A compact immersion grating spectrometer with quantum capacitance detectors for space-borne far-IR spectroscopy
Progress Report

P.M. Echternach
C. M. Bradford, T. Reck, B. Pepper,

Jet Propulsion Laboratory, California Institute of Technology

Electron Beam Lithography by Richard E.Muller
Fresnel lens array by Daniel Wilson

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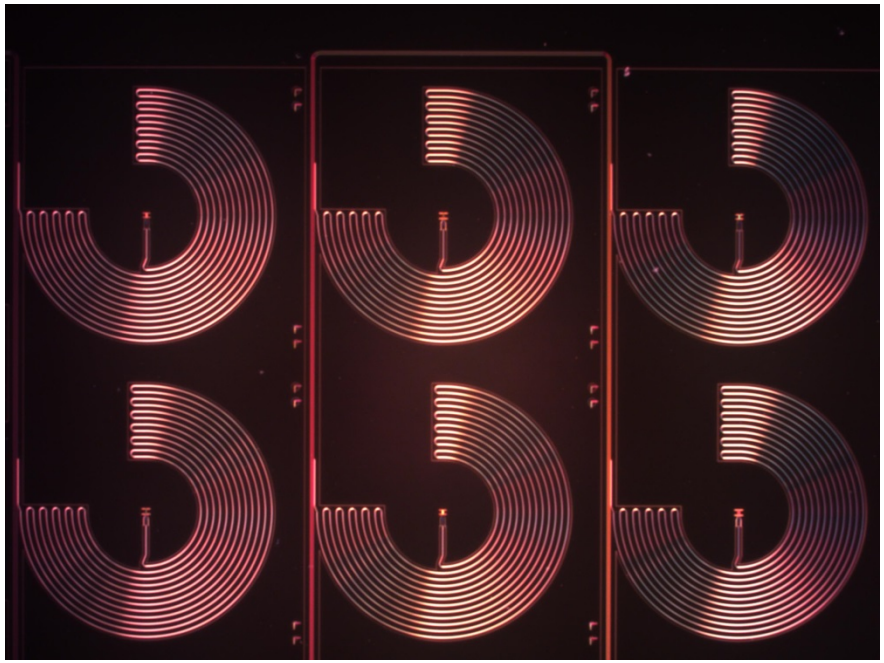
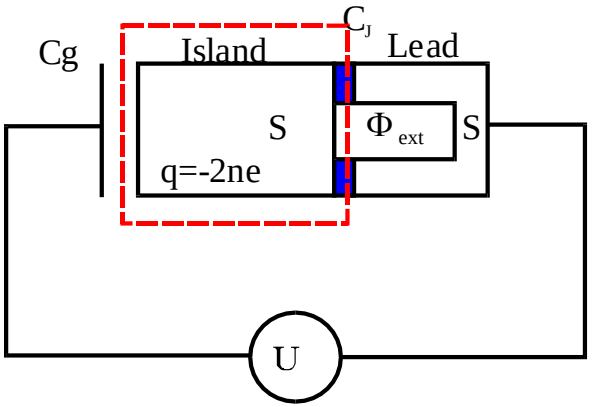
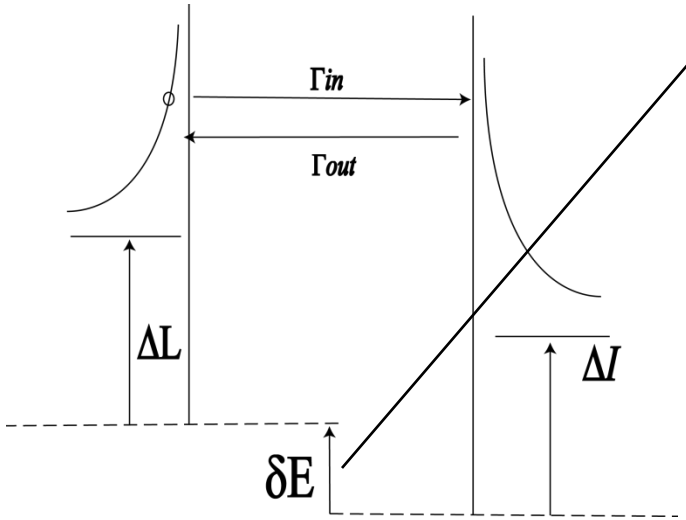
Immersion Grating Spectrometer with Quantum Capacitance Detector Readout

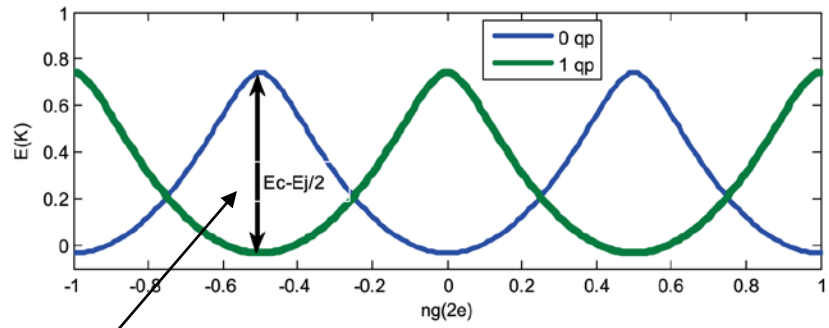
- Develop an immersion R~ 500 grating spectrometer using a readout based on a novel detector based on superconductor pair-breaking in mesoscopic superconducting devices for the far-IR submm spectral range under very low levels of illumination. We will demonstrate a fully multiplexed 256 spectral channel device with shot noise limited detectors for wavelength between 200 and 350 µm.

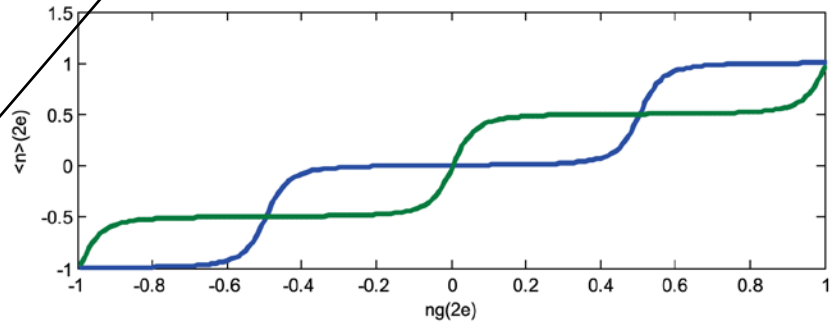


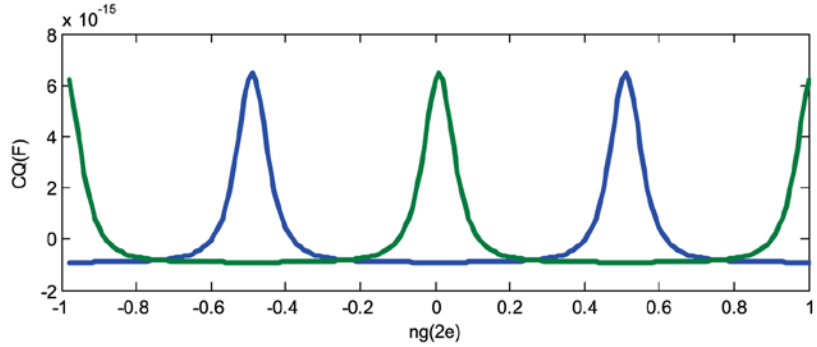
Single Cooper-pair Box (SCB)



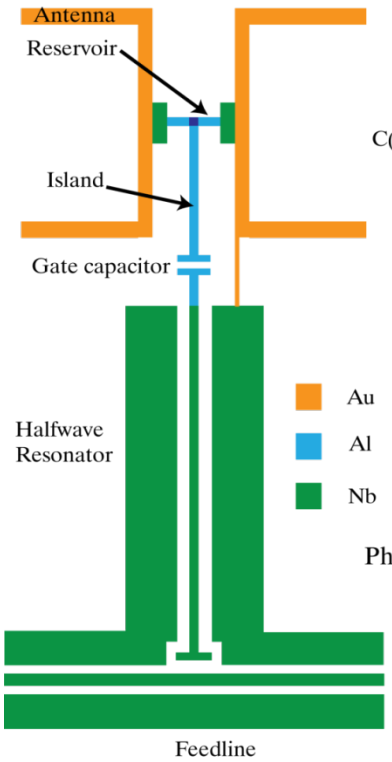


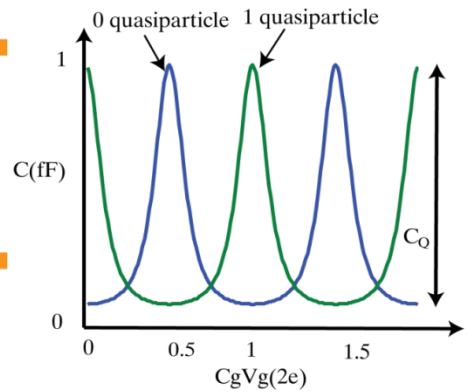


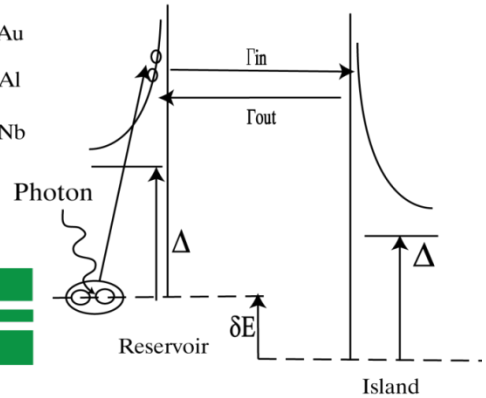


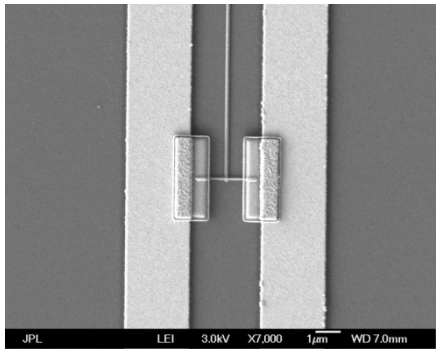


The Quantum Capacitance Detector

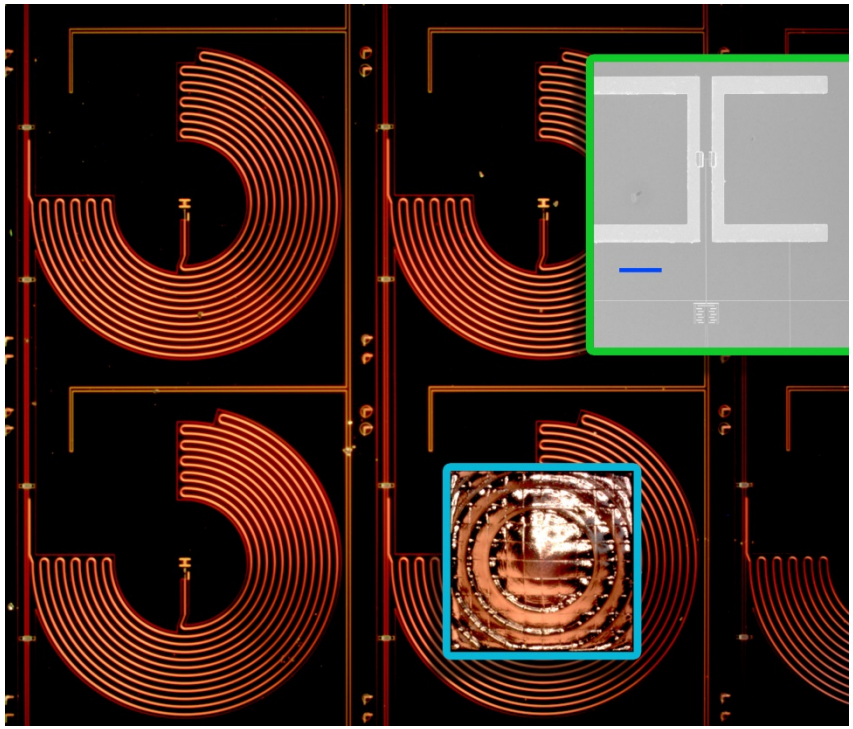




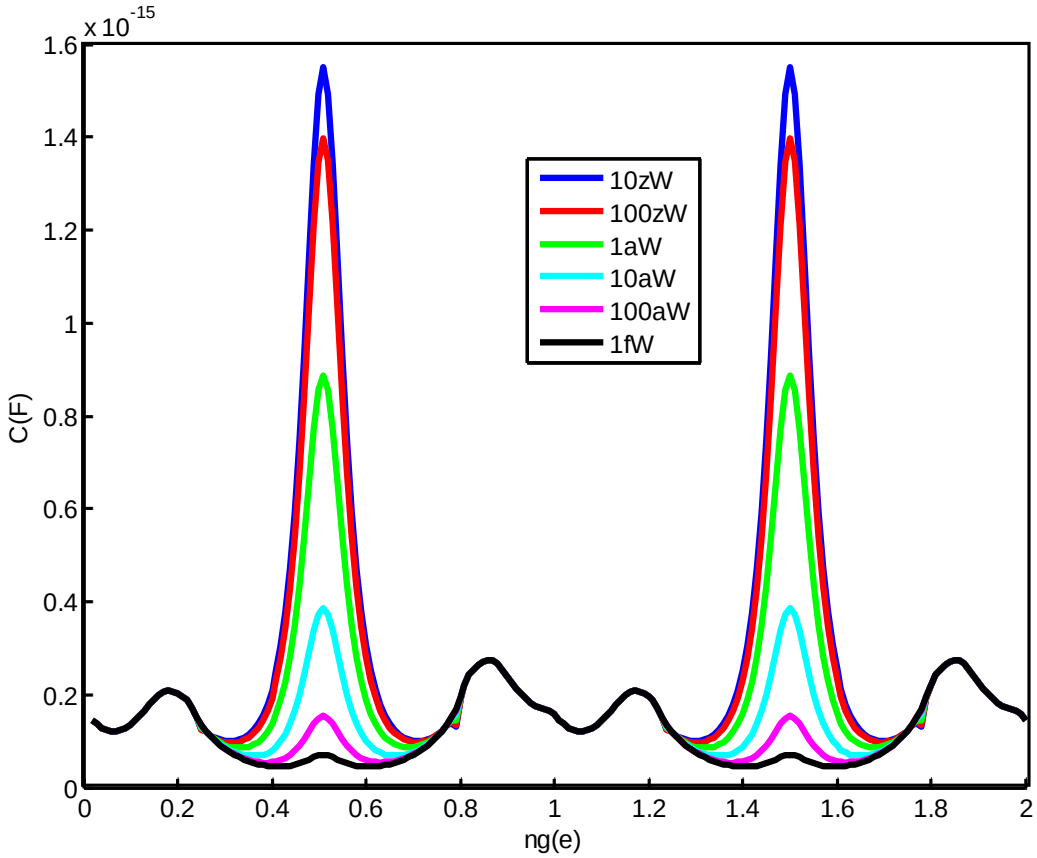




- Radiation coupled by an antenna breaks Cooper pairs in the reservoir (absorber) establishing a density of quasiparticles(QP) proportional to the optical signal.
- QP density in reservoir set by the ratio of tunneling rates onto and out of the island. The average QP occupation on the island ($0<P_{odd}<1$) is proportional to optical power.
- Bias at a peak, then average gate capacitance is a measure of optical power.
- Incorporate gate capacitor into a half-wave microwave resonator, changing C shifts readout frequency. Naturally frequency-domain multiplexed.



