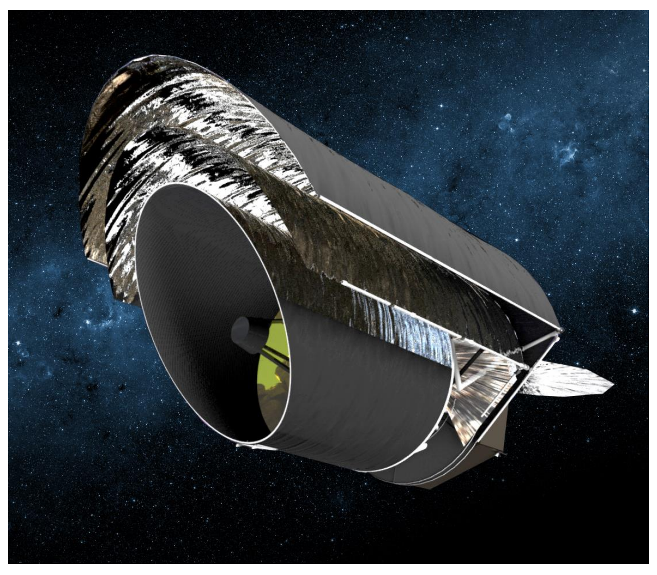
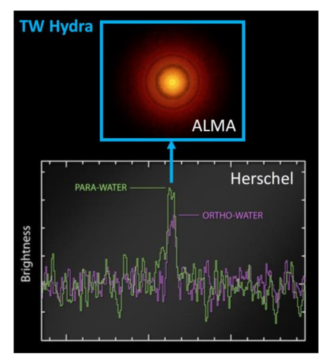
Why Photon Counting Detectors?

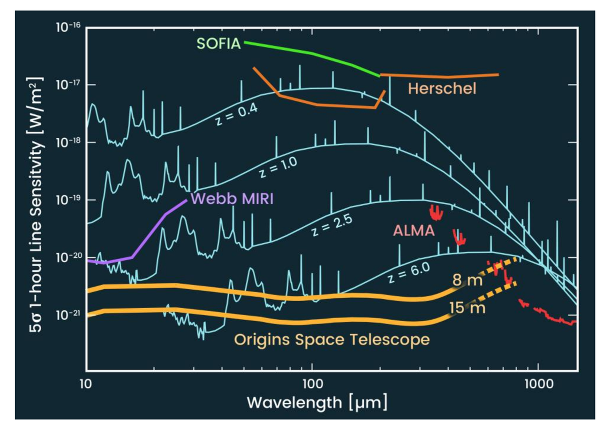
Photon-counting detectors are an enabling technology for future space-based far-infrared spectroscopic instruments such as those proposed as part of the Origins Space Telescope (OST) and would greatly increase the sensitivity and mapping speed of such instruments. Microwave kinetic inductance detectors (KID) are a promising technology for these instruments, where large arrays of detectors with noise equivalent powers (NEP) less than 3×10^{-20} W/Hz$^{-1/2}$ will be required to achieve photon-noise background limited performance. In contrast to superconducting transition edge sensors (TES), KIDs are naturally frequency multiplexed allowing for the simple readout of large arrays, but a factor of nearly ten improvement in NEP is needed to meet the needs of future space-based spectrometers. Our project seeks to develop KID technology and achieve NEPs suitable for future space missions through the use of a novel lumped element KID design with optical coupling implemented at 850GHz. Utilizing ultra-low volume Al inductors to increase responsivity and photonically-choked NbTiN parallel plate capacitors on single crystal silicon to minimize interface defect-driven two-level system (TLS) noise, our design seeks to approach the photon counting limit, where detector baseline calibration is obviated and full duty-cycle observation can be achieved. We are currently studying both NbTiN and Al deposition parameters to achieve films with low TLS densities and high internal quality factors, while simultaneously developing low-defect compatible fabrication processes and an ultra-low background measurement facility with an integrated cryogenic blackbody calibrator to characterize our high sensitivity devices.

