Ligo SURF: Enhancement of SHG for Squeezing in aLIGO

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LIGO's Squeezer

- Dominant quantum noise = shot and radiation pressure
- Q&M predicts that even in absence of light, the electromagnetic field fluctuates in phase and amplitude, "vacuum fluctuations"
  - source of shot noise in LIGO
- BUT, the product of quadrature (operators on E-field in phase and A) deviations in phase and amplitude restricted to some minimum value
- Squeezing reduces deviations in one quadrature at the cost of increasing it in the other

Poisson Statistics

$$p(n) = \frac{\mu^{-n} e^{-\mu}}{n!}$$

$$\sigma_n = \sqrt{\mu}$$

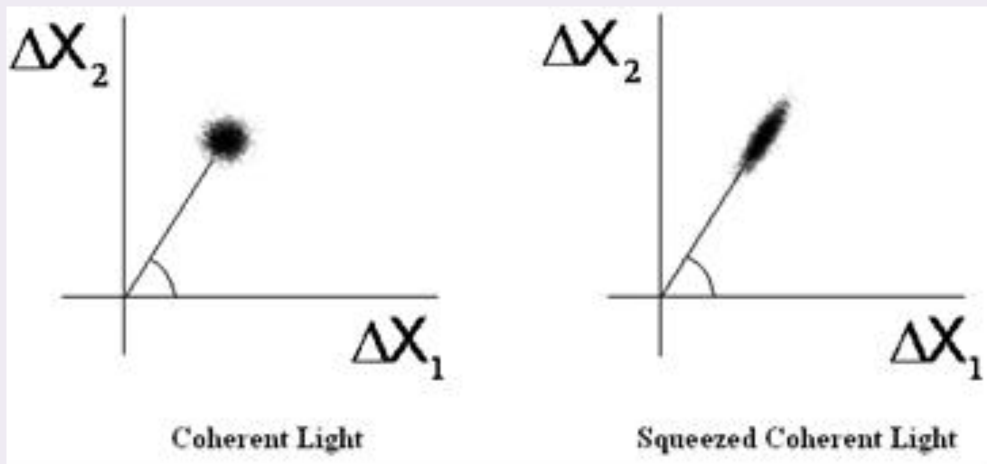


Figure 1 *The ball of uncertainty represents the noise on a signal compared to its amplitude and phase angle. For a squeezed state, this ball is compressed in one direction and stretched in the other.*

Squeezer in LIGO

- Improved sensitivity of the interferometer at the shot noise dominated bandwidth (~100 Hz)
  - LIGO fundamentally measures changes in relative phase of two beams in light traveling down the two arms of the port
- Alternative to boosting beam power to minimize shot noise

Second Harmonic Generation

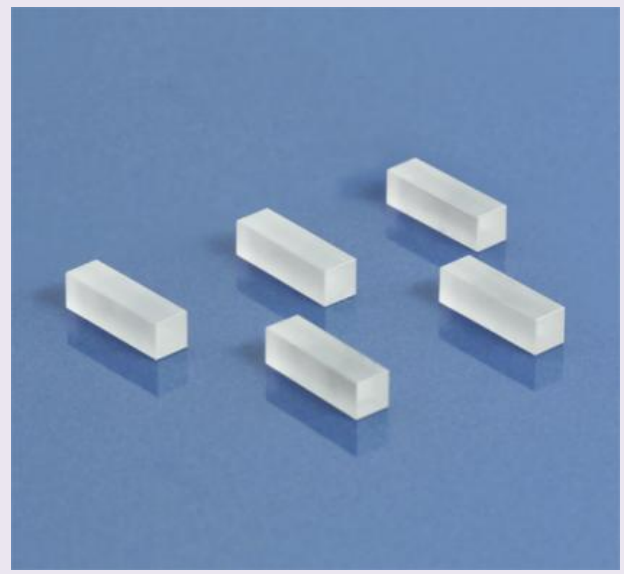
1) SHG is a nonlinear optical effect arising in dielectrics with a nonlinear susceptibility term proportional to the square of an (applied) electric field

$$\mathbf{P} = \epsilon_0(\chi^{(1)}_{ij}E_i + \chi^{(2)}_{ijk}E_iE_j + \chi^{(3)}_{ijkl}E_iE_jE_k + ...$$

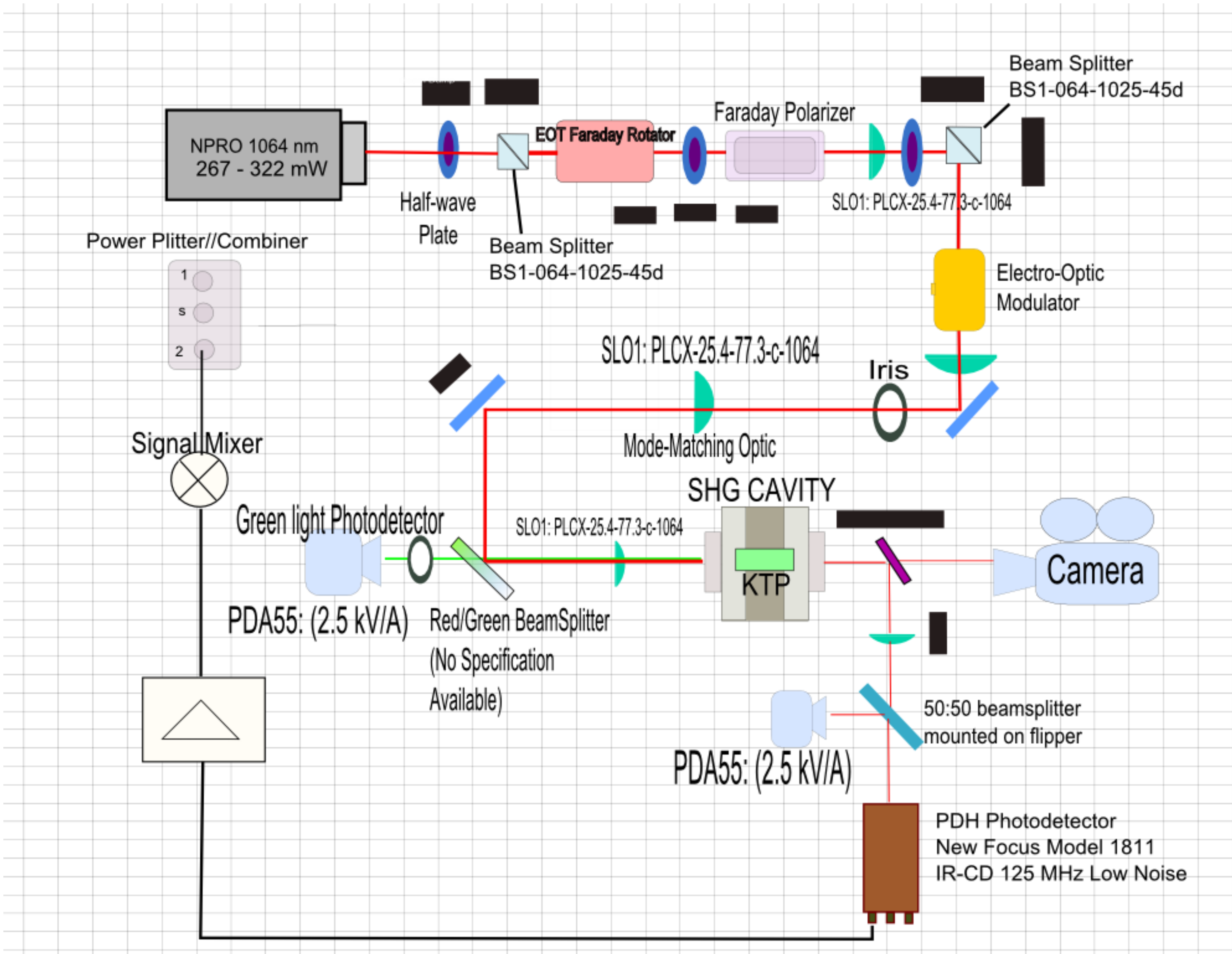
$$\chi^{(2)}_{ijk}(E^2_{0i}e^{-i2wt} + E^{*2}_{0i}e^{i2wt} + E_{0i}E^*_{0i}) + c.c$$

2) Only in non-centrosymetric crystals (variant under r -> -r transformation)