Simulated response

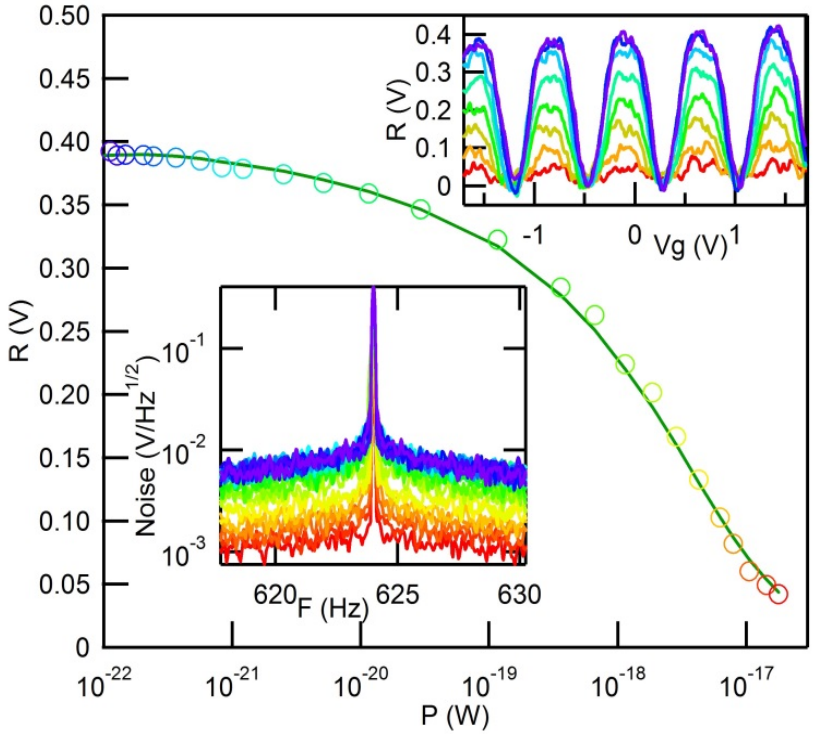


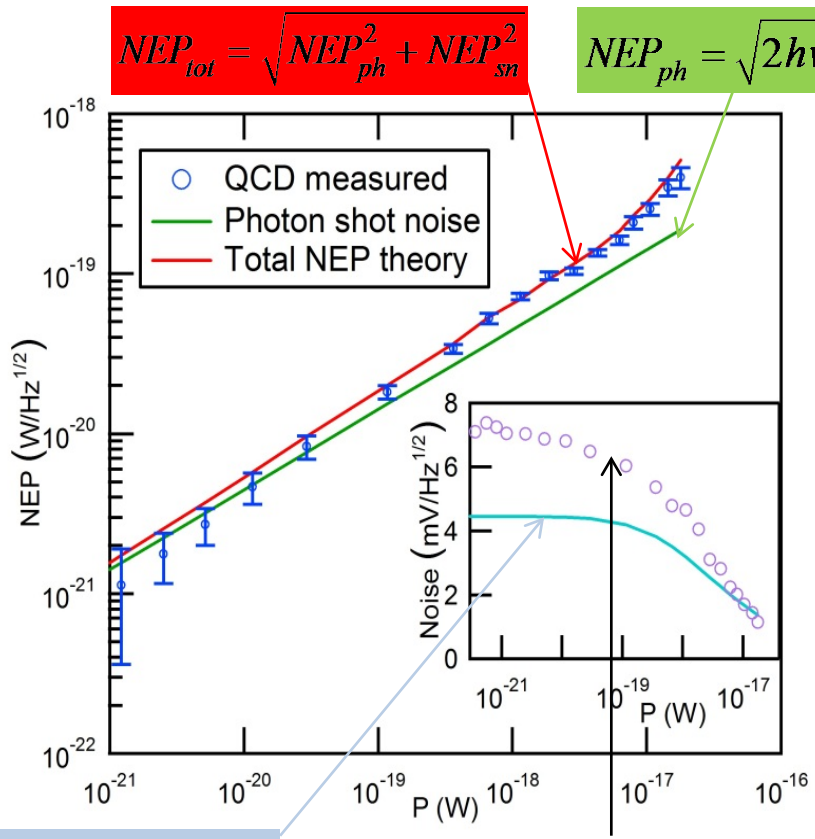
- SCB capacitance x gate voltage (in units of Cooper Pair charge) for various coupled optical signal power

The Quantum Capacitance Detector

Response and noise as a function of optical signal

NEP as a function of optical signal
Photon shot noise limited!





Shot noise of electron tunneling

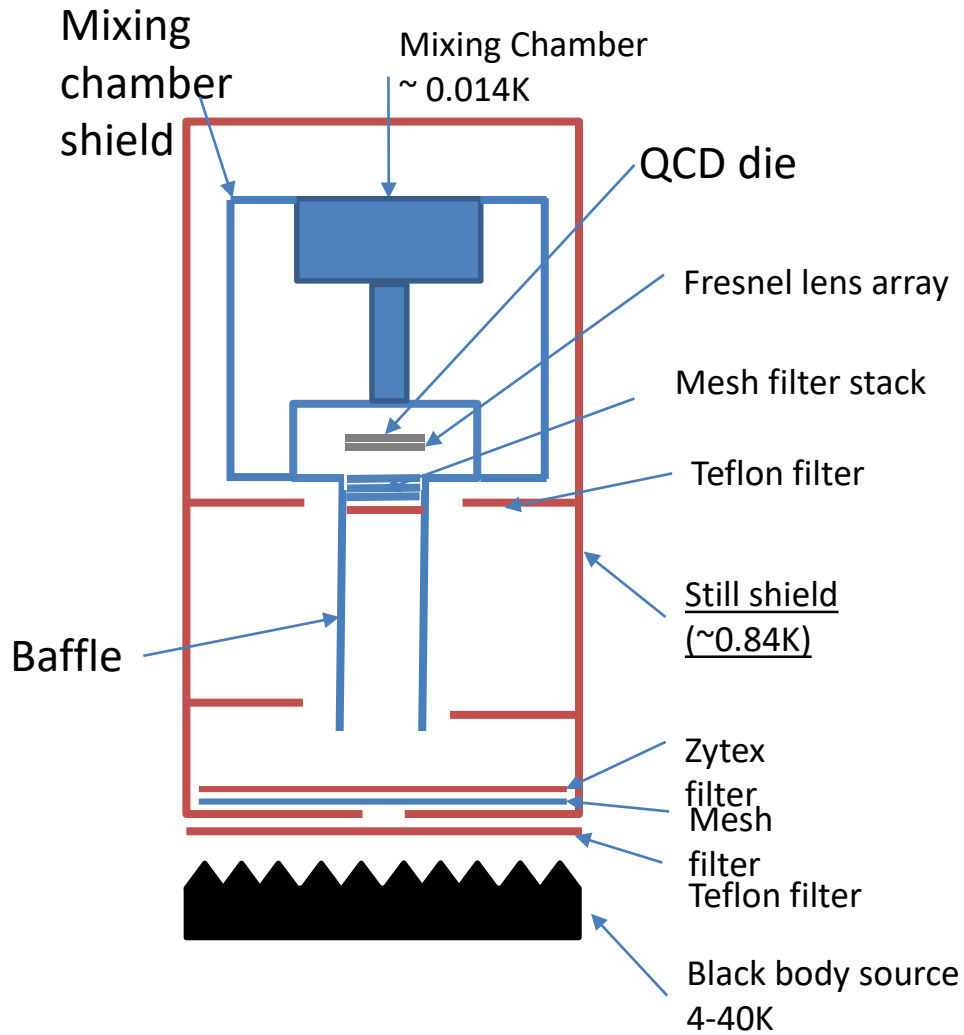
$$S_{sn}(f) = \sqrt{2A^2(\Gamma_{in}\Gamma_{out}/\Gamma_\Sigma)/(\Gamma_\Sigma^2 + (2\pi f)^2)}$$

Total measured noise

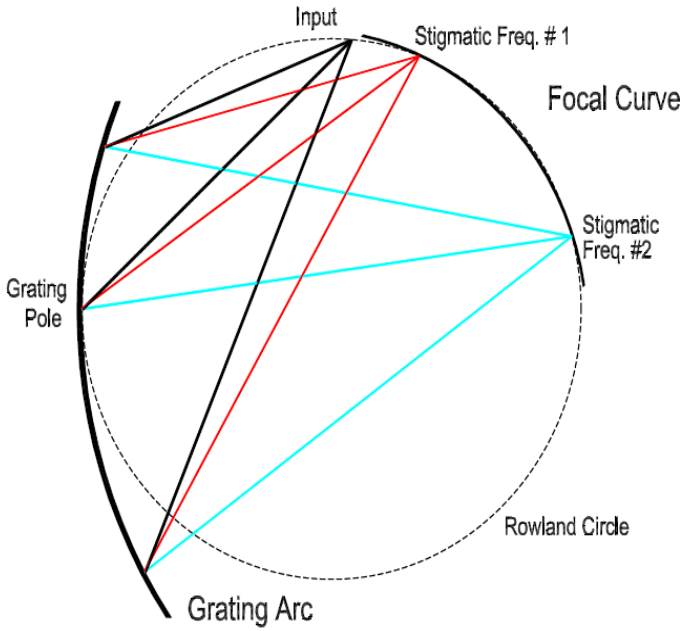
$$NEP_{SN} = S_{SN}(f)/(\frac{dR}{dP})$$

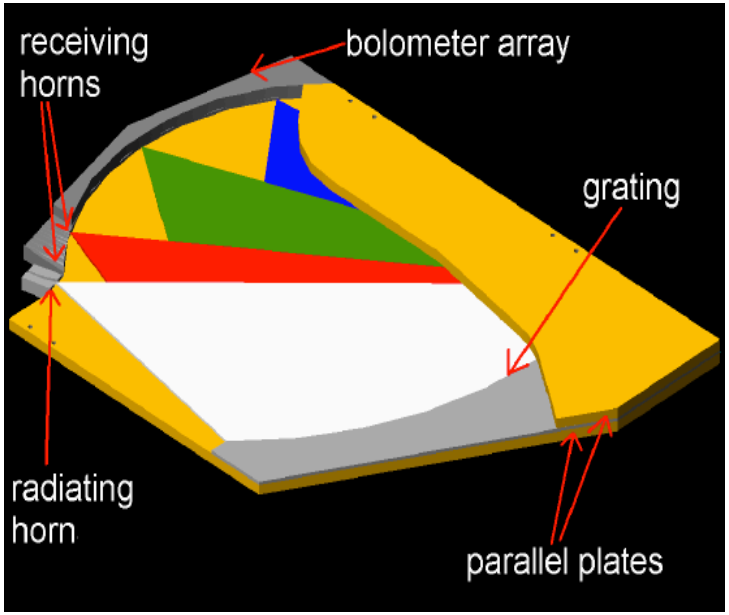
Improved measurement setup

- Added stack of three mesh filters at mixing chamber temperature
- Added Teflon filter before mixing chamber filter stack
- Added Teflon filter before still shield mesh filter
- Added mixing chamber shield -> no response from still temperature changes



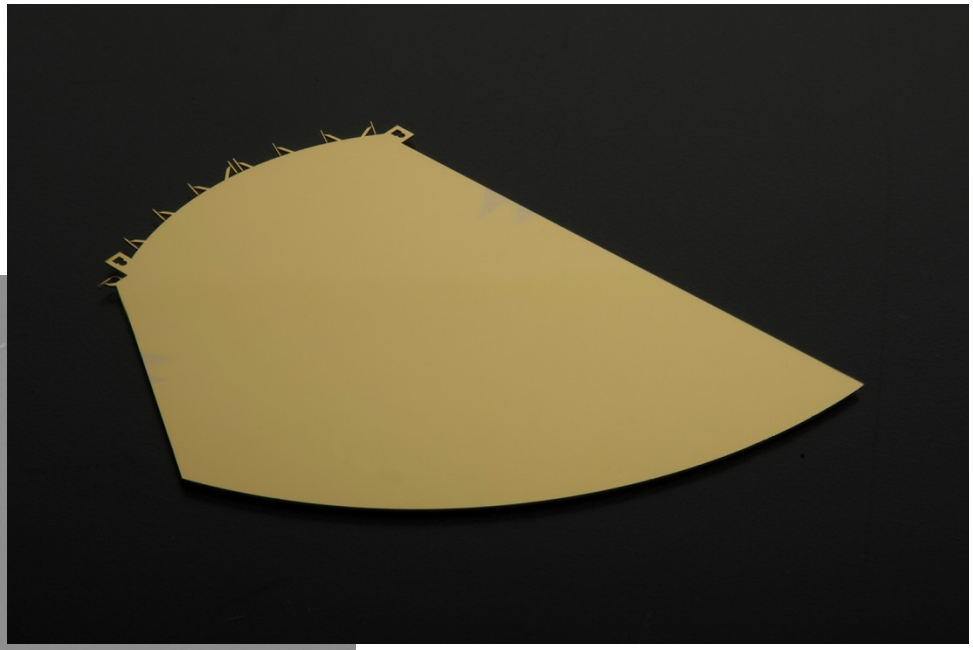
Future – grating spectrometer on a wafer

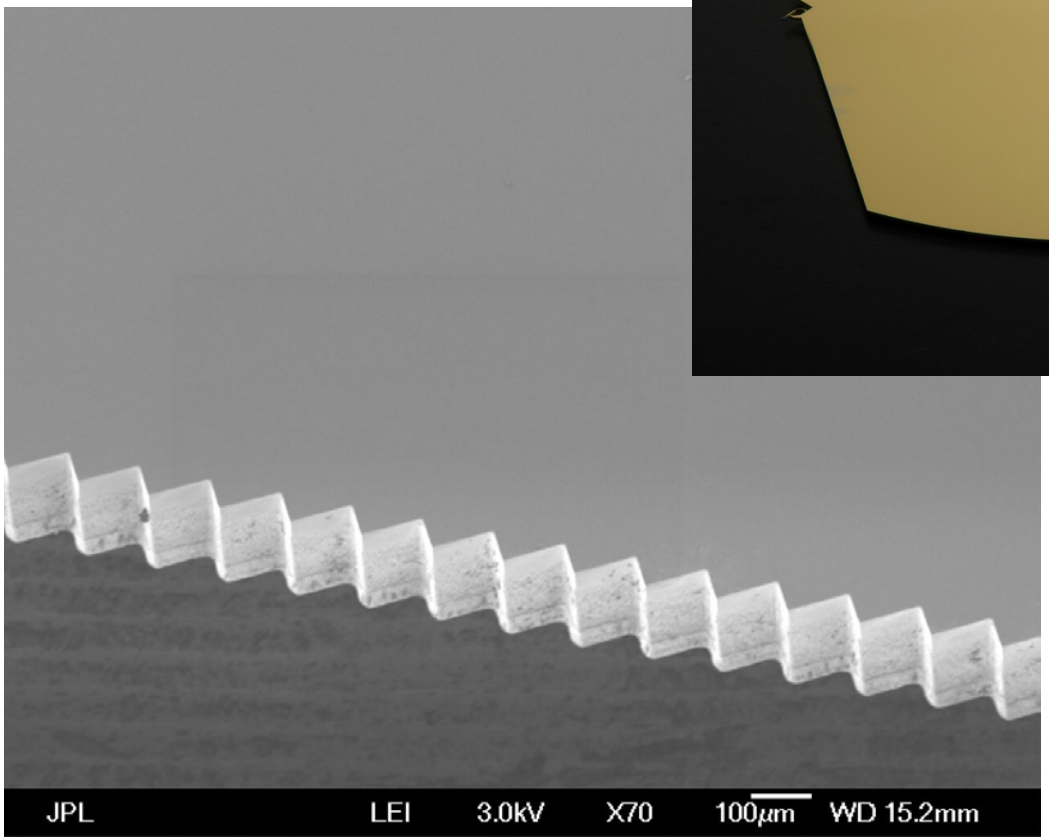




- **Grating Spectrometer concept: Facets on the grating arc both diffract and focus the radiation to locations on focal curve.**
- **Each facet individually positioned to provide perfect performance at the two stigmatic frequencies.**
- **Longest interference path possible.**
- **Eliminates the second dimension by confining the propagation makes for easy and efficient coupling to detectors.**