OST Mission Concept

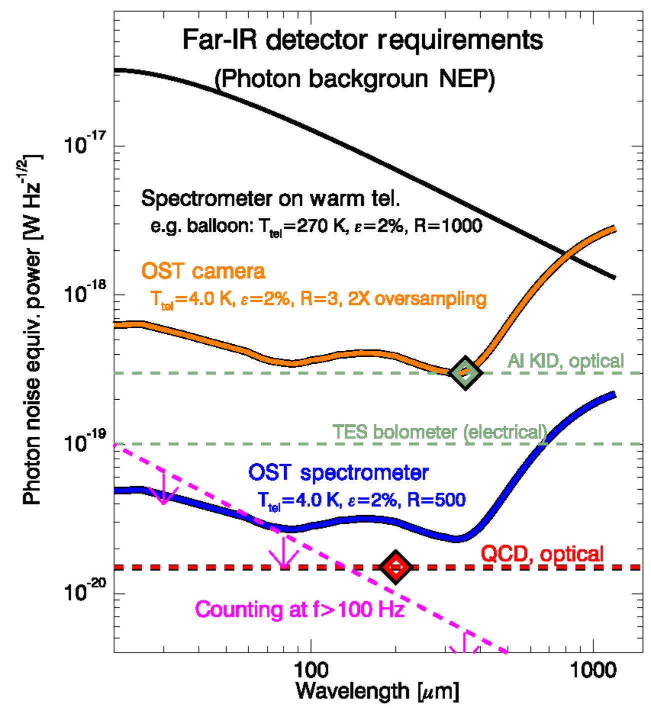


Far-IR Spectroscopy Science

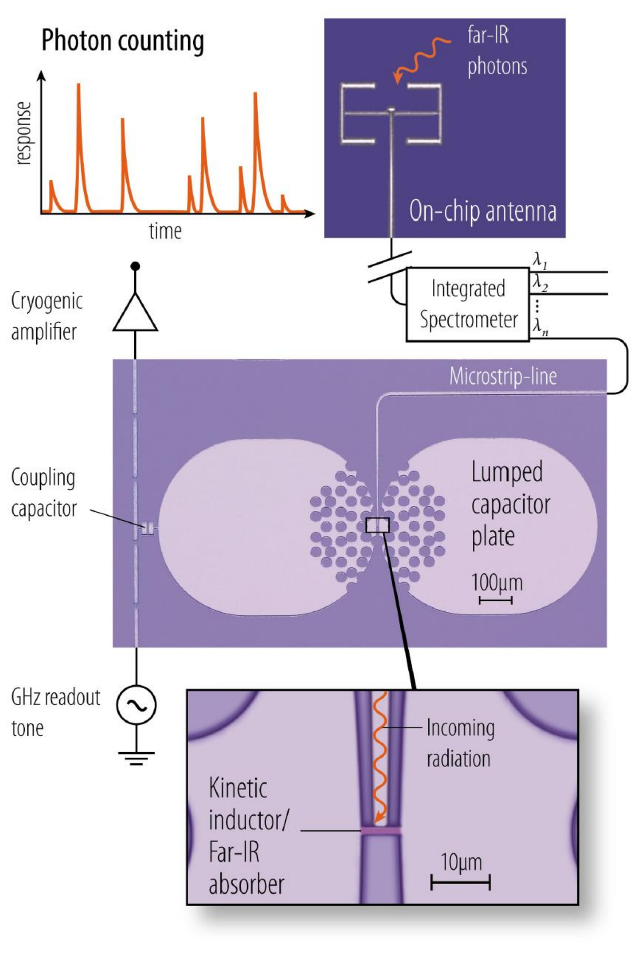




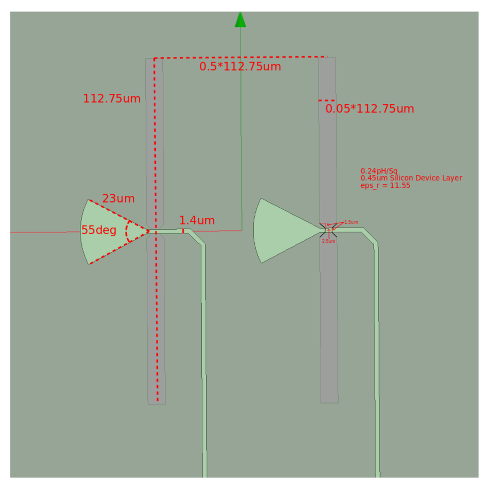
OST Detector Needs



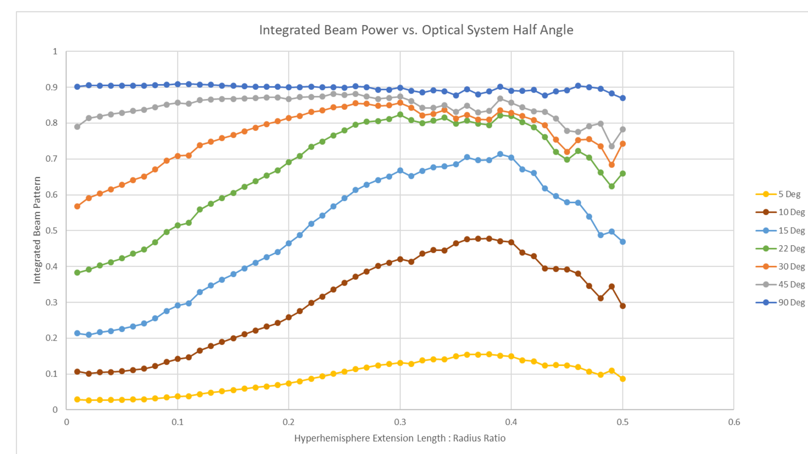
Photon-Counting Detector Concept



The prototype photon counting detector will consist of an on-chip antenna to couple light onto a NbTiN microstrip line. A double half-wave bandpass filter in concert with quasi-optical filtering then defines a narrow band to simulate one channel of a medium resolution spectrometer. This signal is fed to a small volume Al inductor at the center of a lumped element resonator. The capacitive elements in the resonator are NbTiN parallel plate capacitors, which are patterned with a photonic choke to reflect pair breaking photons back to the inductor area. Expected loading levels for photon counting at 850GHz are in the 0.1-5 attowatt range giving a quasi-particle