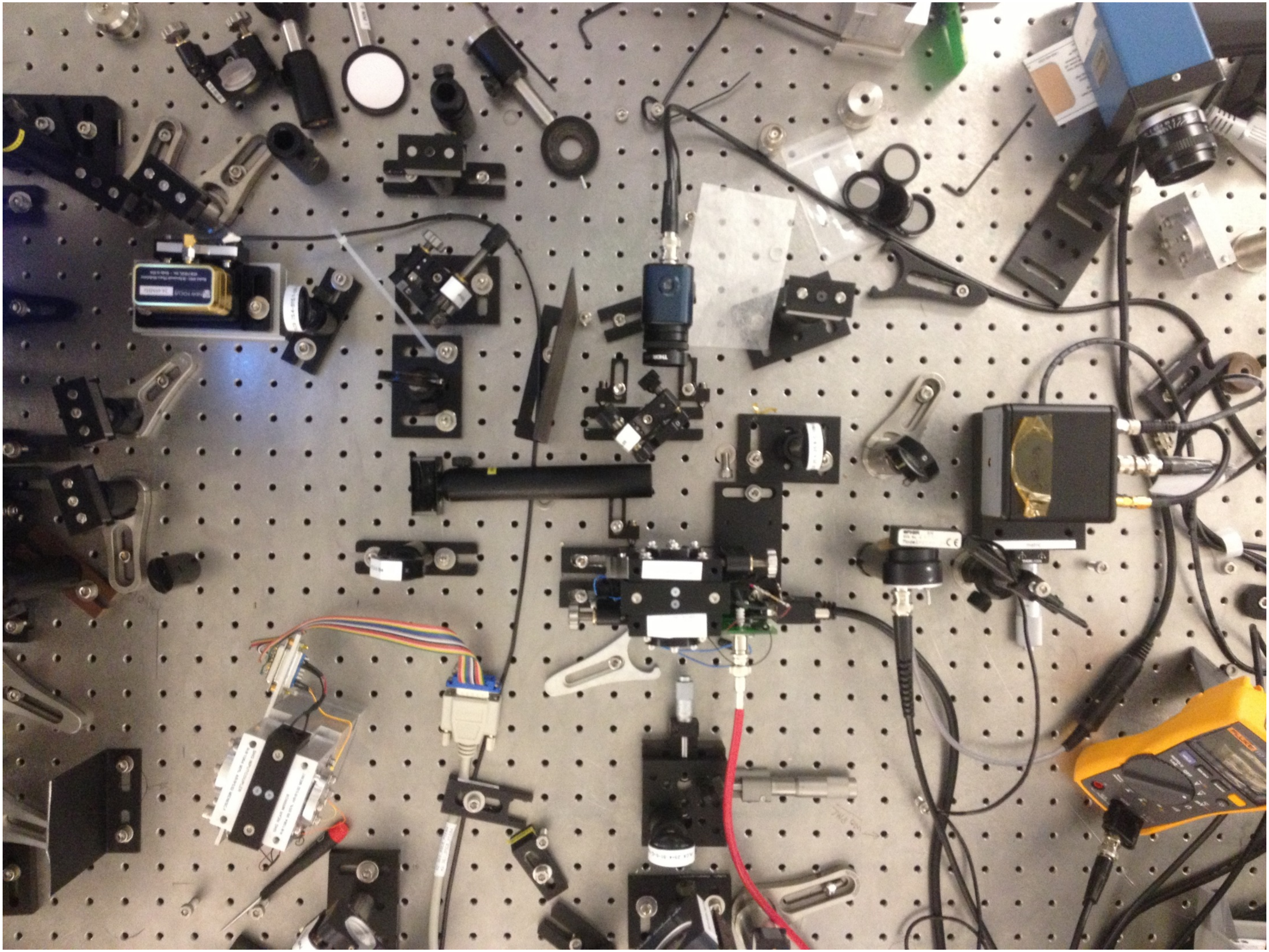
3) SHG crystal = Periodically poled KTP



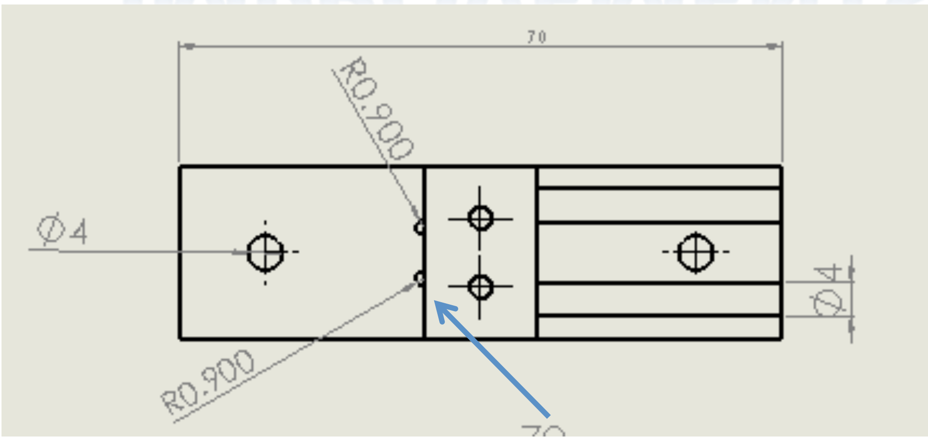
A resonant cavity enhances SHG; higher achievable optical intensities (unconverted beam remains in cavity for more passes)



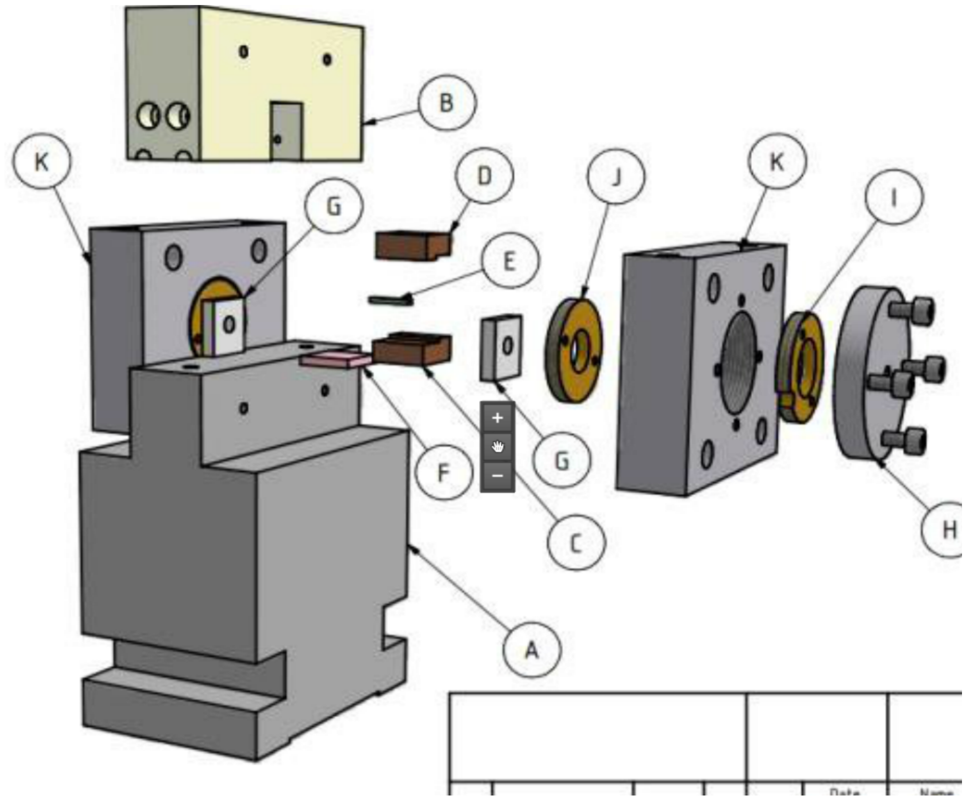
NPRO 1064 nm
267 - 322 mW
Half-wave
Plate
Beam Splitter
BS1-064-1025-45d
EOT Faraday Rotator
Faraday Polarizer
Beam Splitter
BS1-064-1025-45d
SLO1: PLCX-25.4-77.3-c-1064
Power Plitter//Combiner
1
s
2
Electro-Optic
Modulator
SLO1: PLCX-25.4-77.3-c-1064
Iris
Mode-Matching Optic
Signal Mixer
SHG CAVITY
Green light Photodetector
SLO1: PLCX-25.4-77.3-c-1064
KTP
Camera
PDA55: (2.5 kV/A)
Red/Green BeamSplitter
(No Specification
Available)
50:50 beamsplitter
mounted on flipper
PDA55: (2.5 kV/A)
PDH Photodetector
New Focus Model 1811
IR-CD 125 MHz Low Noise