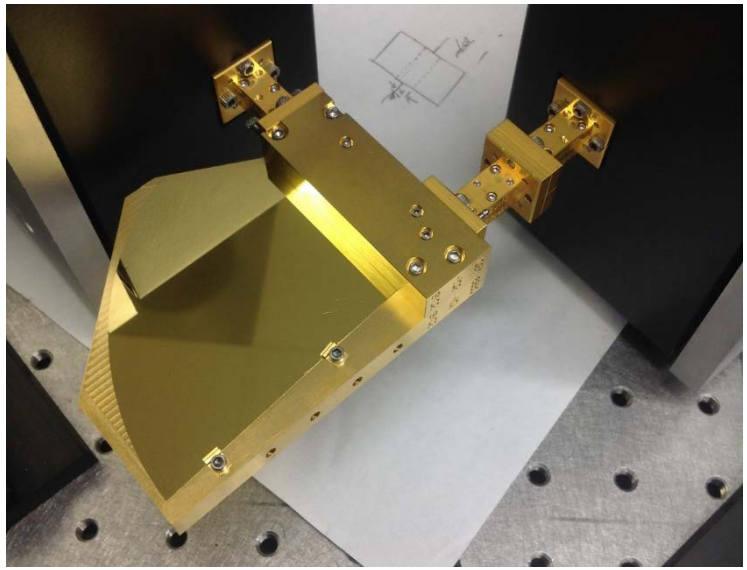
Grating spectrometer on a wafer



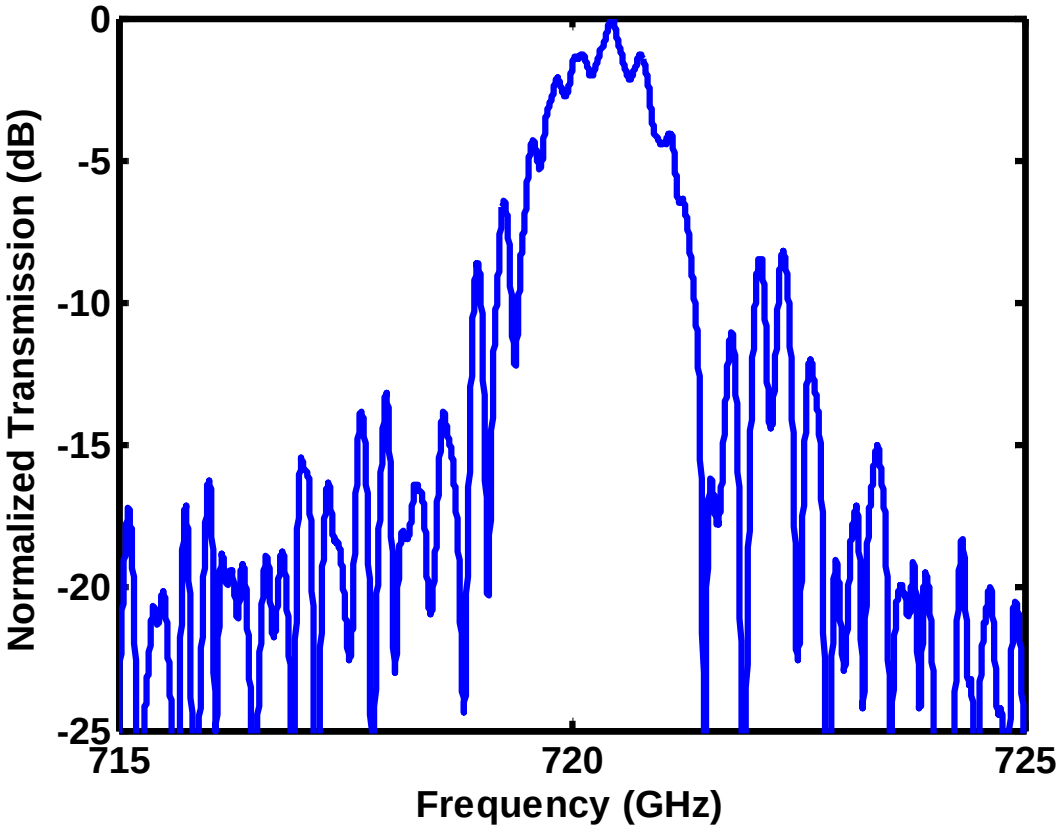


Grating spectrometer on a wafer

- Redesigned wafer spectrometer with flat feeds
- Redesigned test fixture with waveguide transitions split in the middle



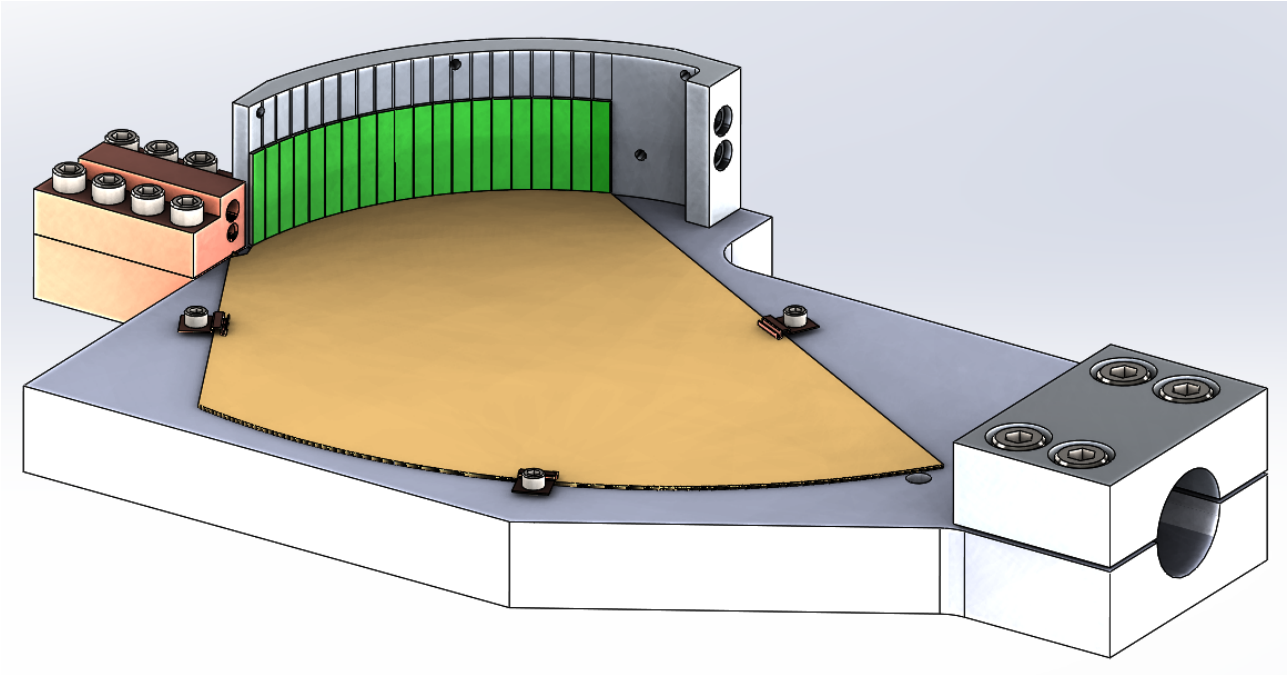
Grating spectrometer on a wafer



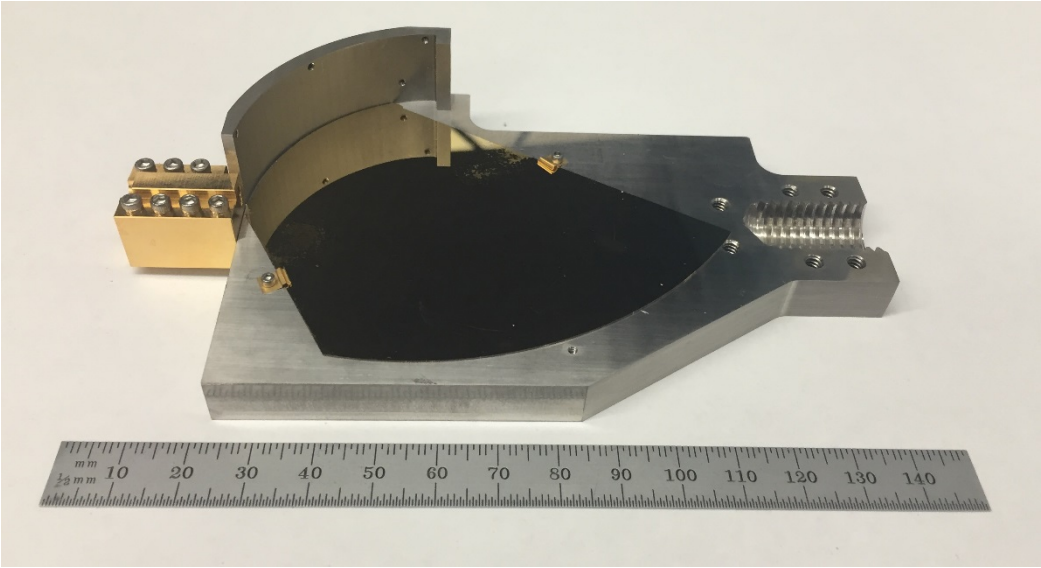
- VNA measurement of transmission between input feed and 720GHz output feed
- R ~ 600

Integrating Spectrometer and QCDs

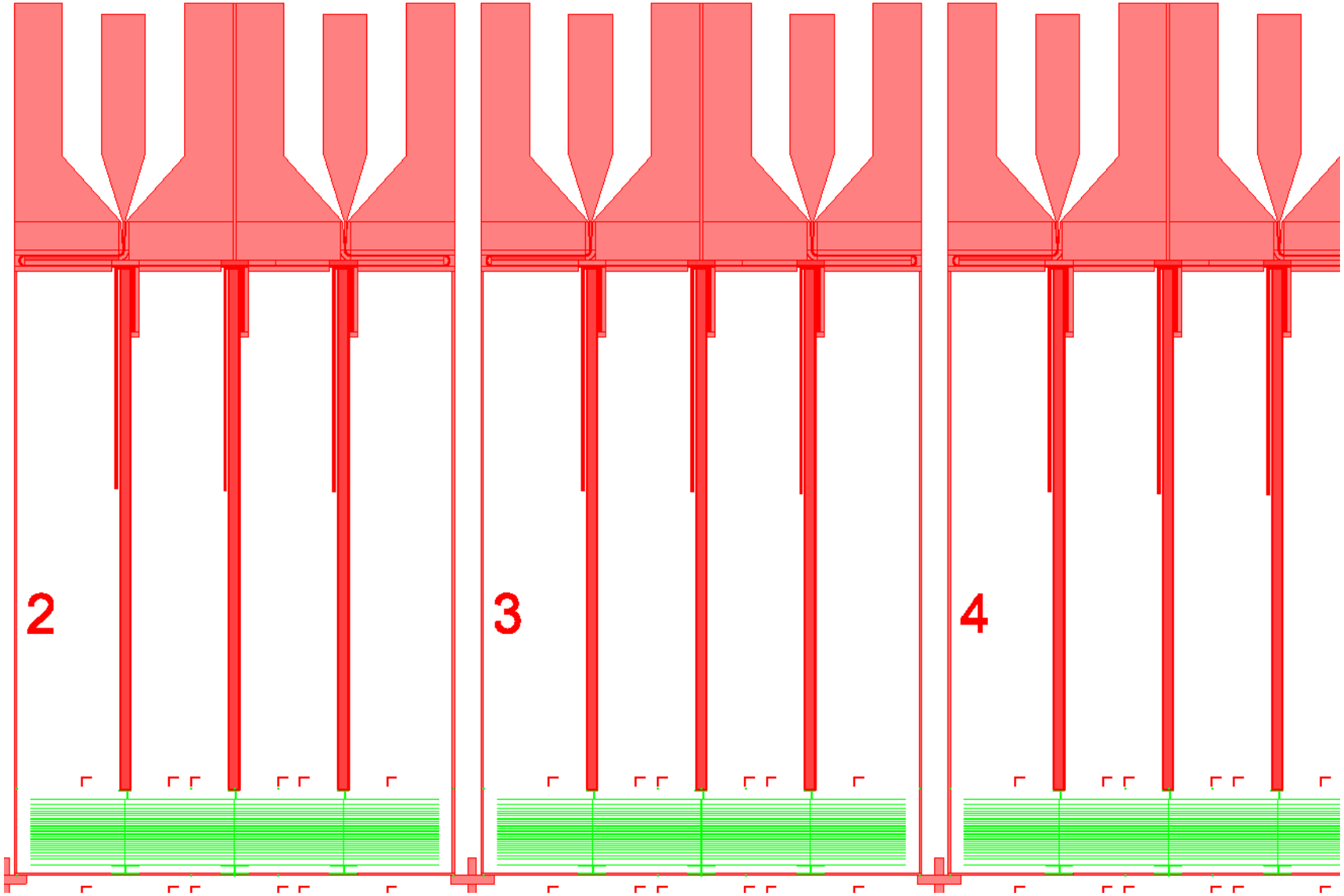
- Original idea of having a detector wafer on top of silicon spectrometer is problematic
  - Coupling between waveguide modes and QCD antenna difficult
- Obtain higher efficiencies by coupling directly to a mesh absorber
- QCD dies placed directly against spectrometer wafer facets