lifetime of ~1ms. To increase responsivity, the aluminum volume is kept in the range of 0.1-1 μm^3 using demonstrated high-Q_i 20nm thick films.

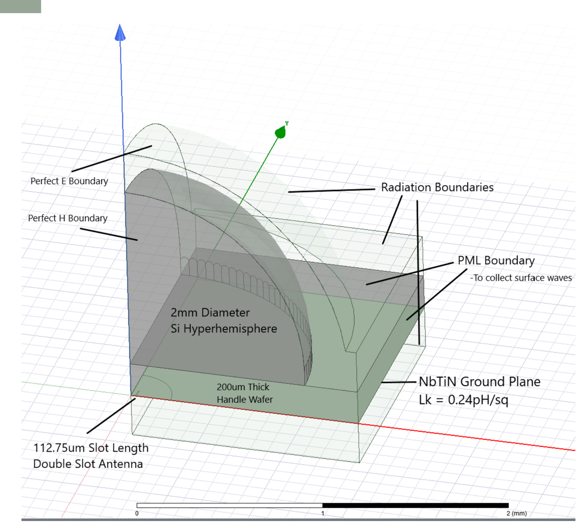


HFSS design of a double slot antenna in 300nm thick NbTiN on a 450nm thick SOI device layer. The antenna is fed by two microstrip radial probe cross-overs, which are combined in-phase into a single 12Ω microstrip input. The design achieves a 22% bandwidth (η > 90%) at 850GHz with feature sizes ≥ 1.4μm.

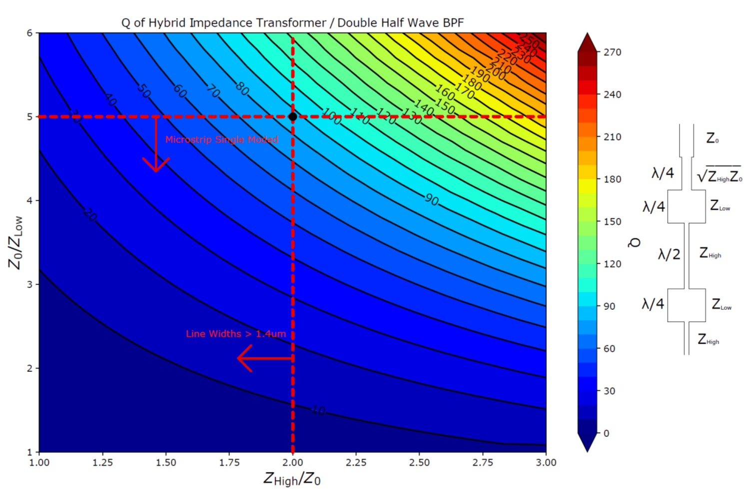


An efficient and well known coupling of the antenna beam pattern to a cryogenic blackbody load is needed to calibrate the detector's responsivity and NEP. HFSS models of the silicon hyperhemisphere/antenna system allow one to accurately estimate the blackbody's beam filling fraction as a function of the optical system's angular acceptance. To optimize this coupling for our project we have chosen EL/R ~ 0.3.