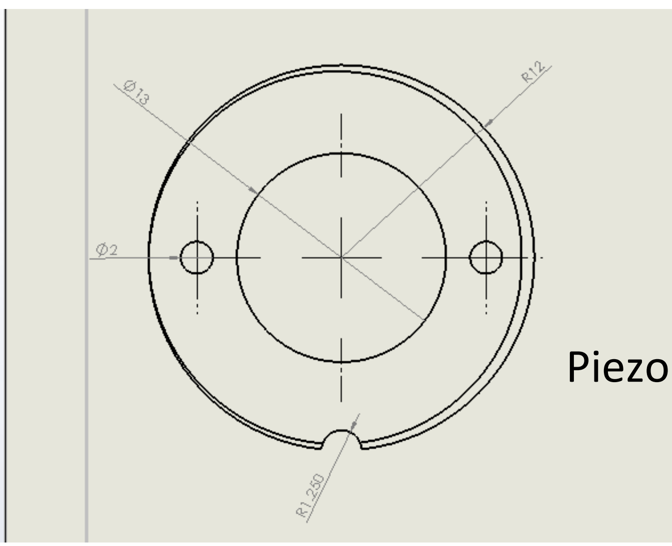


INSTALLATION IMPROVEMENTS



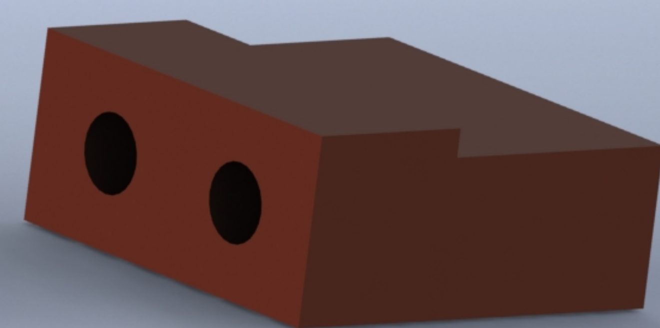
Thermistor Wire Slats



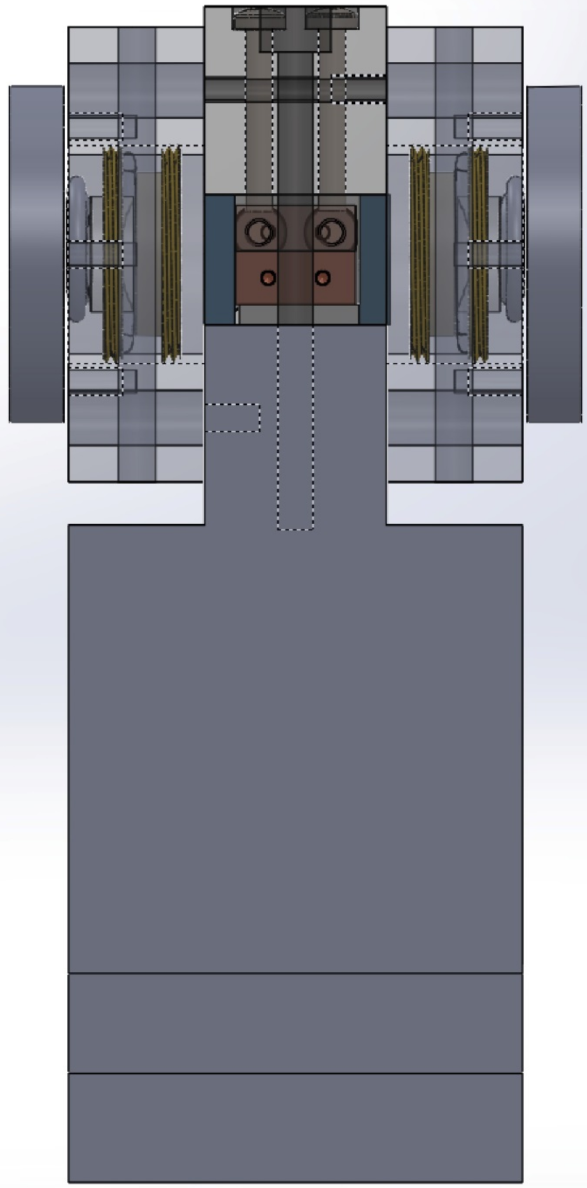


Piezo wire Slot

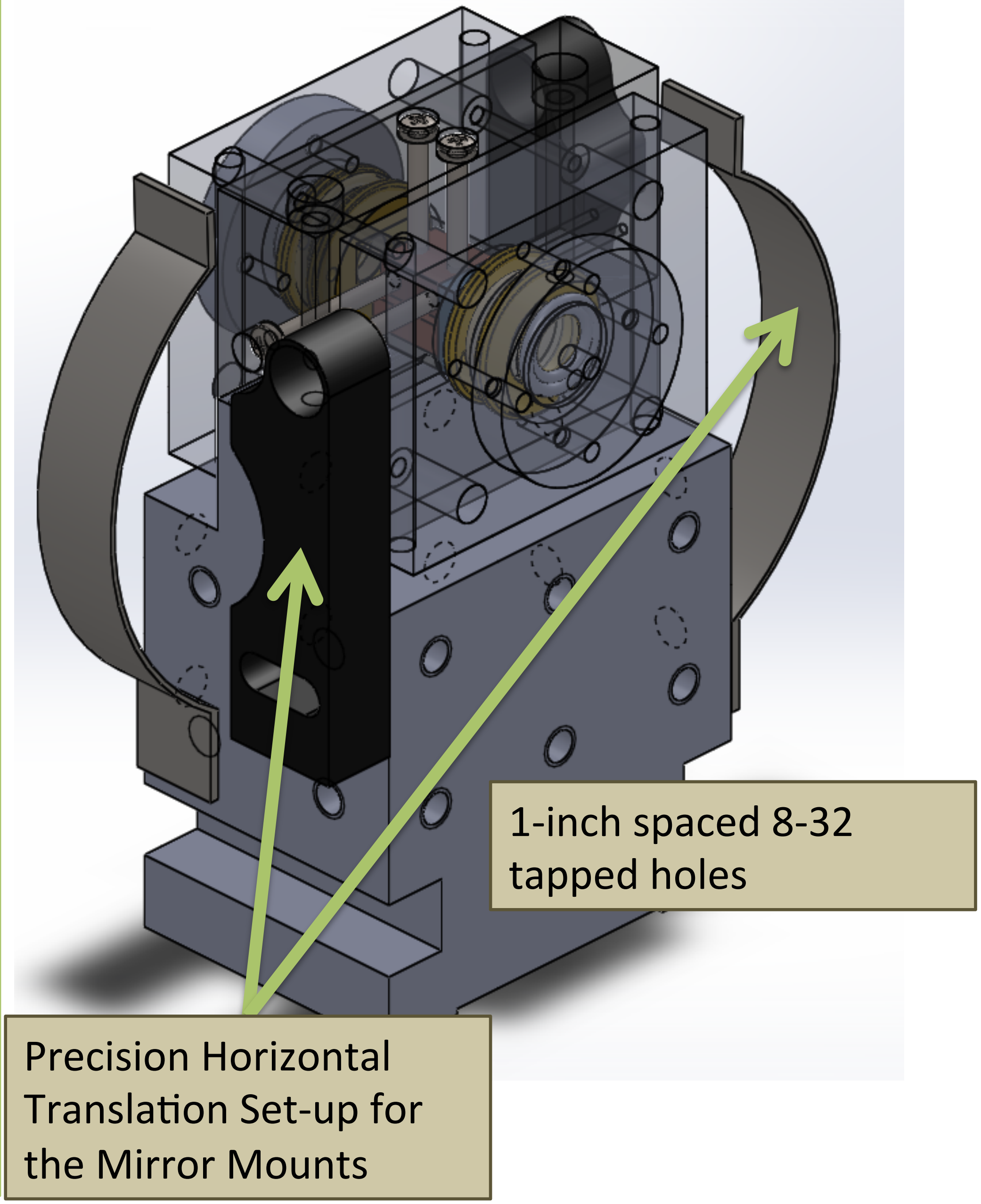
Enlarged Thermistor Ports