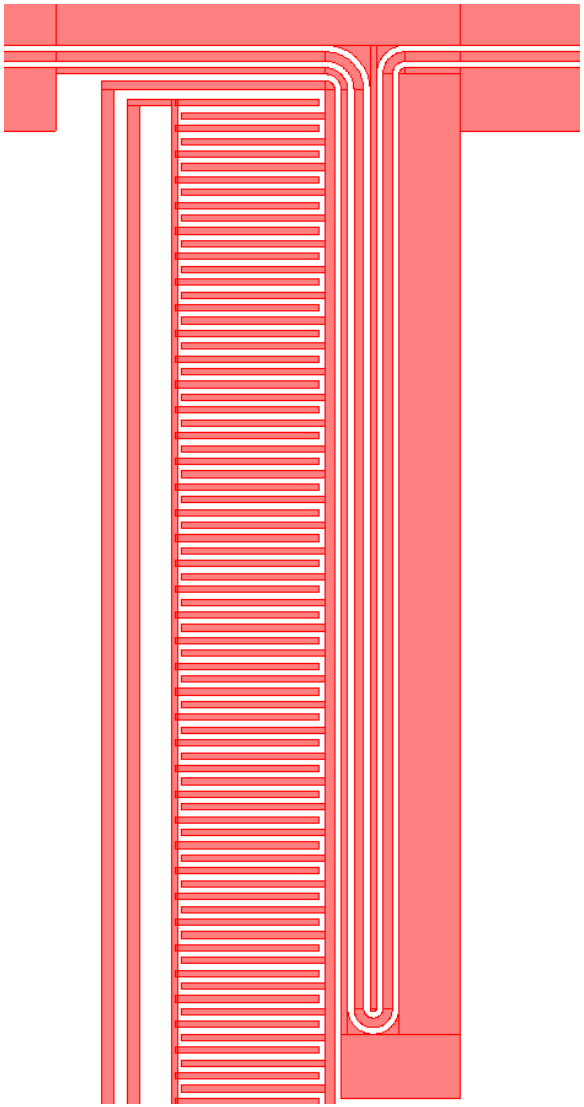
Integrating Spectrometer and QCDs



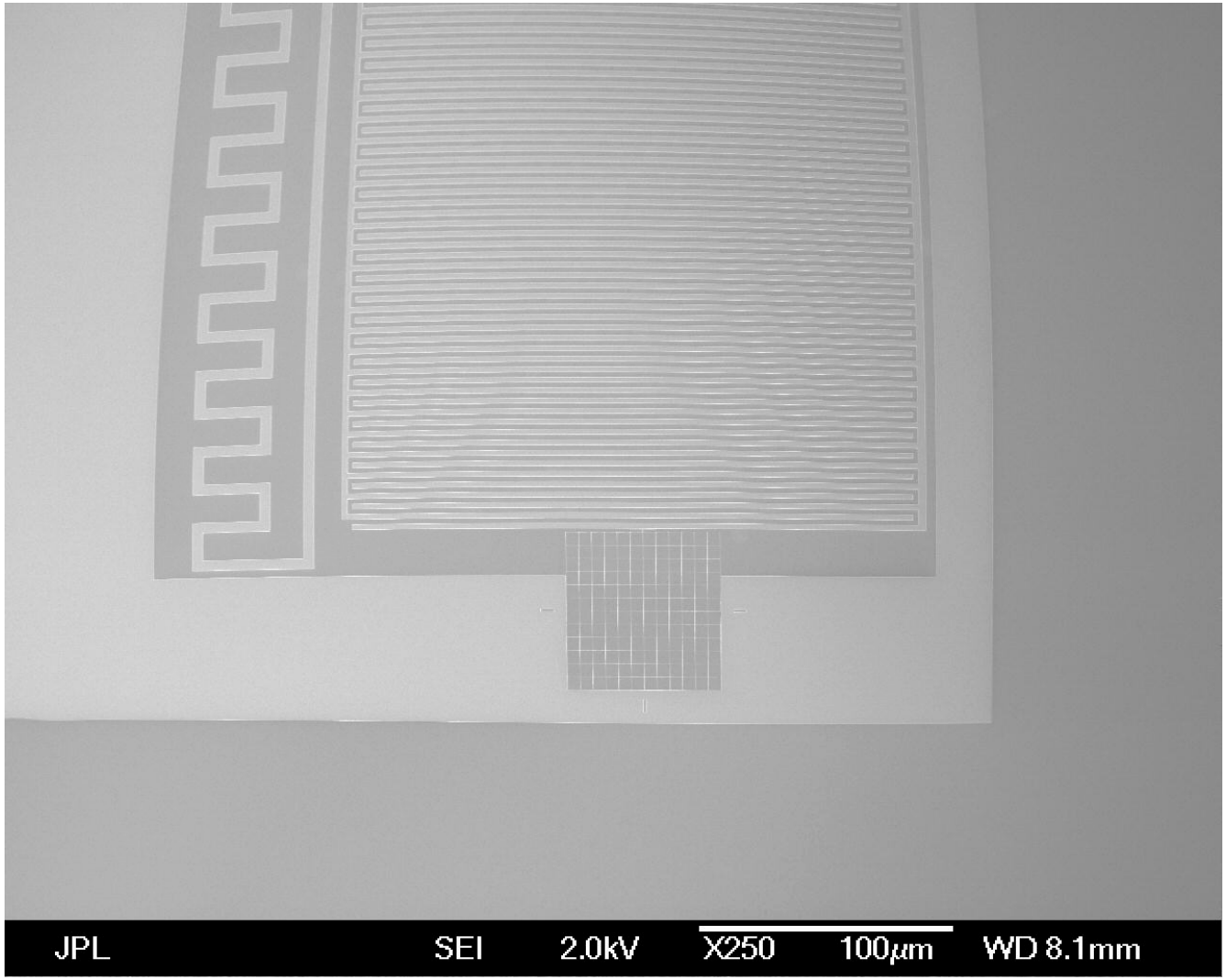
Spectrometer Readout Design



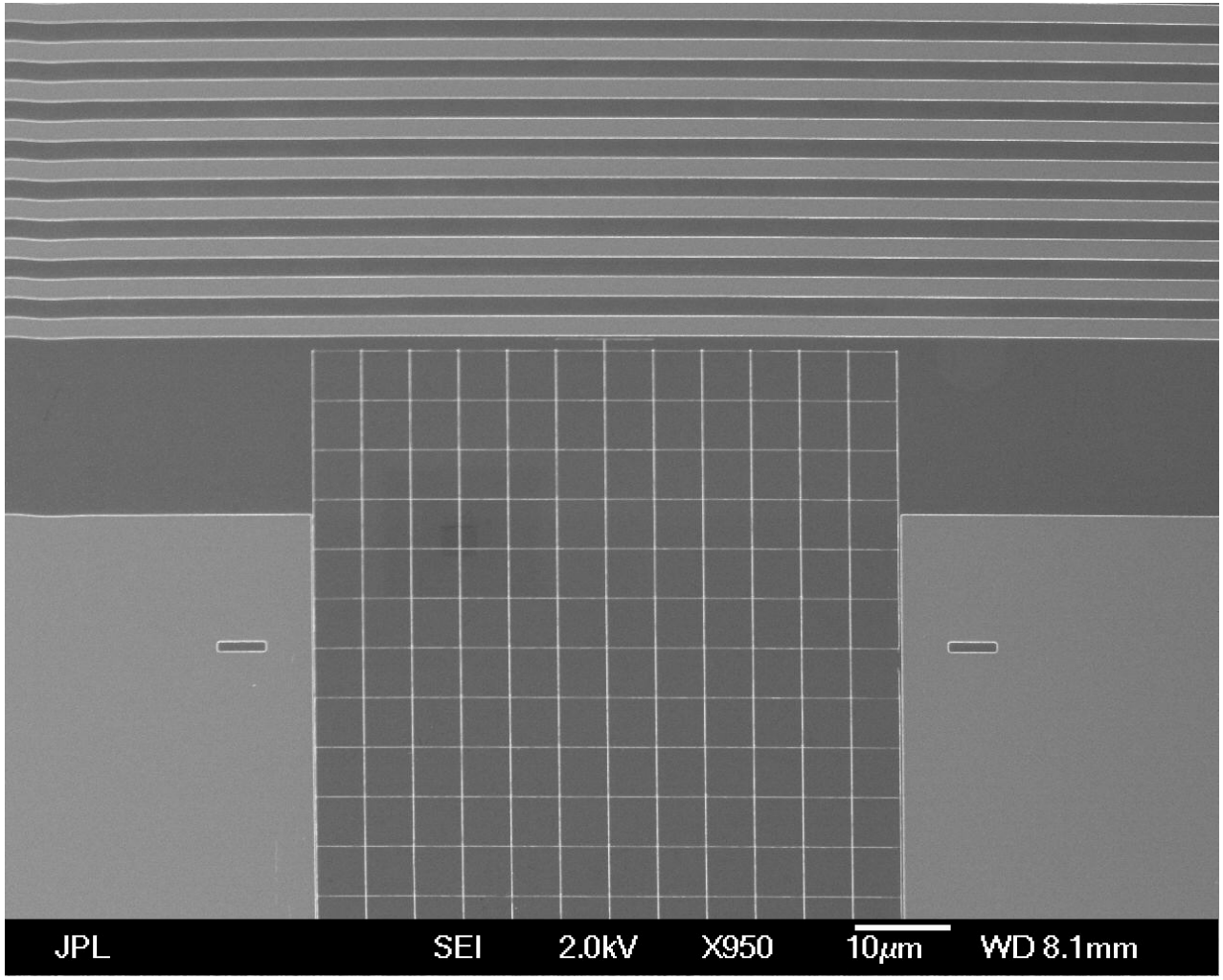
Spectrometer Readout Design



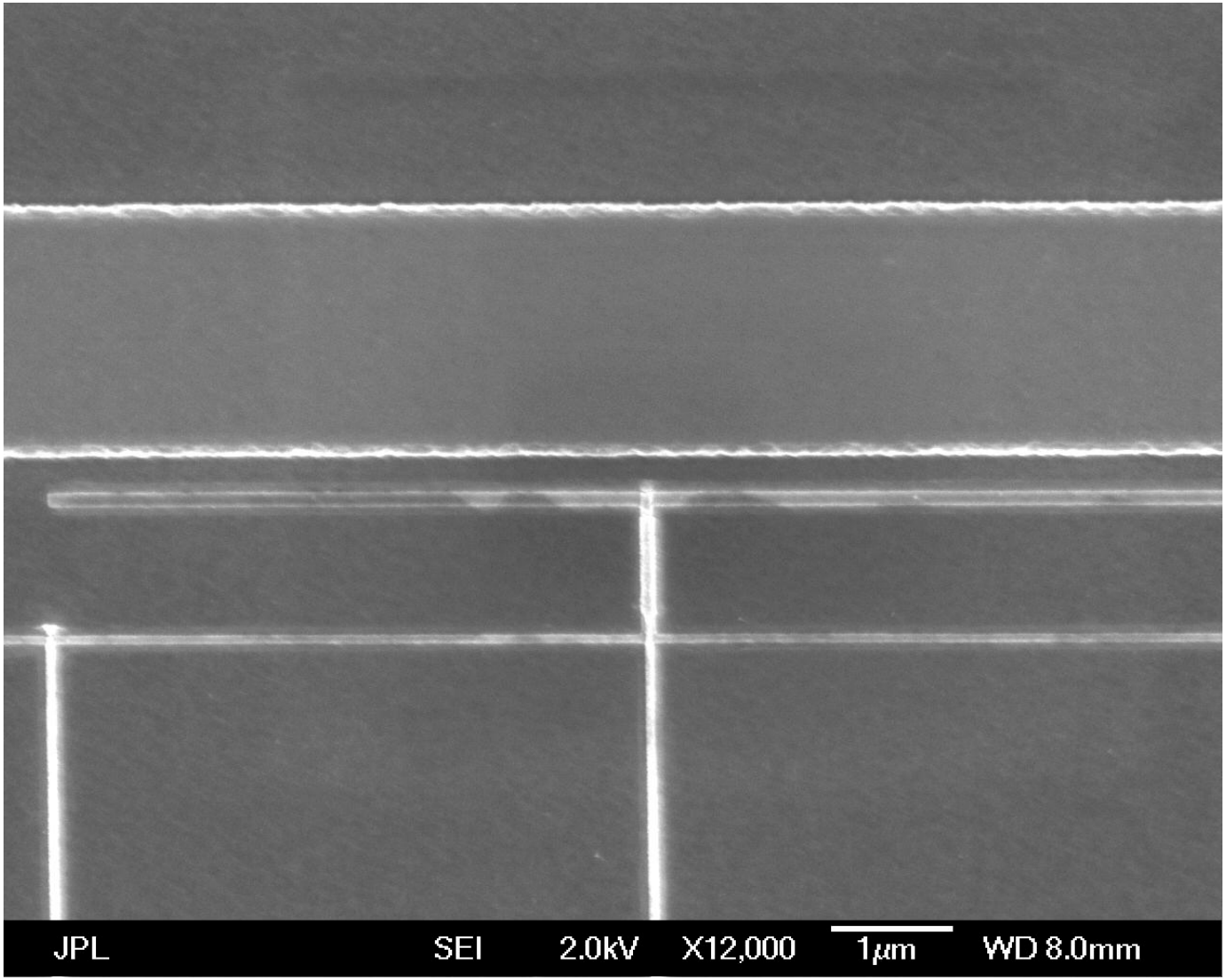
Lens coupled mesh absorber LEQCD



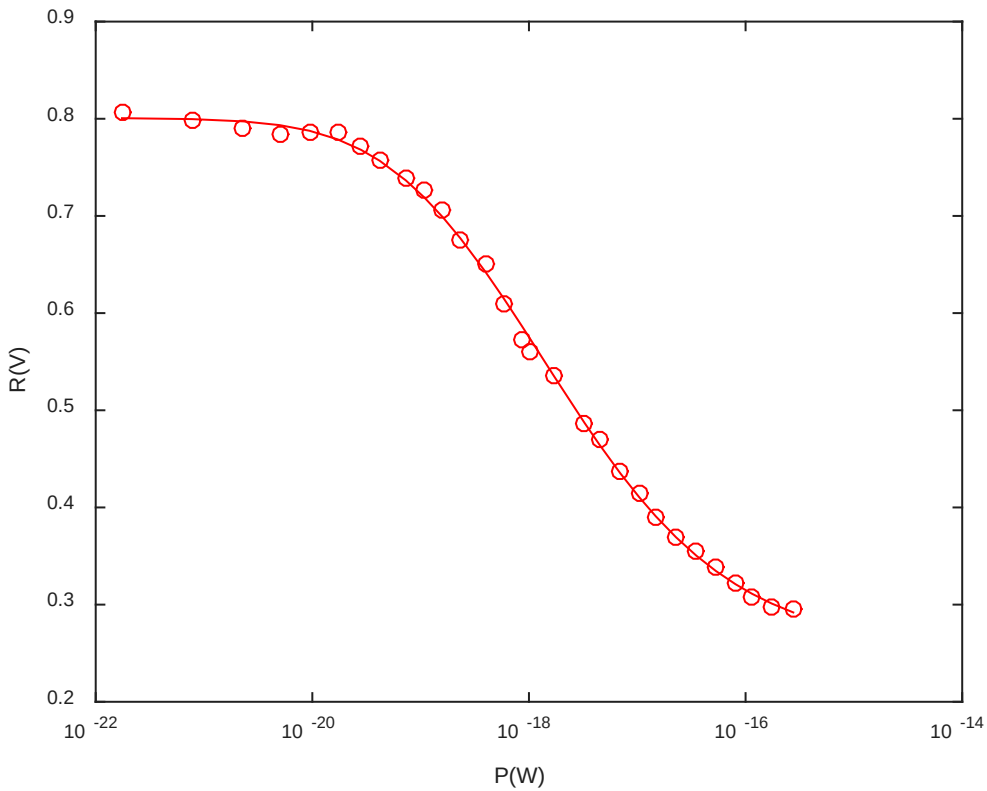
Lens coupled mesh absorber LEQCD



Lens coupled mesh absorber LEQCD



Lens coupled mesh absorber LEQCD



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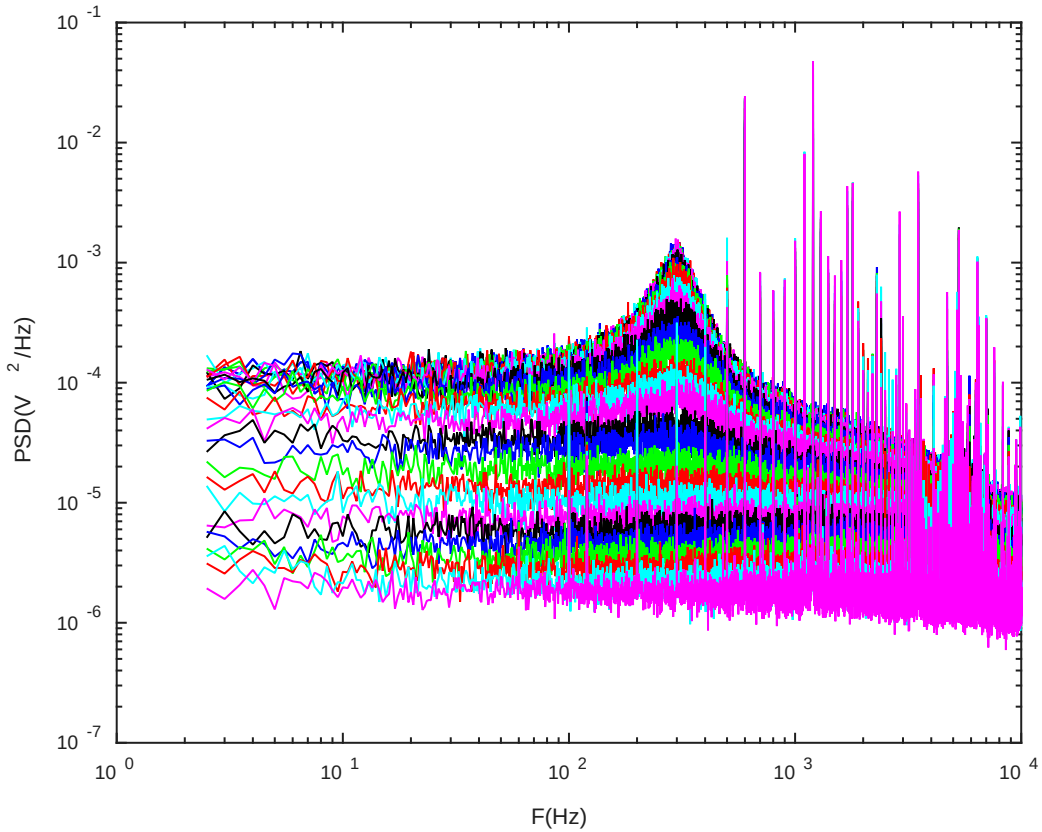