The double slot antenna will be focused using a 4mm HRFZ silicon hyperhemisphere. HFSS models of this system have been used to determine far-field beam patterns as well as near field quasi-optical beam parameters such as beam waist size and position as a function of extension length to diameter ratio. This information allows the design of a simple quasi-optical coupling system for testing.

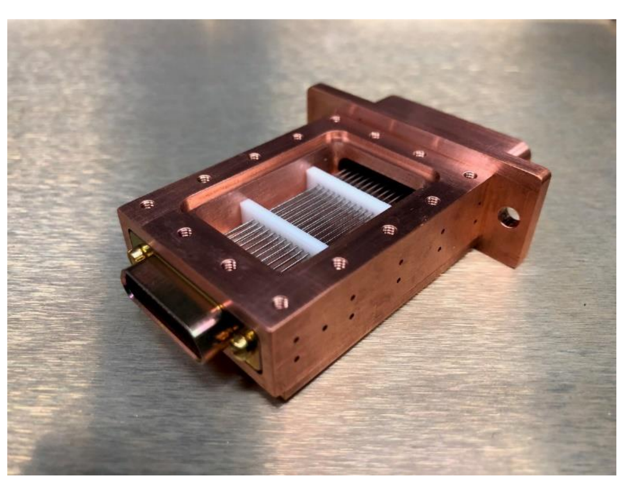


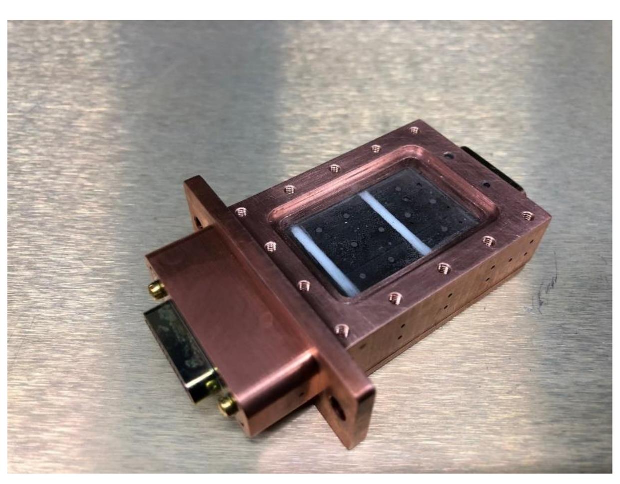
To simulate the typical power levels expected in a space-based Far-IR spectrometer, we use a double half-wave bandpass filter to restrict the bandwidth of the antenna input. Resonant bandpass filters could achieve a higher Q, thus simulating a higher R spectrometer, but their fabrication requires very tight tolerances, resulting in large uncertainties. The bandwidth of a double half-wave filter is solely determined by ratios of transmission line impedances and is thus far less susceptible to fabrication tolerances.