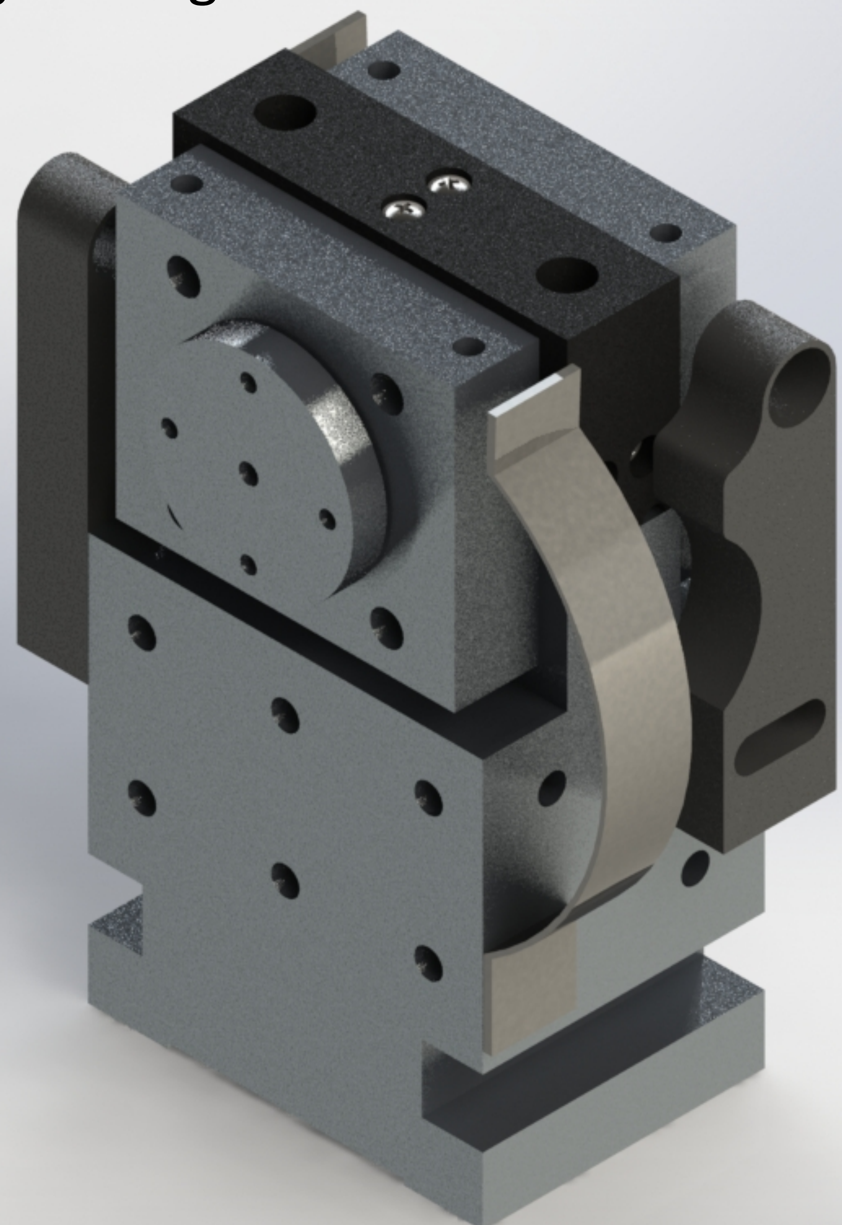
Old SHG (aka SHG 1.0)



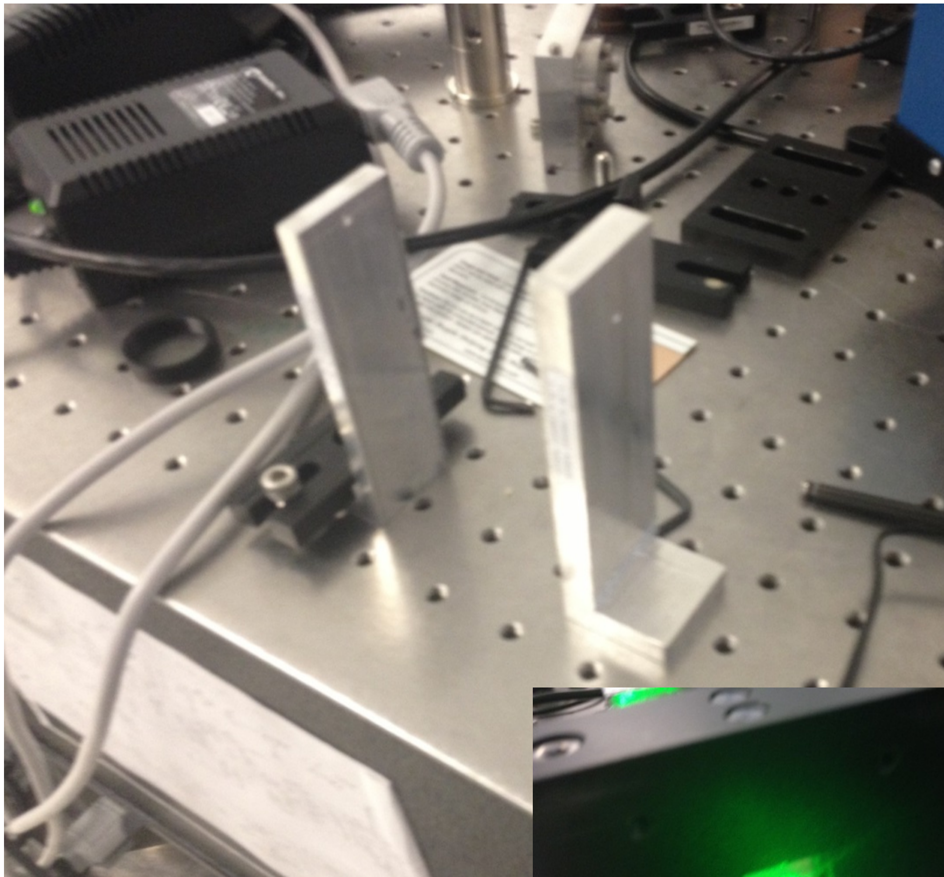
New SHG (v. 2.0)

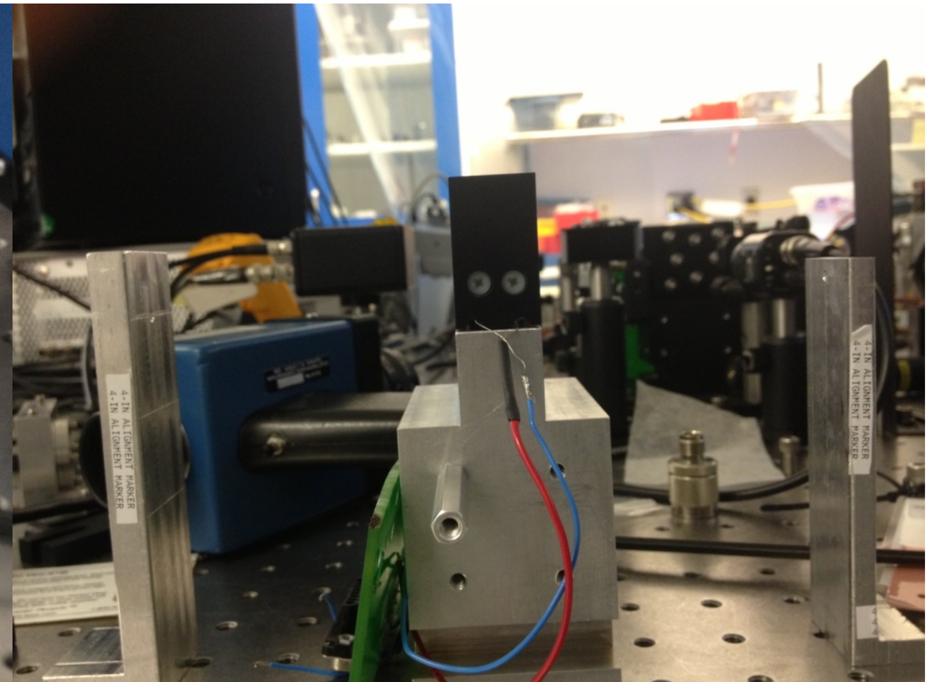


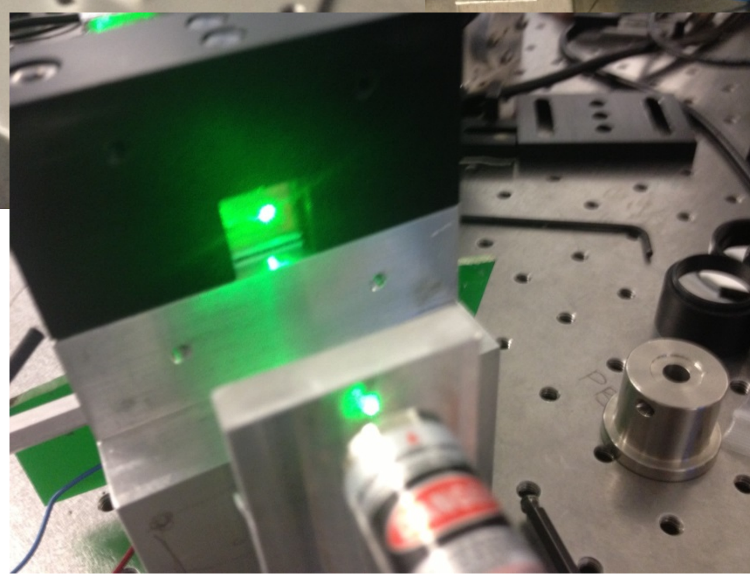
All New Design Changes Documented in SolidWorks2013