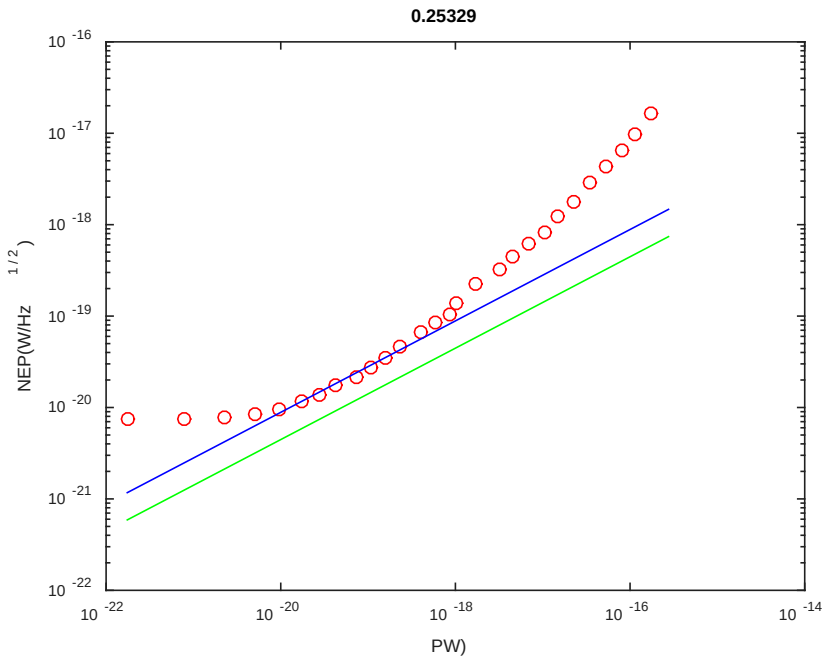
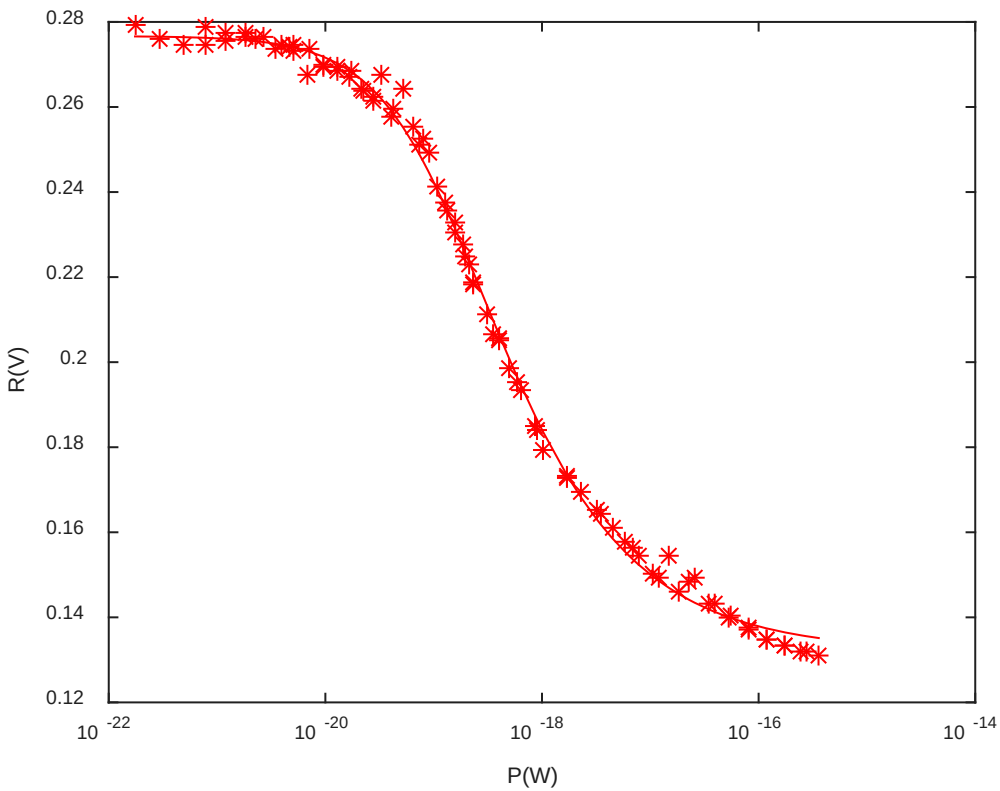


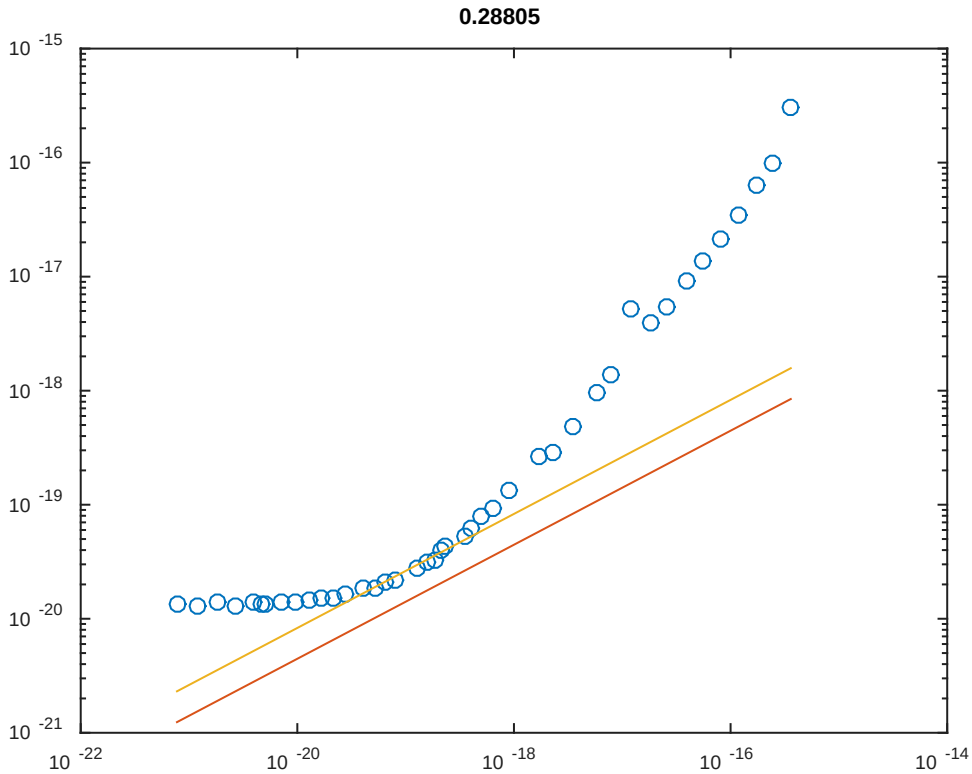
Lens coupled mesh absorber LEQCD

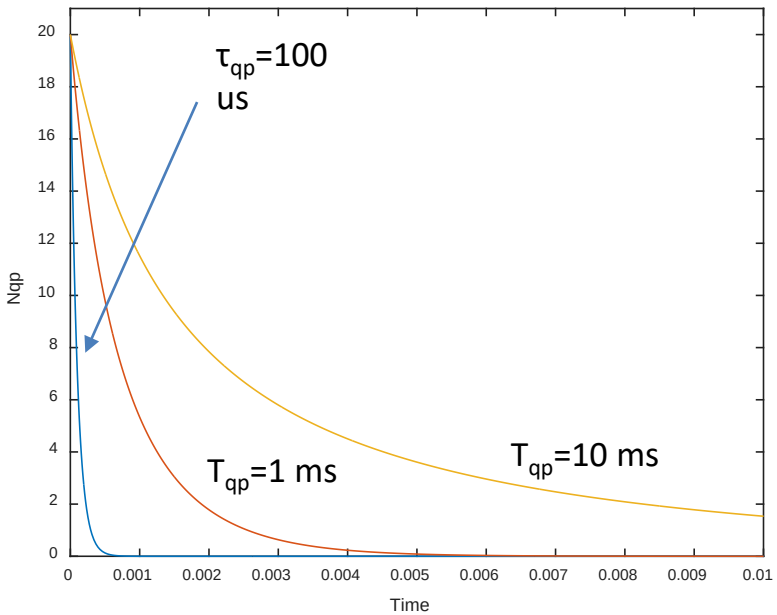


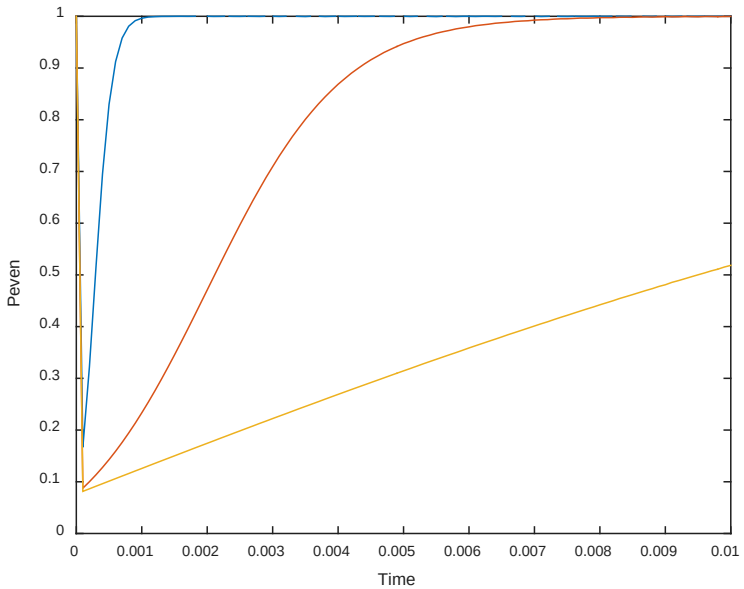
Lens coupled mesh absorber LEQCD



NEPometer taken with a lower carrier amplitude – hence the smaller voltage (smaller noise too -> NEP the same)

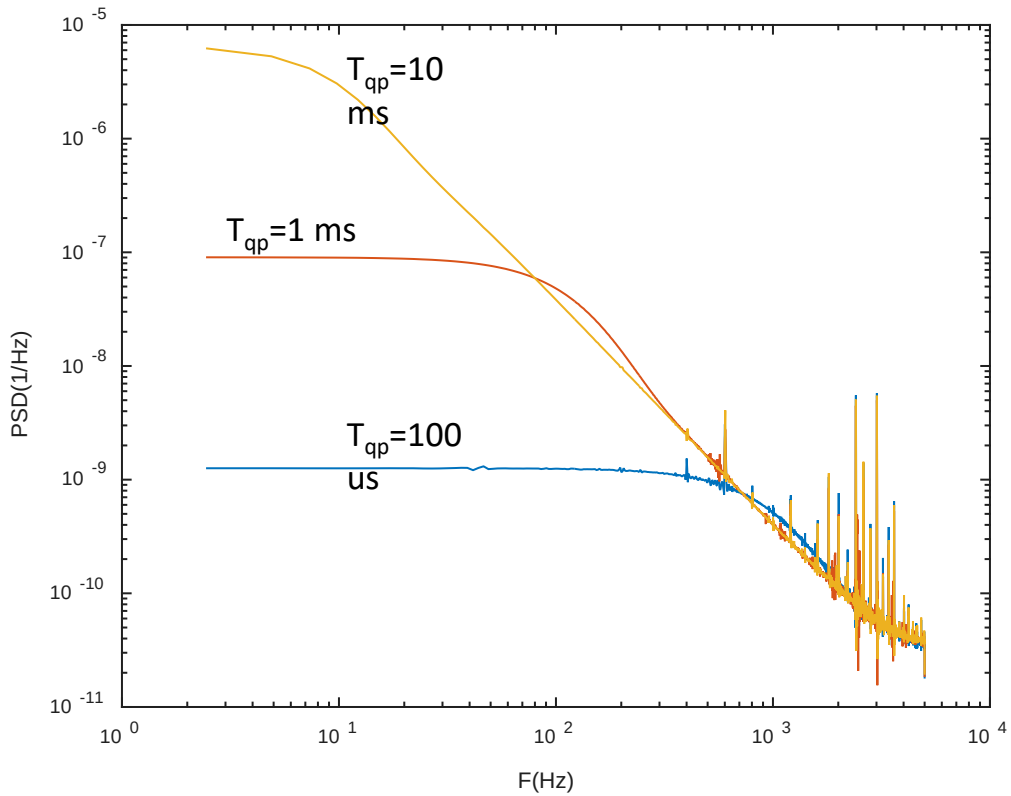

0.28805
10 -15
10 -16
10 -17
10 -18
10 -19
10 -20
10 -21
10 -22
10 -20
10 -18
10 -16
10 -14