DC and Microwave Powder Filters

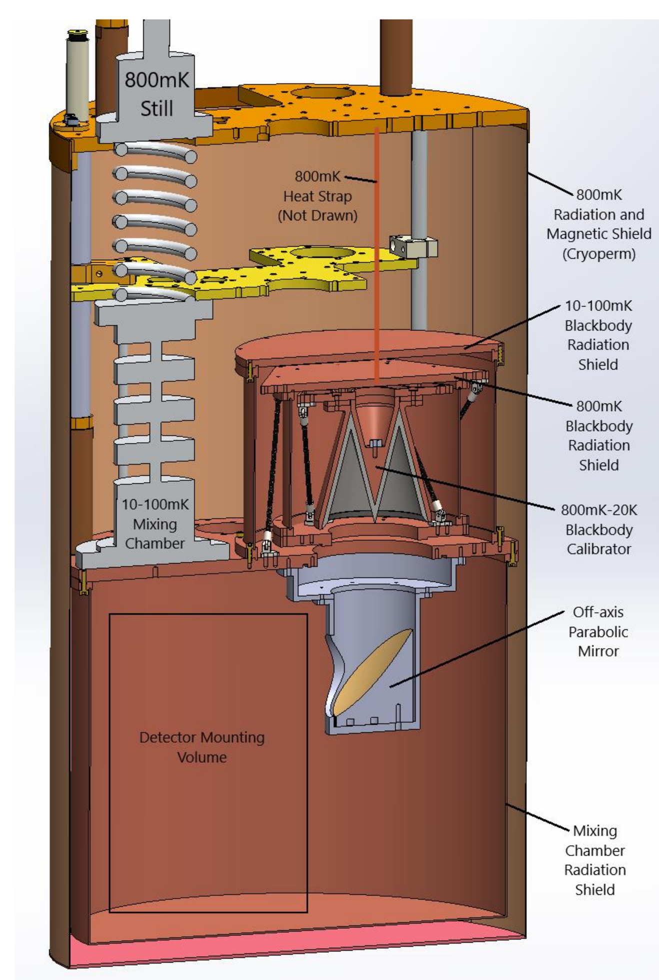
Assuring light-tightness of a dark test-volume requires all electrical penetrations into that volume be filtered to reduce the flux of pair-breaking photons to well below the rate associated with the quasi-particle lifetime. Thermometry, heaters, and other readout wiring can be effectively filtered using a heavily conductor loaded epoxy in a compact package without affecting <20MHz signals. We have developed a light-tight bulkhead-mounted MDM-connectorized filter which should nominally offer > 120dB of attenuation at > 90GHz.



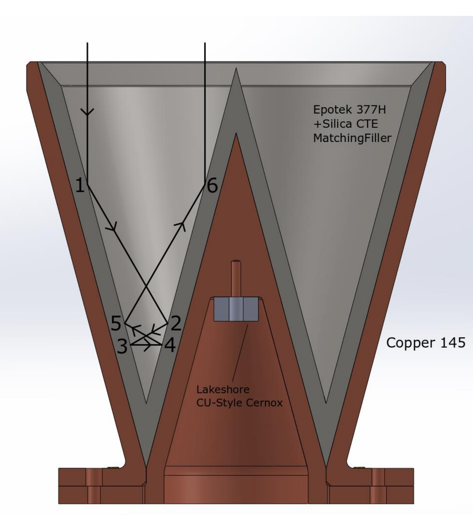


The filter body is machined from a solid block of copper 145, with multi-step tight fitting lids to allow construction of the filter while maintaining strict light-tightness. Once the filter wiring is soldered, the interior volume is filled with a stainless steel powder loaded Stycast mixture and thinned with a low percentage of acetone to allow efficient and void free casting. Pin to pin resistance has been measured to be greater than 1GΩ. Measurements of the transmission characteristics of the filter at both low frequency and high frequency using a calibrated VNA approach are underway.

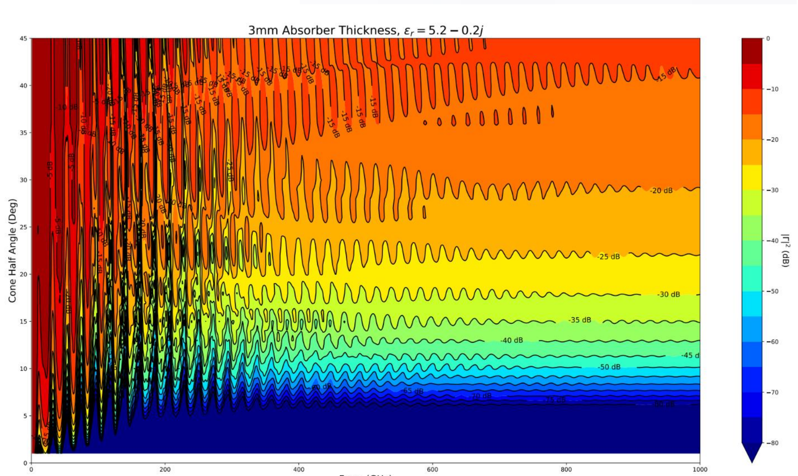
Dark Test Volume and Integrated Blackbody Calibrator



Detectors for space-based Far-IR spectroscopy will be designed with very low saturation powers and thus require very dark environments, <10^{-20}W incident, to test and characterize potential detectors. We are in the process of modifying a BlueFors dilution refrigerator system to provide additional levels of radiation and magnetic shielding to create a "light-tight" detector testbed. Integrated into this testbed is a high precision blackbody load for calibrating detector responsivities and NEPs. The blackbody is heat sunk to the 800mK still stage to allow a larger conducted heat load and thus a faster thermal time constant. Radiation shields surrounding the blackbody at 800mK and 100mK limit stray radiation on the detector.