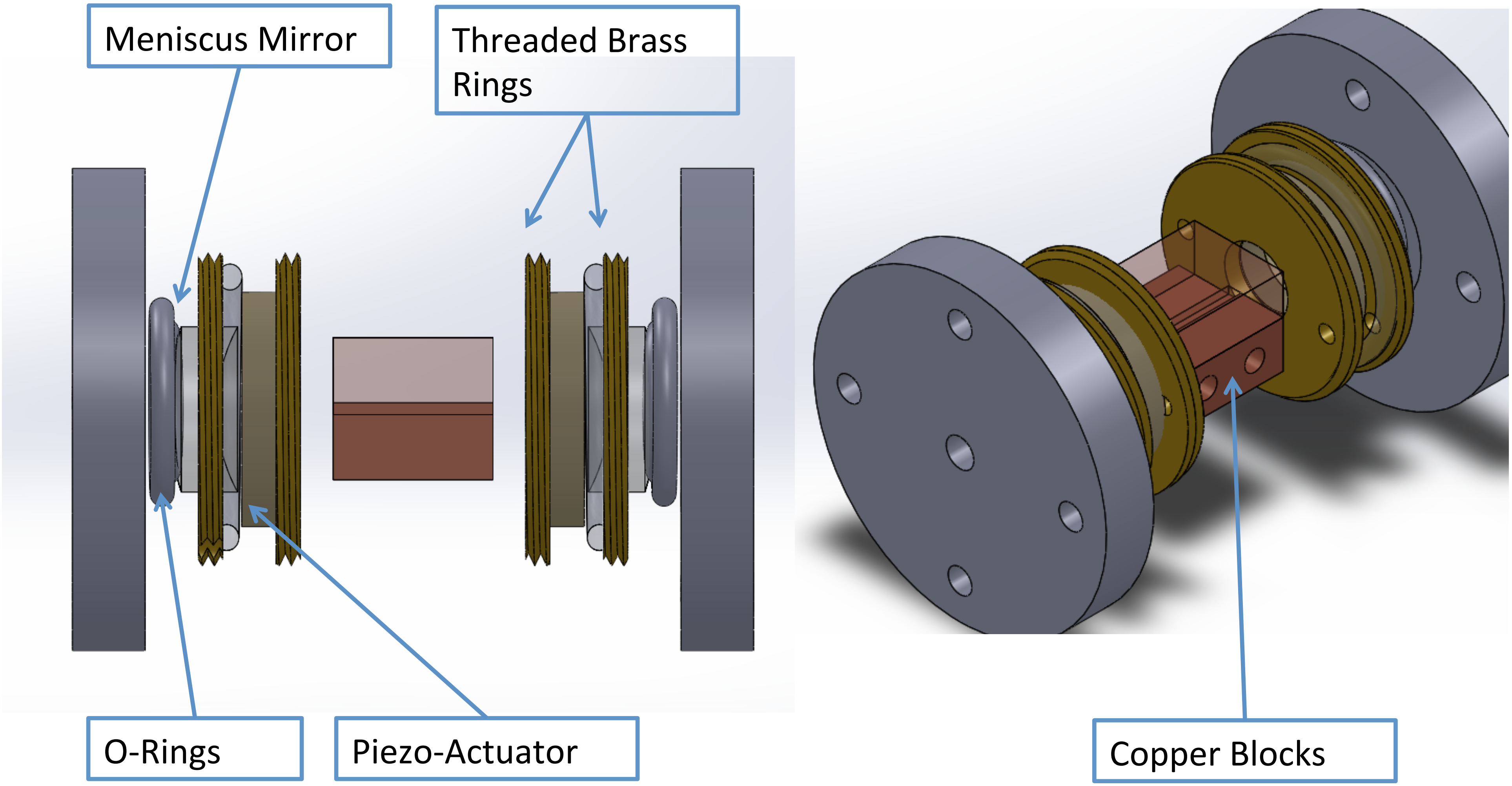
Alignment Improvement: Beam Marker







Inside the Cavity



SHG 2.0: Cavity Resonated in 3 Days!

Resonances from SHG 1.0;
Not as clean

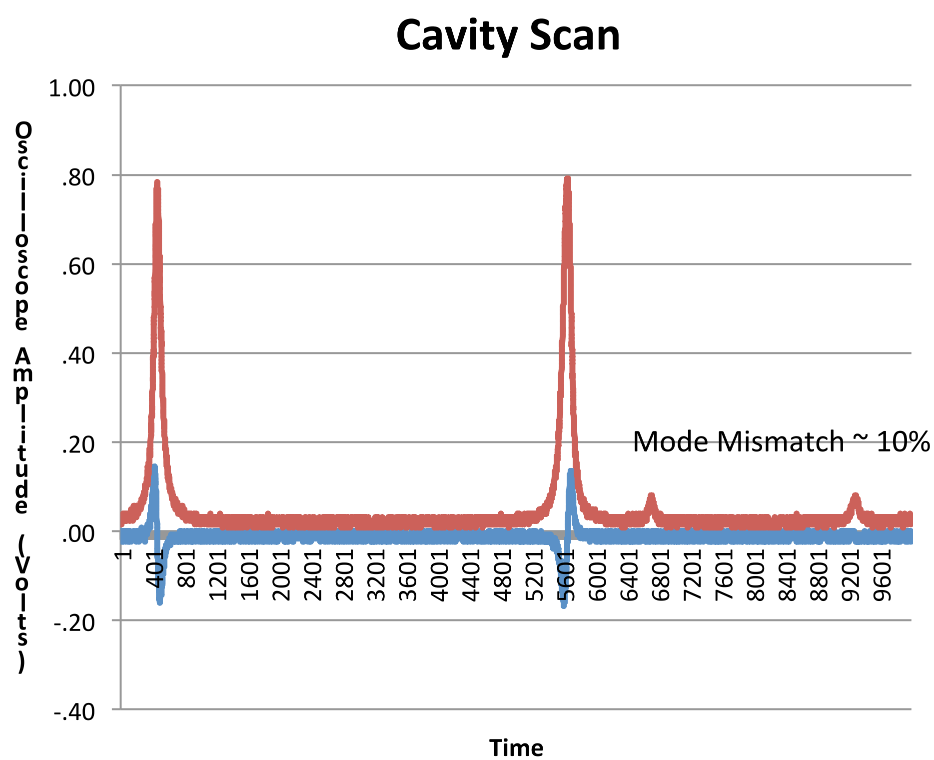
Control Diagram

Cavity Stabilization

- Pound-Drever-Hall servo stabilizes the cavity to peak transmission of 00 resonance.
- Gets an indirect measurement of the difference between the resonant frequency versus laser frequency by using the reflectivity of the cavity (mirrors)
- Reflection coefficient of the cavity is dependent on this difference:

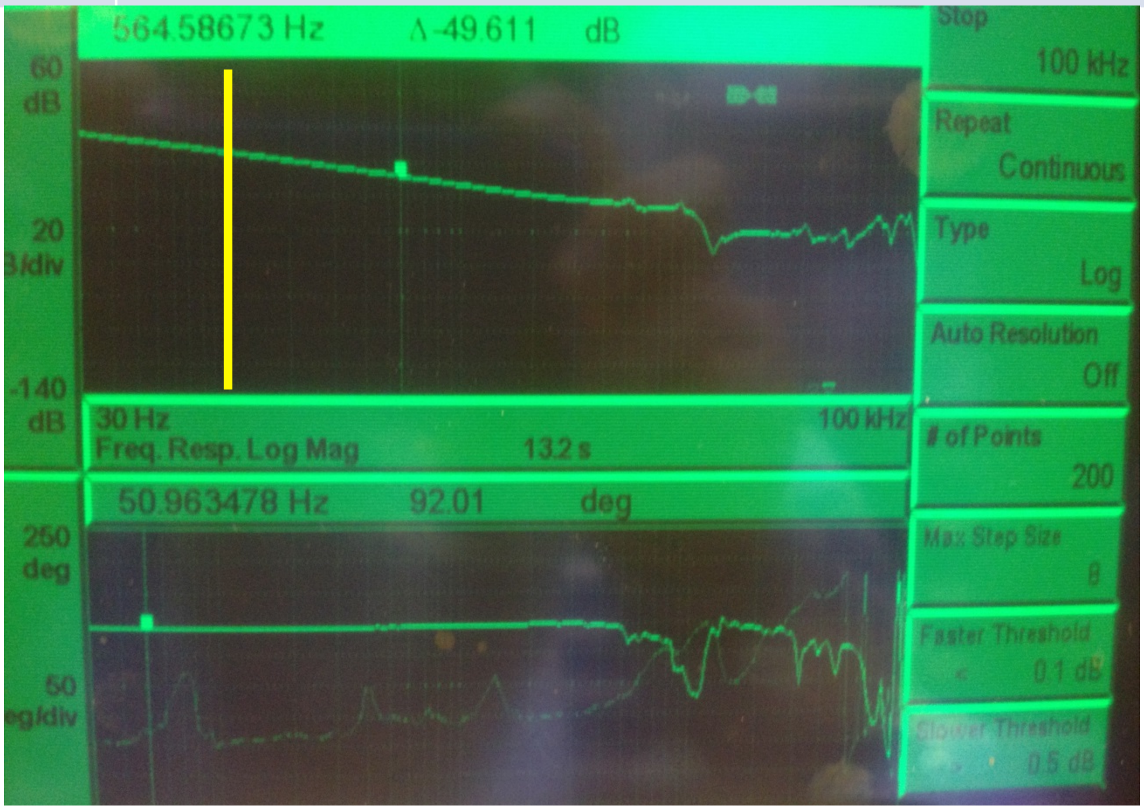
$$F(\omega) = \frac{r(e^{\frac{i\omega}{\Delta\nu_{fsr}}} - 1)}{1 - r^2 e^{\frac{i\omega}{\Delta\nu_{fsr}}}}$$

- Derivative with respect to frequency gives an antisymmetric function about the resonant frequency
  - Contains information as to whether the cavity should be shortened or lengthened
  - AND the servo is invariant to intensity noise

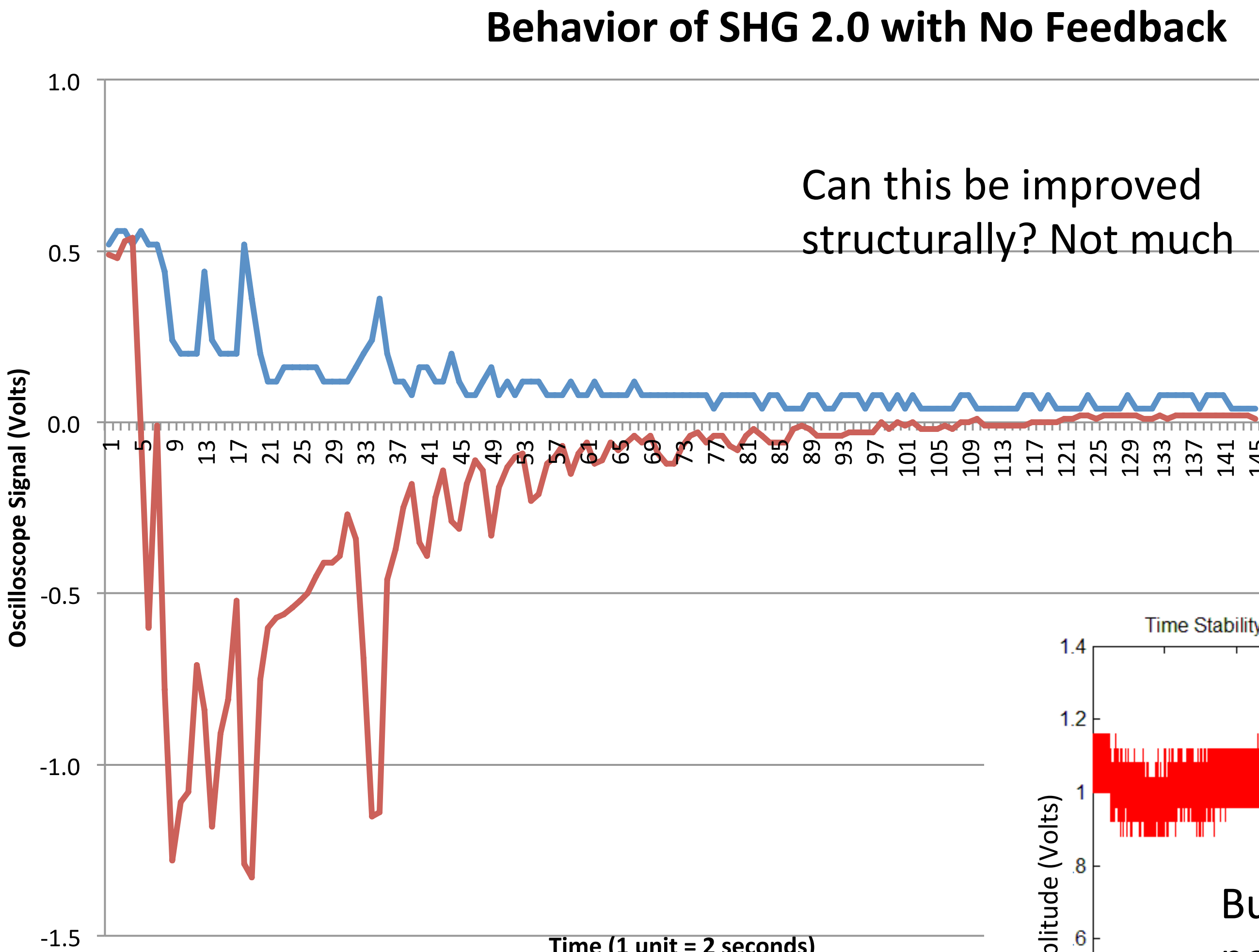


Frequency Response (Open Loop)

Data for PDH Frequency Response	
Unity Gain Frequency	~170 Hz
PZT Resonance	~10 kHz
Phase Margin	~270 degrees
Gain Margin	N/A (can't tell where -180 degrees really is)
Low frequency gain	18-20 dB