$$\frac{dN_{qp}}{dt} = -RN_{qp}^2 - \frac{N_{qp}}{\tau}$$

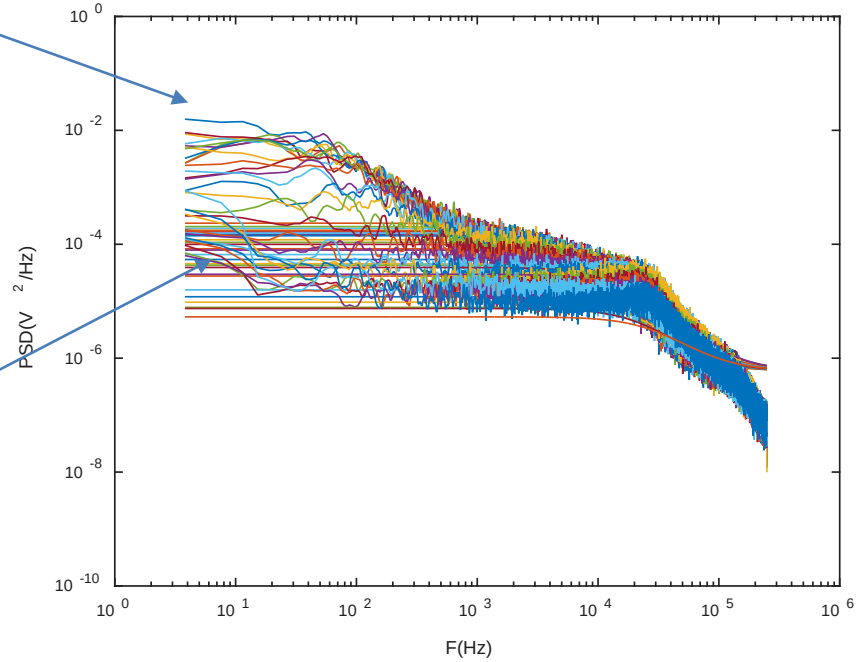
$N_{qp}(t)=(\tanh(\operatorname{atanh}(2N_{qpo}R\,\tau+1)+t/2\,\tau)-1)/2R\,\tau$

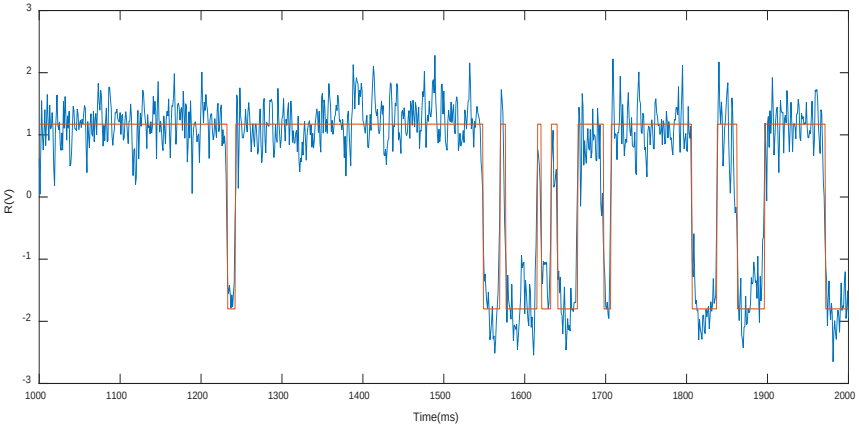

T_{qp}=10 ms
T_{qp}=1 ms
T_{qp}=100 us
PSD(1/Hz)
F(Hz)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

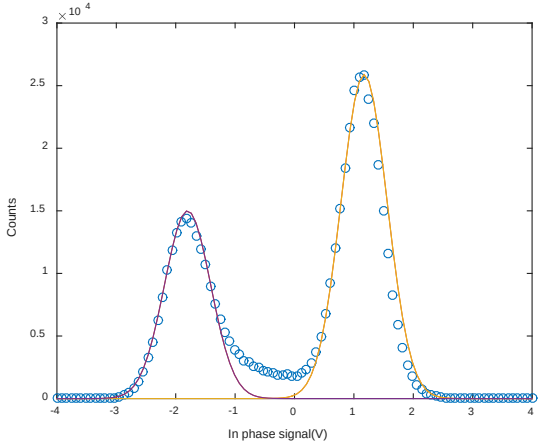
PSD of time traces for DC bias at degeneracy point

Low illumination

High illumination

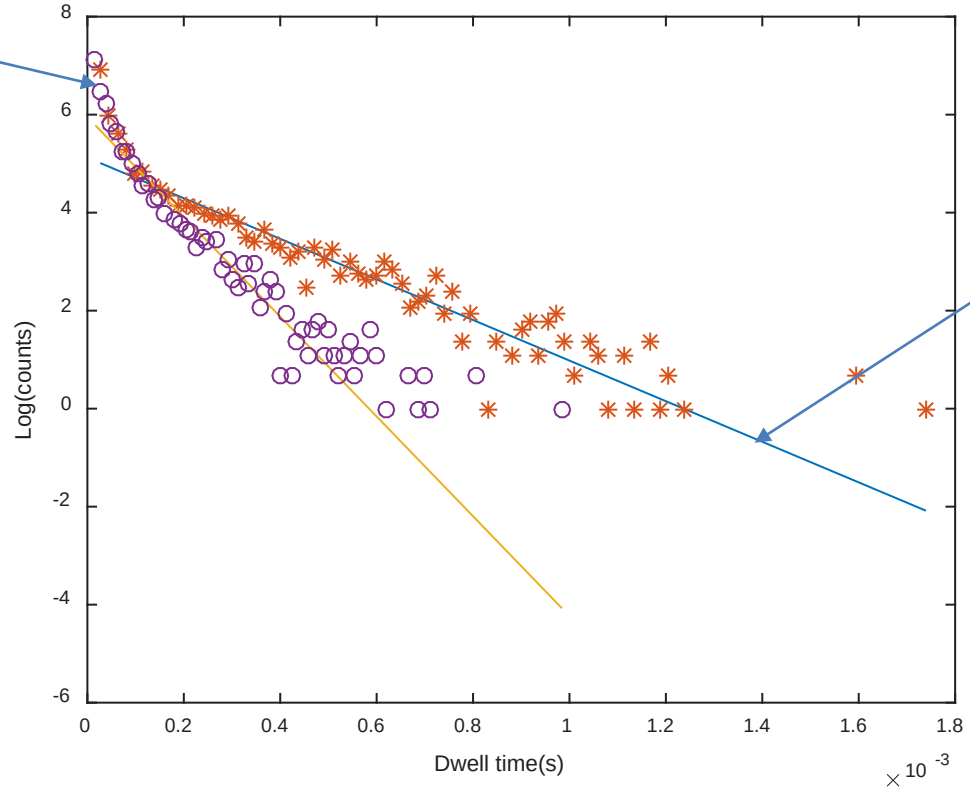




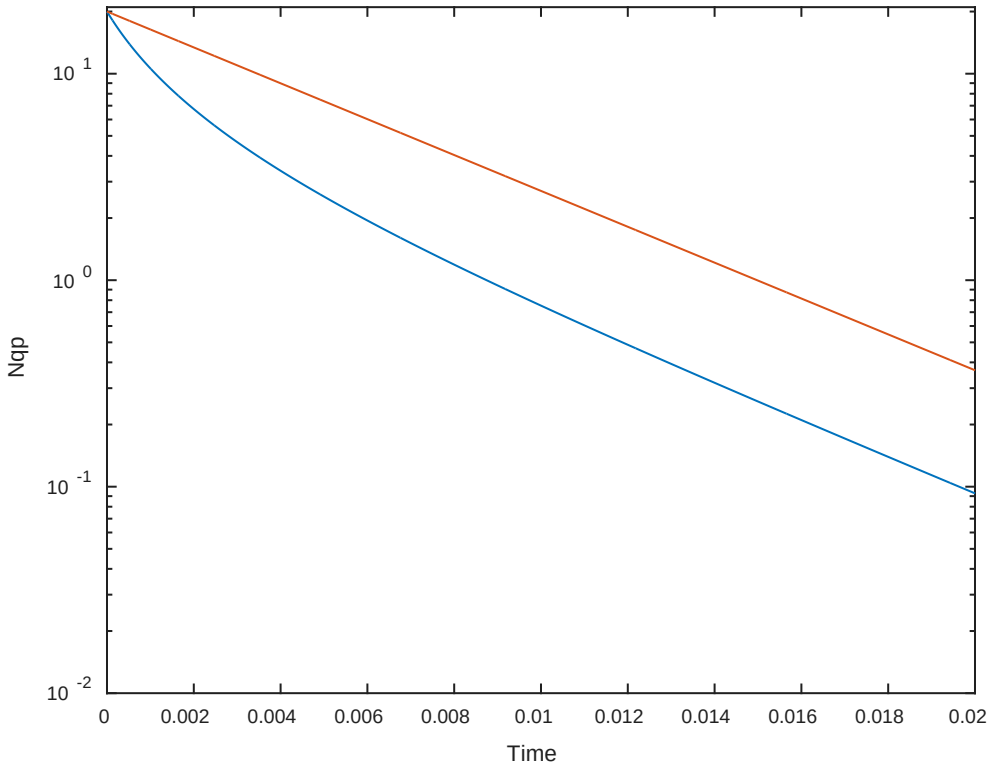


Low illumination levels

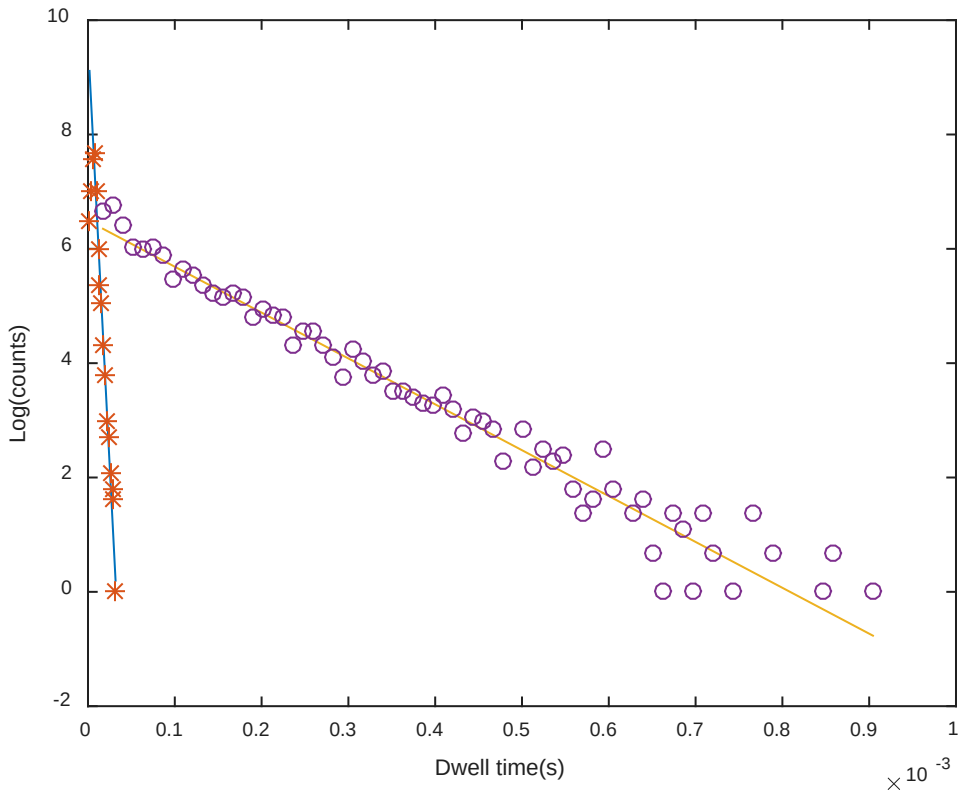
Faster initial decay



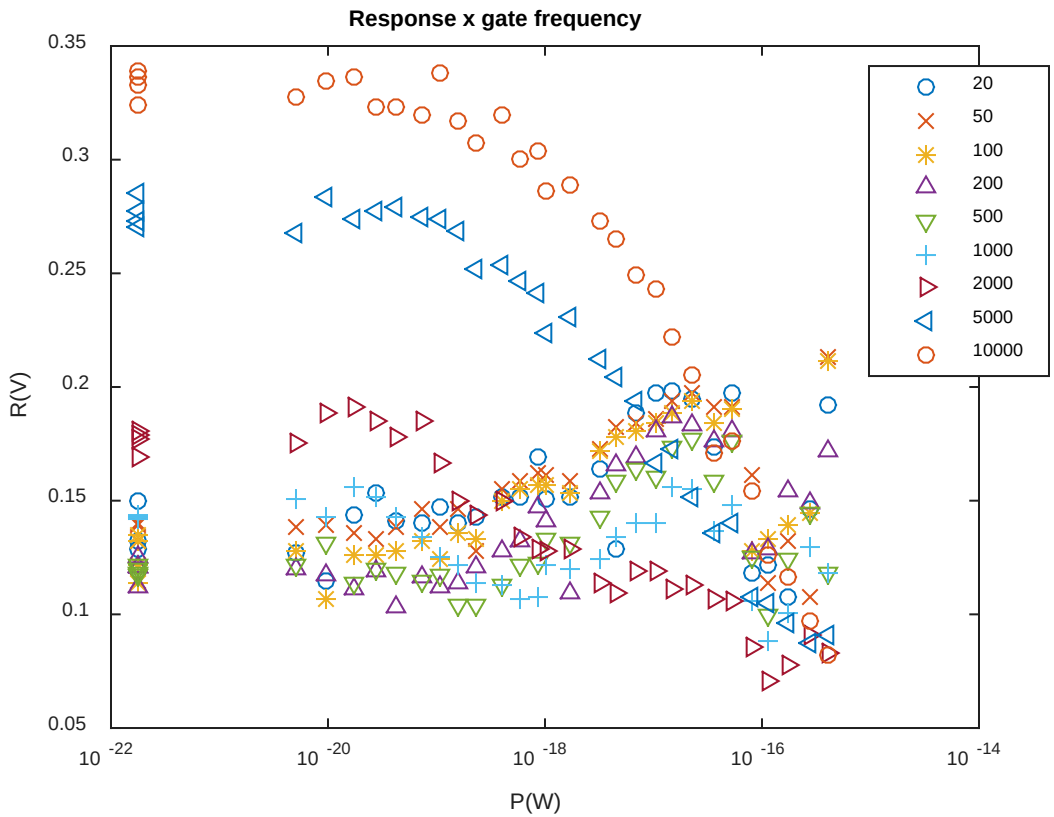
Exponential decay with “residual” lifetime


10 1
10 0
10 -1
10 -2
Nqp
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
Time