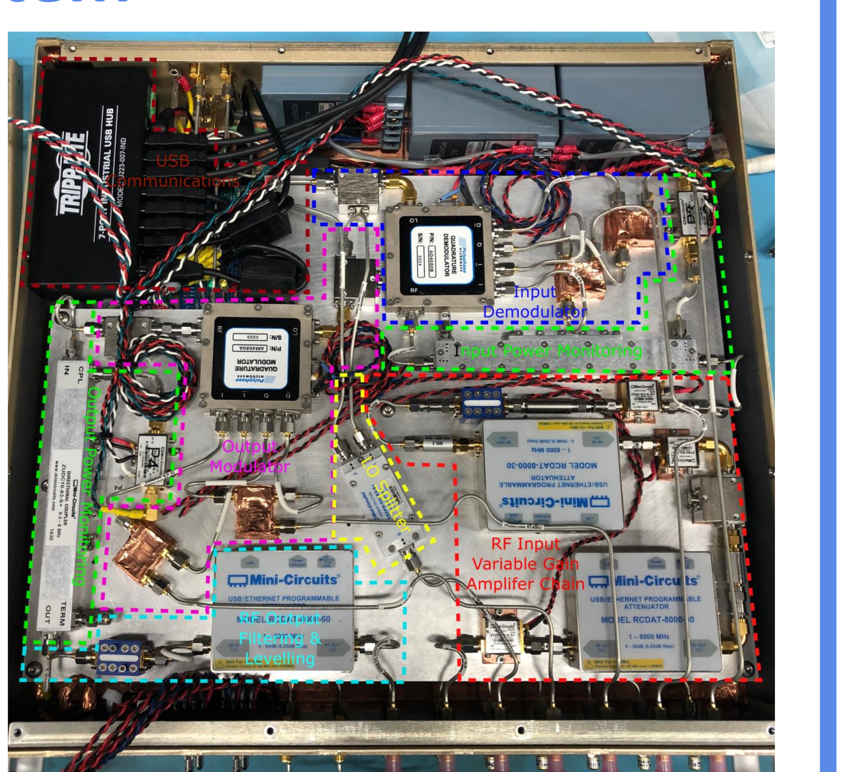


The blackbody calibrator is designed in the many-mode limit to work from 400GHz to 5THz with a reflection < -30dB. The blackbody uses a cast non-magnetic conductively loaded epoxy as an absorptive layer over a 15deg half-angle folded copper cone. Thermal mass is kept to a minimum in order to achieve a time constant of < 15 minutes up to 10K.



Microwave IF Readout System

We have developed a dual-band (2-4GHz and 4-8GHz) microwave I/Q Up/Down converter system to interface KIDs and μMux chips with I/Q-based baseband DSP systems such as ROACH2 or RFSoC. System consists of an input amplifier chain, input demodulator, output modulator, output filtering and levelling, input and output power monitoring and LO distribution sub-systems. Both input and output chains have 60dB of variable gain/attenuation to accommodate varying resonator read powers. Input and output chains are isolated to better than 100dB through the use of isolators and a high isolation Wilkinson splitter. All components are COTS except a single custom equalizer per band to flatten the input gain. The entire readout dissipates < 50W and fits in a 2U rack-mounted box. Variable attenuator settings are controlled through a single EMI-filtered USB input. Eight temperature sensors and the four power detectors are read using an Arduino which is also command-able via USB.



NbTiN & Al Film Characterization

Both NbTiN and thin Al film characterization work is on going using our BlueFors DR microwave testbed. Resonator center frequencies and internal/coupling quality factors are measured by fitting VNA-measured transmission data to a physics-based resonator model. Resonator read power is varied at base temperature to understand the influence of TLS density and quasi-particle heating. Temperature sweeps are performed to measured the TLS-induced frequency shift, which provides the most accurate estimate of the effective TLS density, F*Tan(δ). By varying deposition methods and parameters, and varying etch techniques, we have begun to optimize our NbTiN films for low TLS density and high intrinsic Q. Our sputtered thin Aluminum films (10-25nm) have been demonstrated to have high internal Q (>10^6) but the effects of a hybrid NbTiN/Al fabrication process and aging on them have not been fully studied. Additionally both NbTiN-compatible Al etch processes and NbTiN liftoff processes are in development.