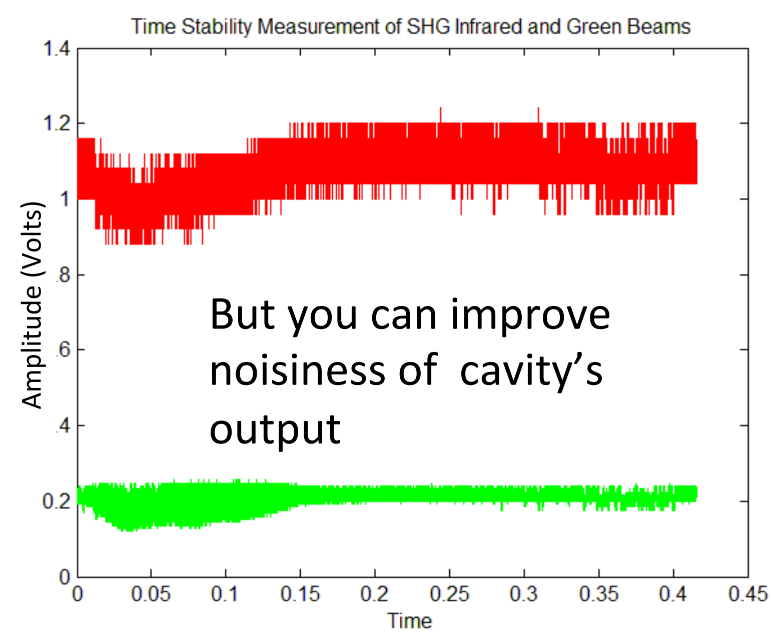


Cavity without Lock



Can this be improved structurally? Not much

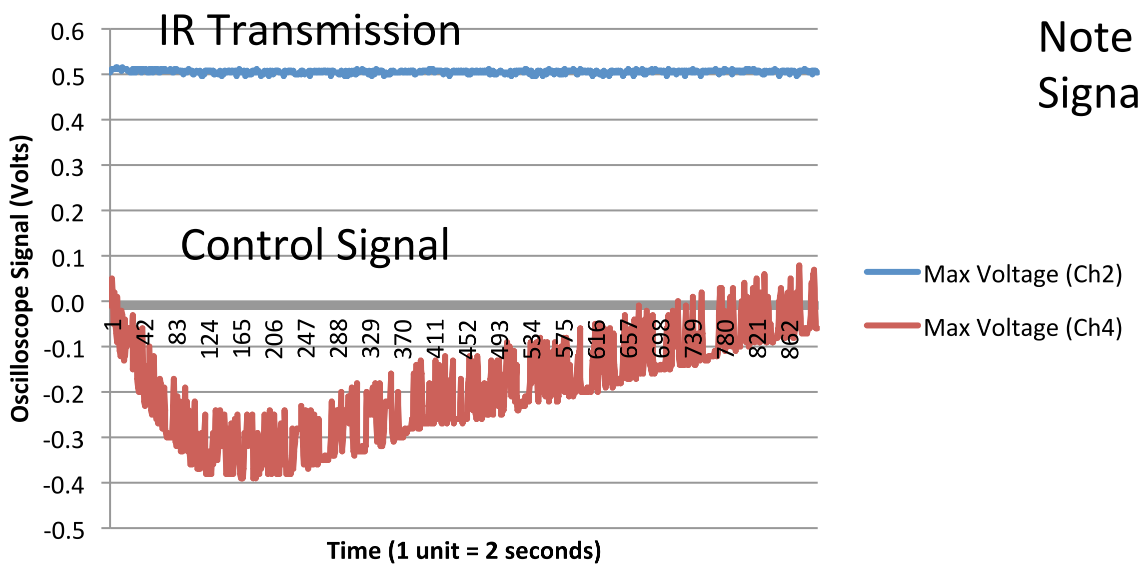
Falls out of resonance largely due to frequency instability of laser

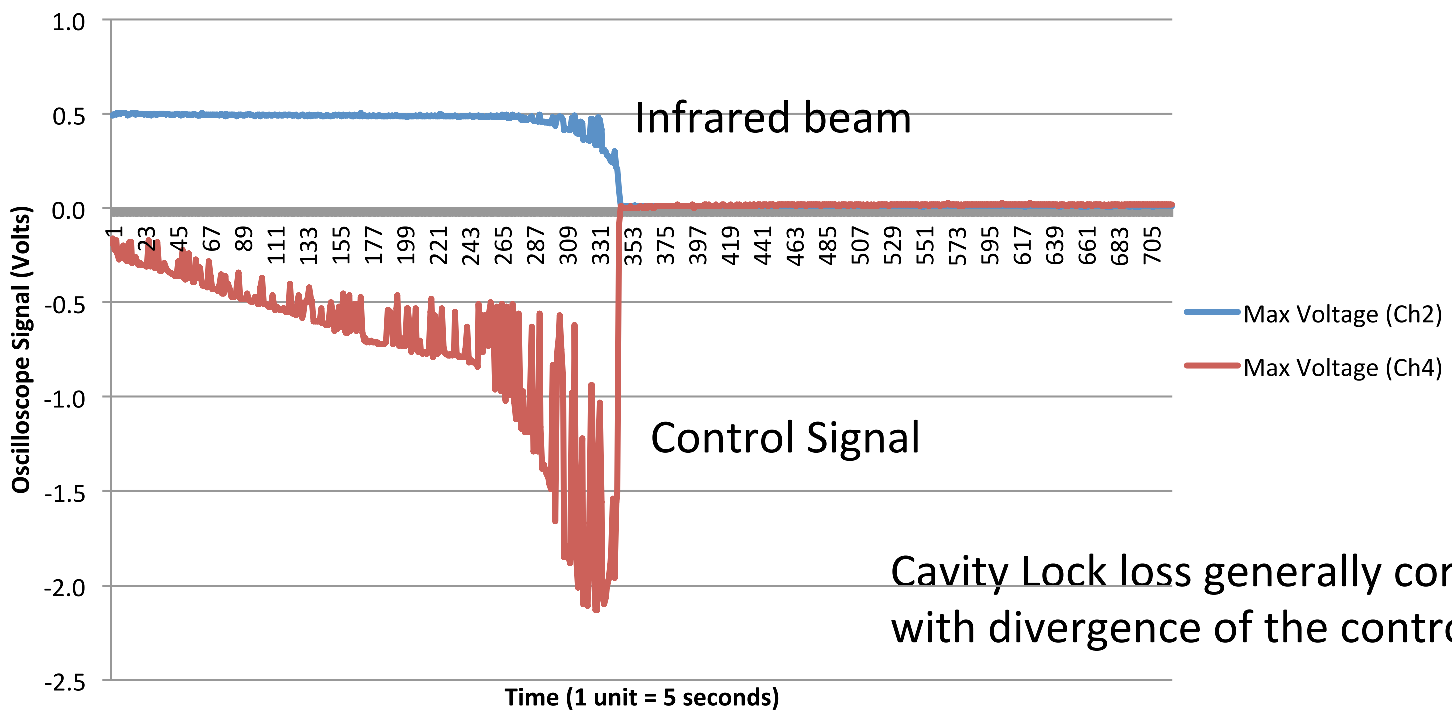


But you can improve noisiness of cavity's output

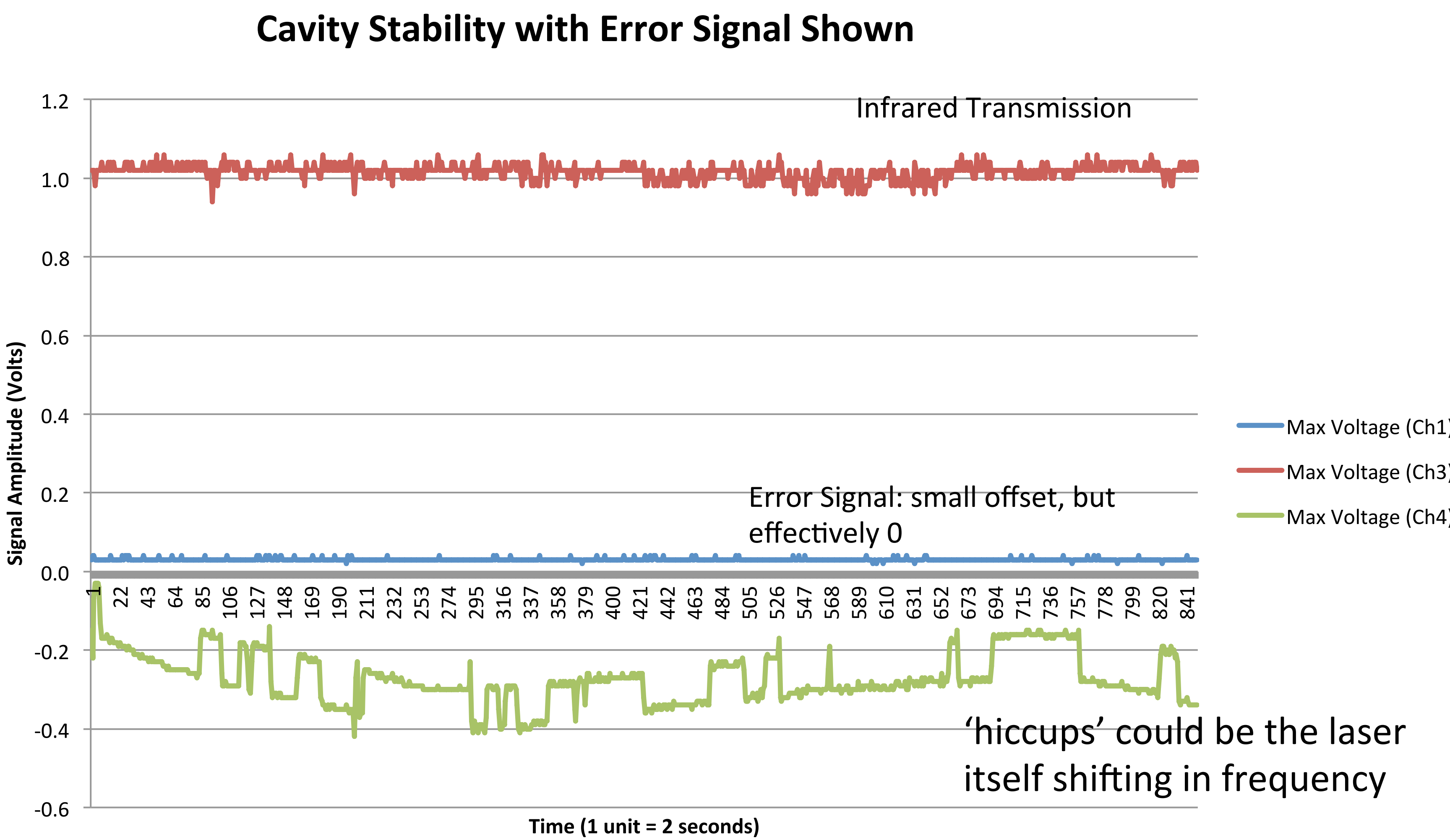
Comparison of Error Signal and Infrared Beam Lock