High illumination level – just exponential decay



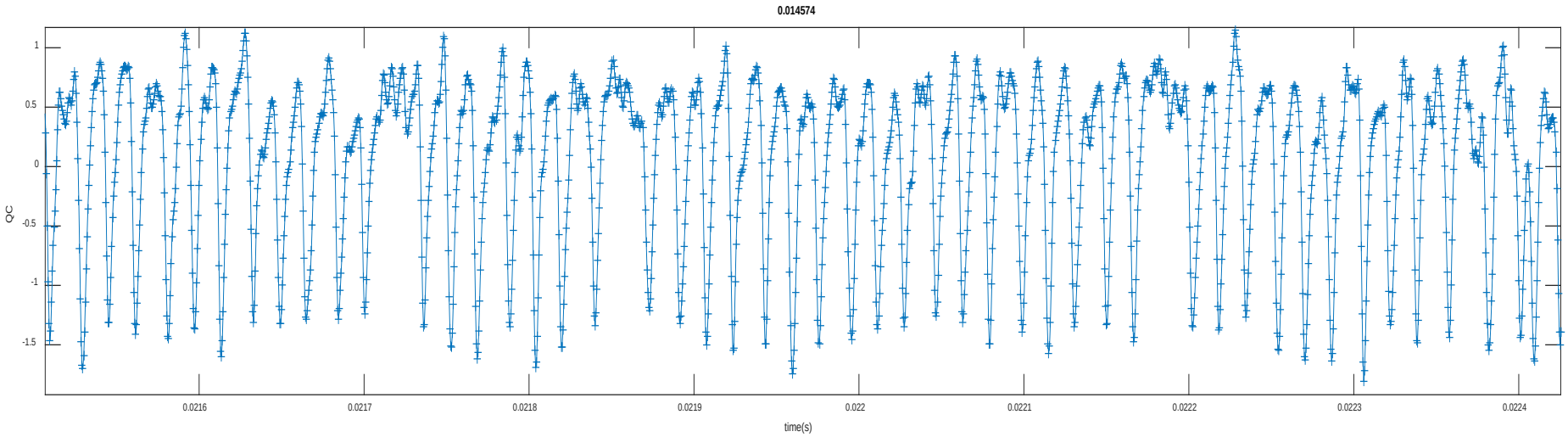
How to filter out background tunneling



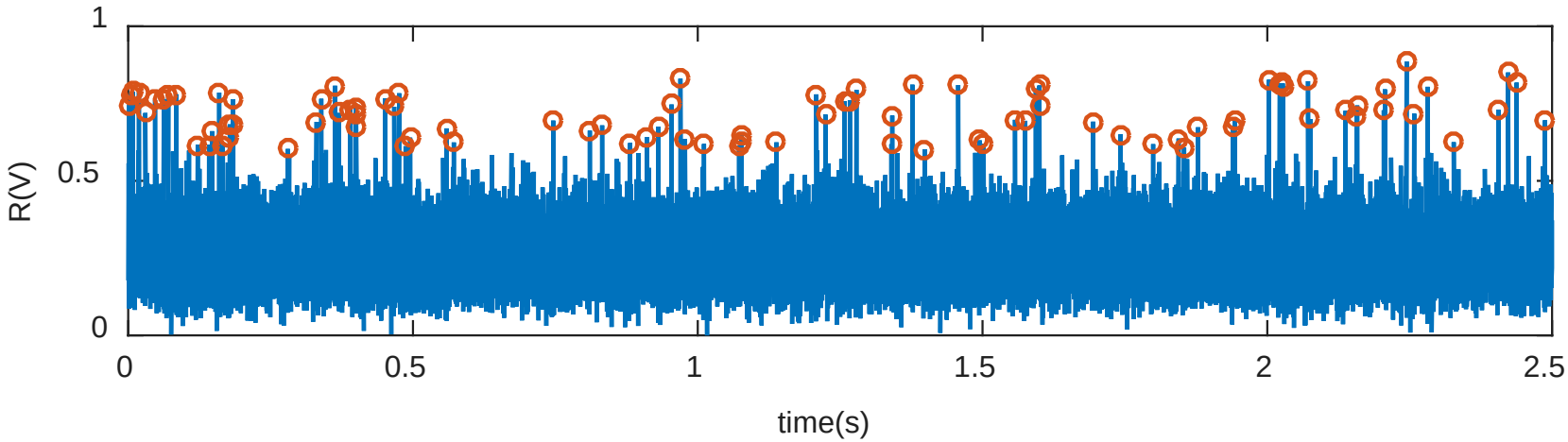
- Averaging trace on scope and then taking the standard deviation
- Random tunneling will cause the signal to average out
- Sweeping faster unpoison this sample => if we cross the degeneracy point in last time that it takes for a quasiparticle to tunnel due to background tunneling events, we don't see those events anymore
- Photon hits yield temporarily extremely high tunneling rates and those events will be visible

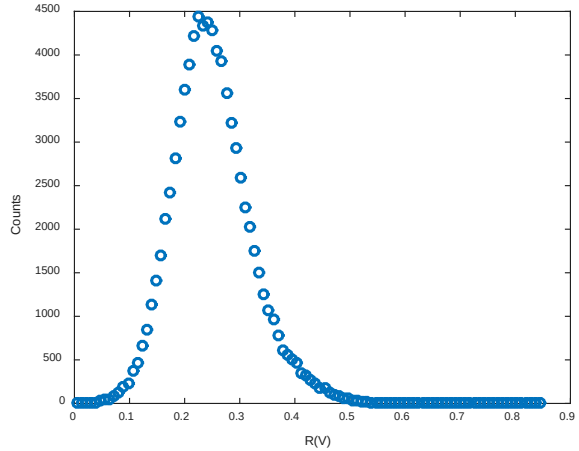
Measuring QC traces in a single time stream with fast sweep rate

- Raw QC time trace should be absolutely periodic
- Gaps are due to high tunneling in suppressing the qc signal
- Either due to background tunneling or photon hits
- Sweeping fast to suppress background tunneling



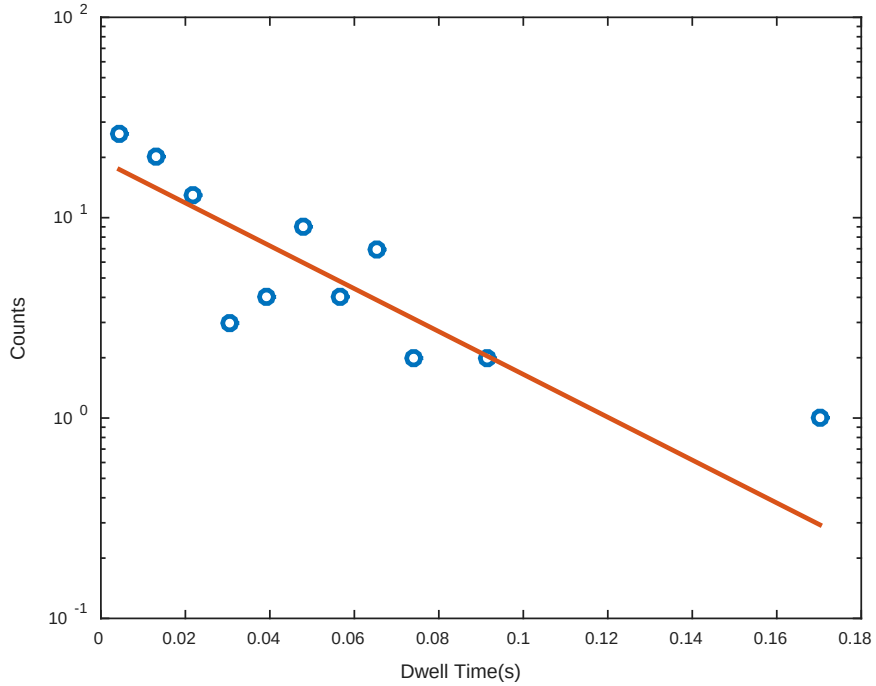
Calculate amplitude of chunks of raw trace

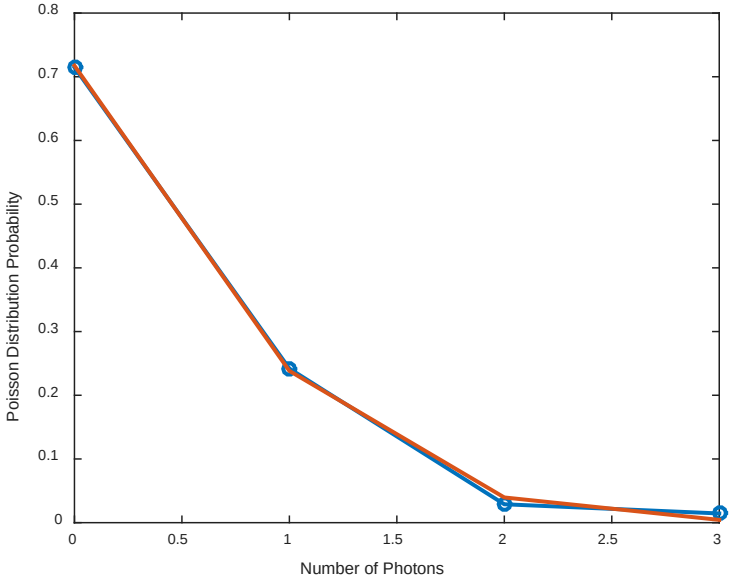




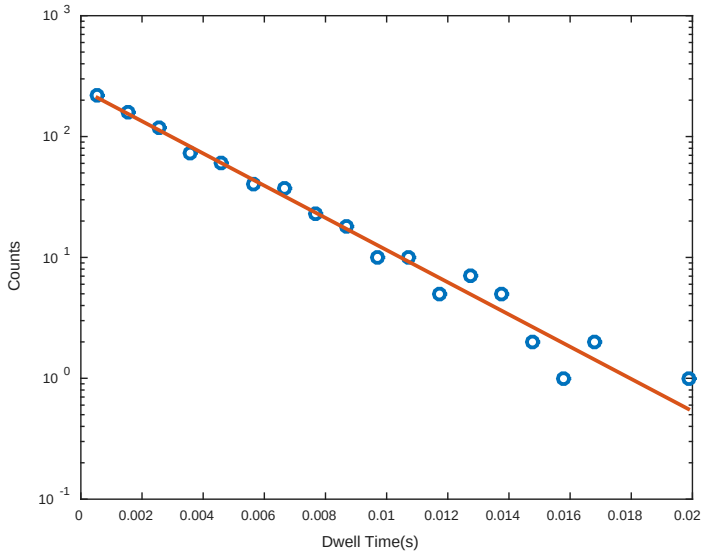
- From time traces calculated standard deviation of slices corresponding to 2 QC peaks (to avoid problems at the edge of sweep with e-shifts)
- Subtracted this trace from the maximum of the traces
- “gaps” in the qc will show up as peaks, i.e. background tunneling events or photon hits
- Do this for all blackbody temperatures

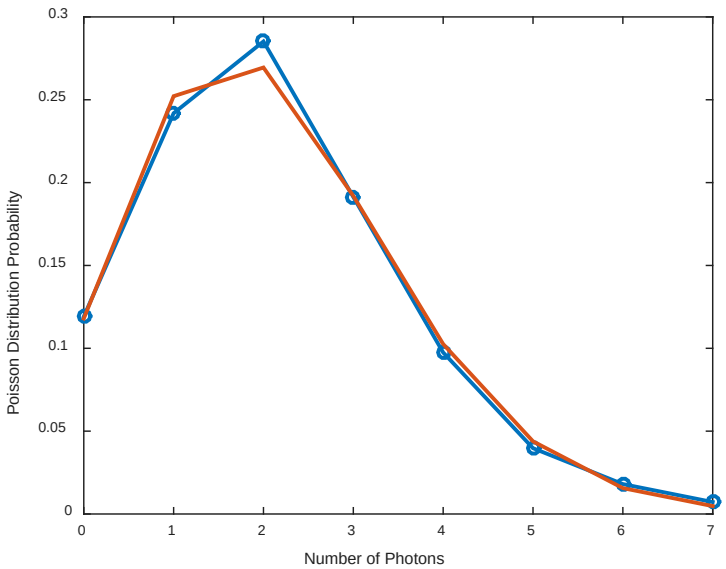
- From the photon time traces, extract dwell time histograms – exponential decay corresponds to Poisson statistics
- Calculate probability of having N photons for a time interval 36ms
- Plot probability x number of photons; blue is measured, red Poisson statistics (no fit, just using measured average number of photons)

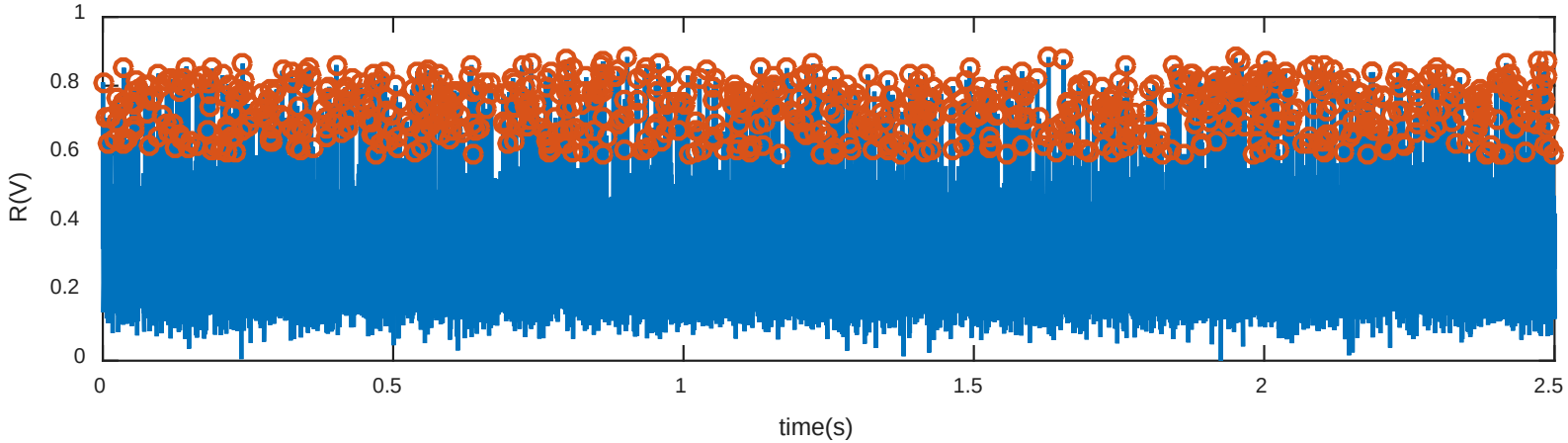




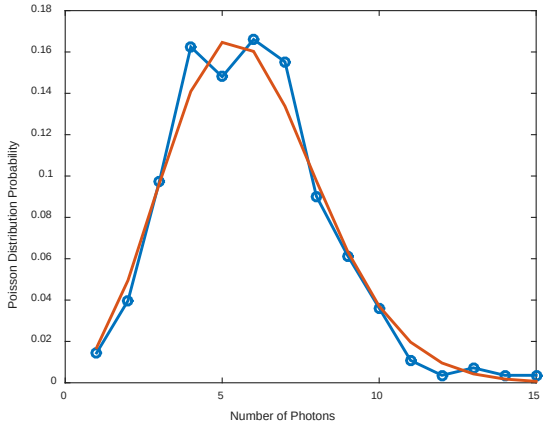
SOMEWHAT HIGHER BLACK BODY TEMPERATURE

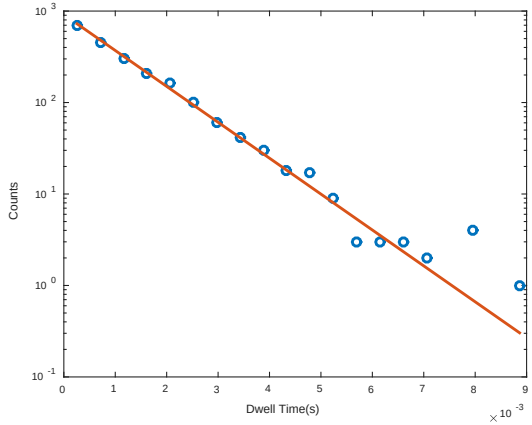


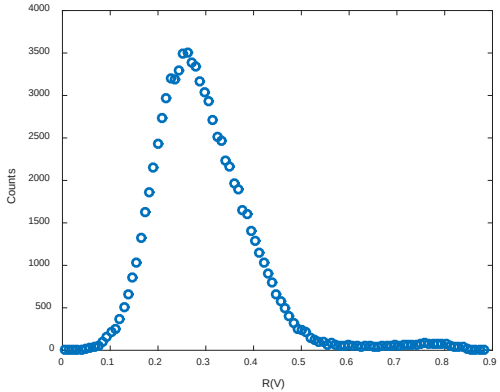


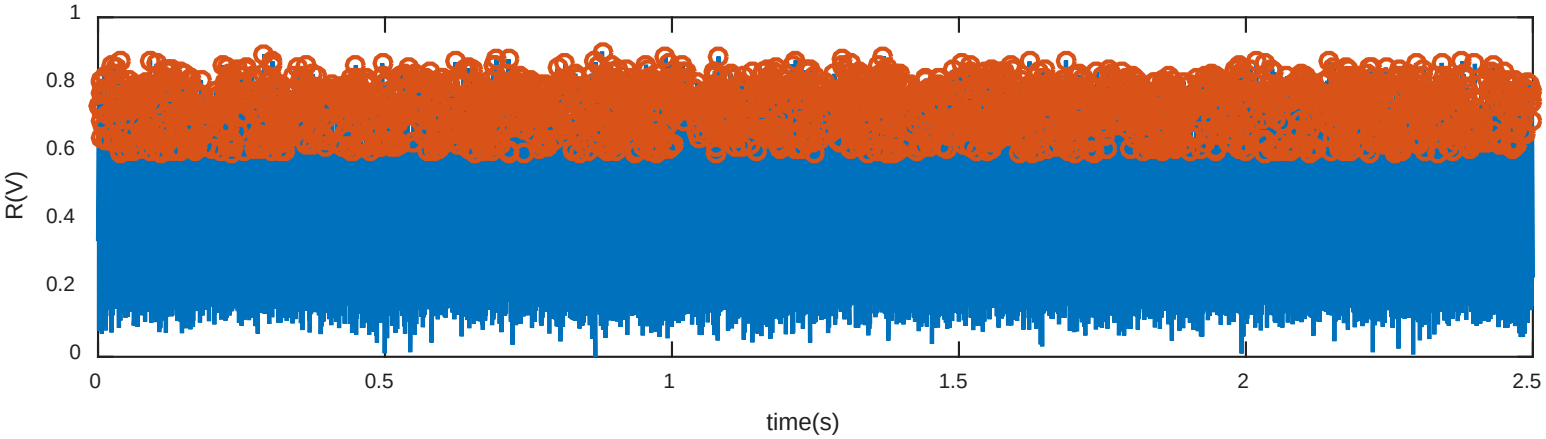


SOMEWHAT HIGHER BLACK BODY TEMPERATURE



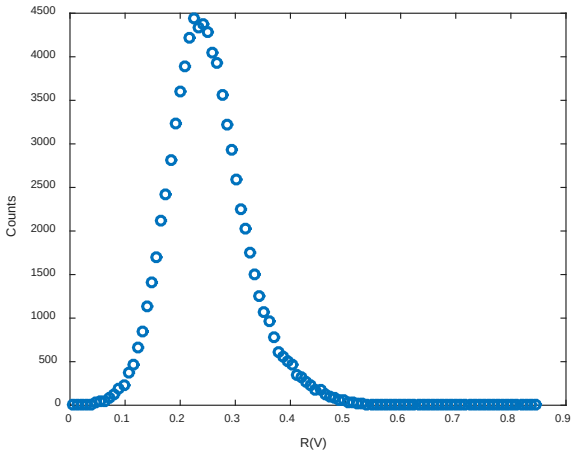




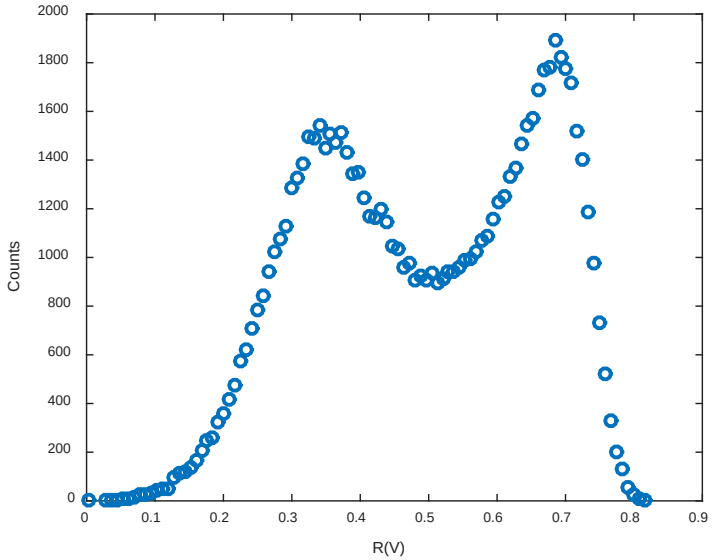


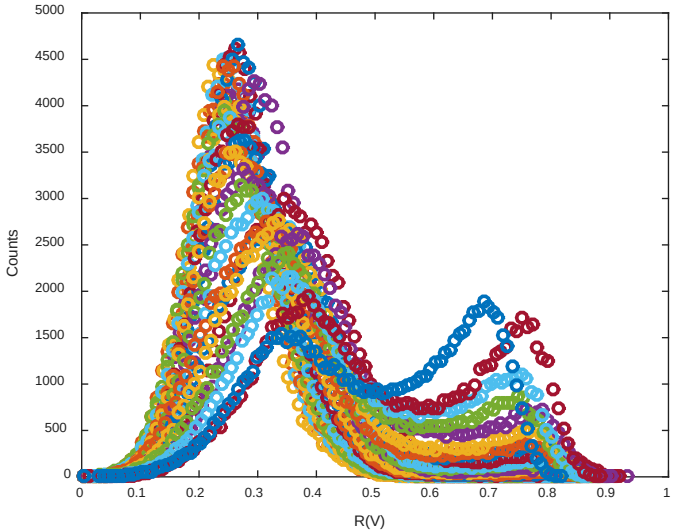
Histogram of response for various black body temperatures
For cold black body only peak around 0.25 exists
For hot black body peak around 0.6-0.7 is larger than peak at 0.25

Cold black body

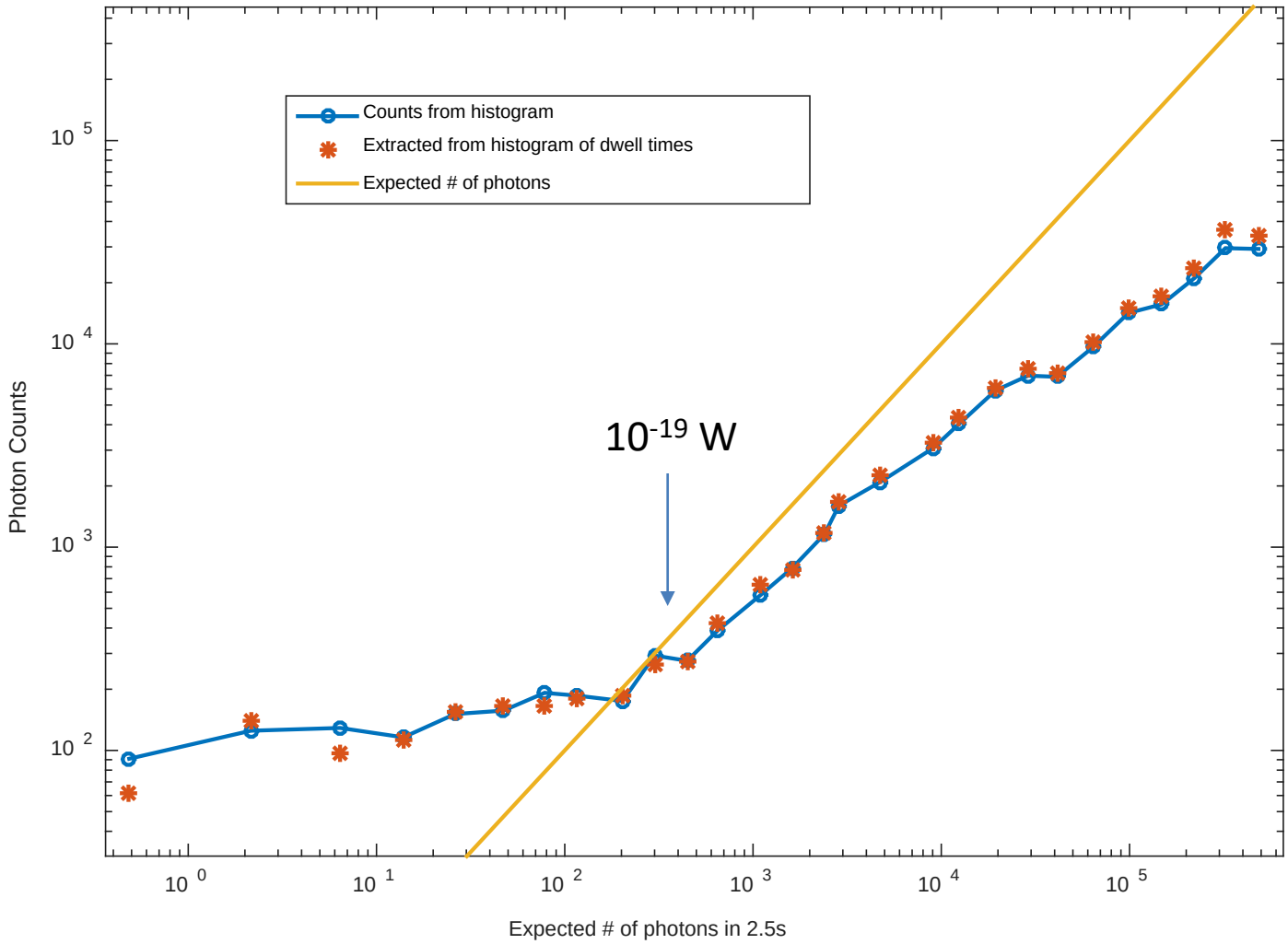


Hot black body

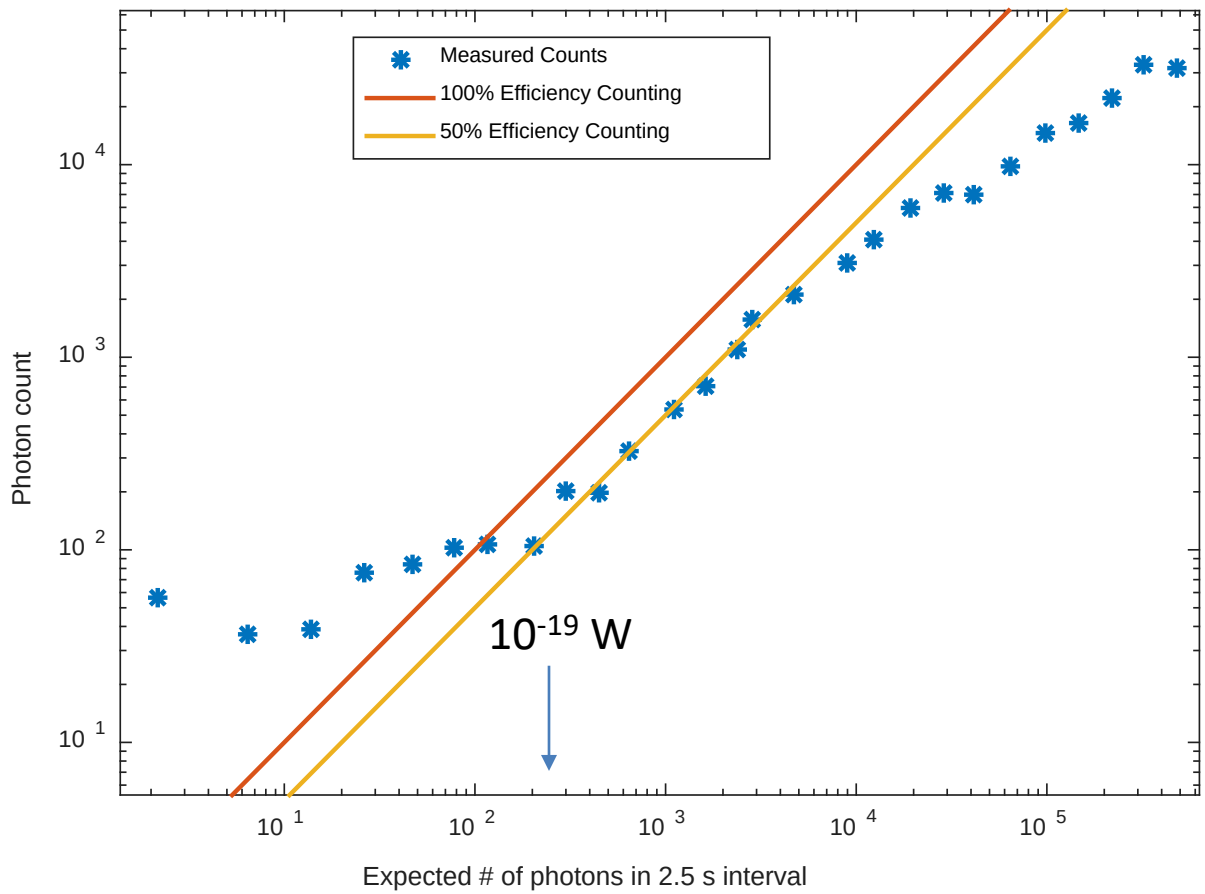




Counts of response between 0.6 and 0.9 versus number of expected photons



Subtracting the minimum count as a background rate
Averaging counts from histograms and counts extracted from dwell time histograms



Conclusion

- Stand alone QCDs shot noise limited and with reasonable efficiency
- Spectrometer on wafer with R ~ 600
- Demonstrated mesh absorber QCD shot noise limited and with good efficiency
- Designed and procured spectrometer holder fixture
- Designed Spectrometer Wafer, Mesh absorbers, QCD Readout Circuit
- Procured Photomask for fab
- SOI wafer for fab ordered
- Demonstrated Single Photon Counting at 1.5THz with Lumped Element Mesh absorber QCD