Note how the control Signal Drifts in Time



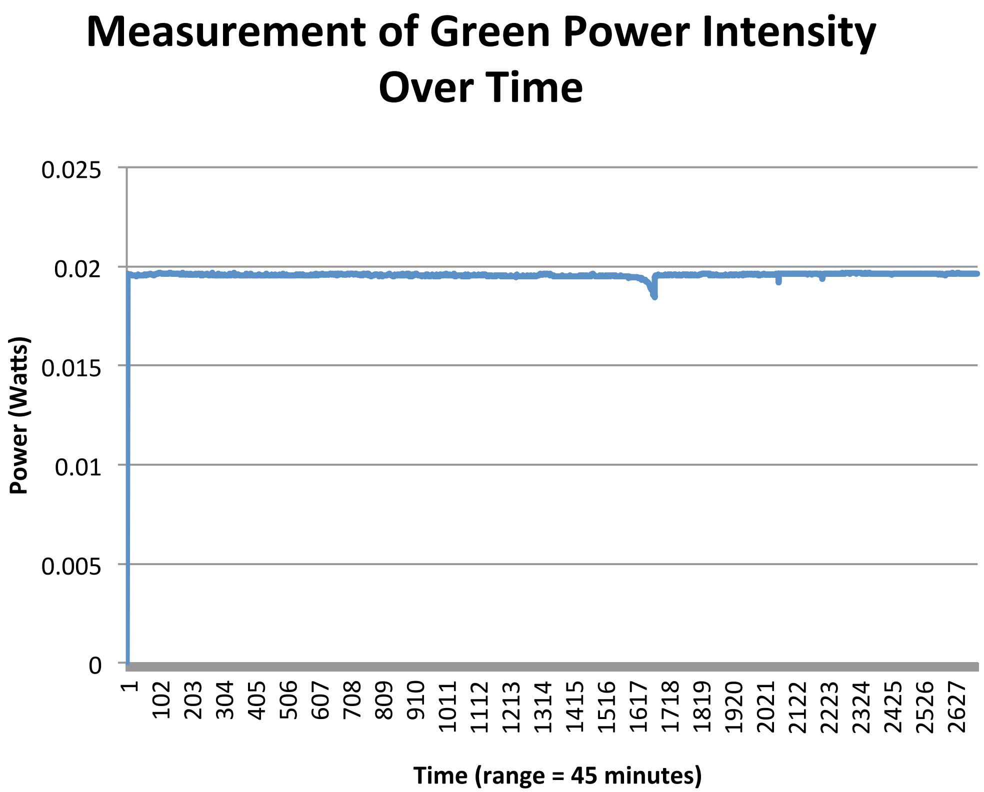


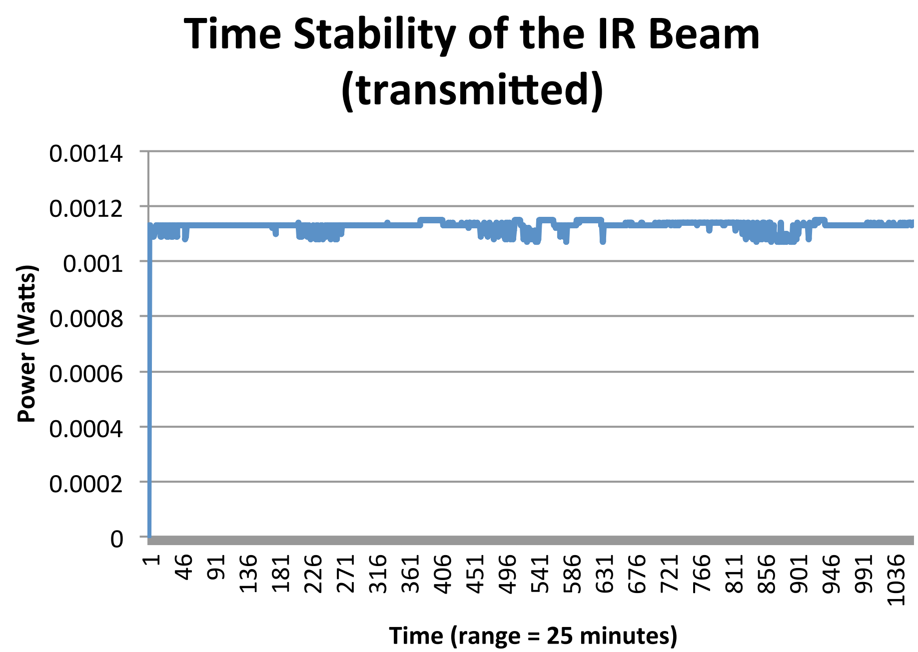
Cavity Lock loss generally corresponds with divergence of the control signal

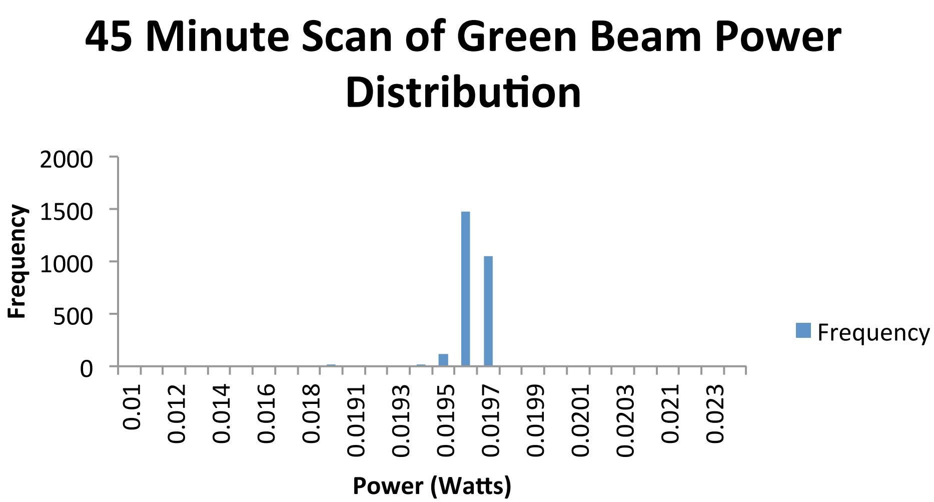


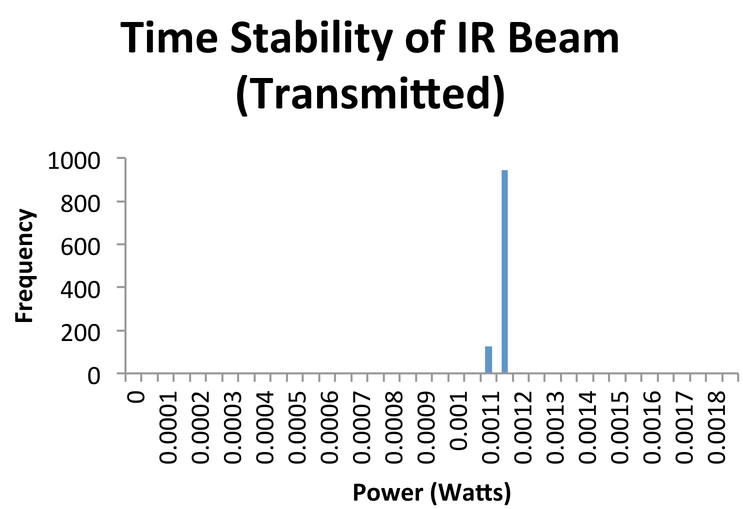
The Integral Control (which in the PDH is assumed by the pre-amp) creates a control signal of the form: $C(t) = G_{prop}\varepsilon(t) + G_{int}\int_{t_0}^{t} \varepsilon(t')dt'$

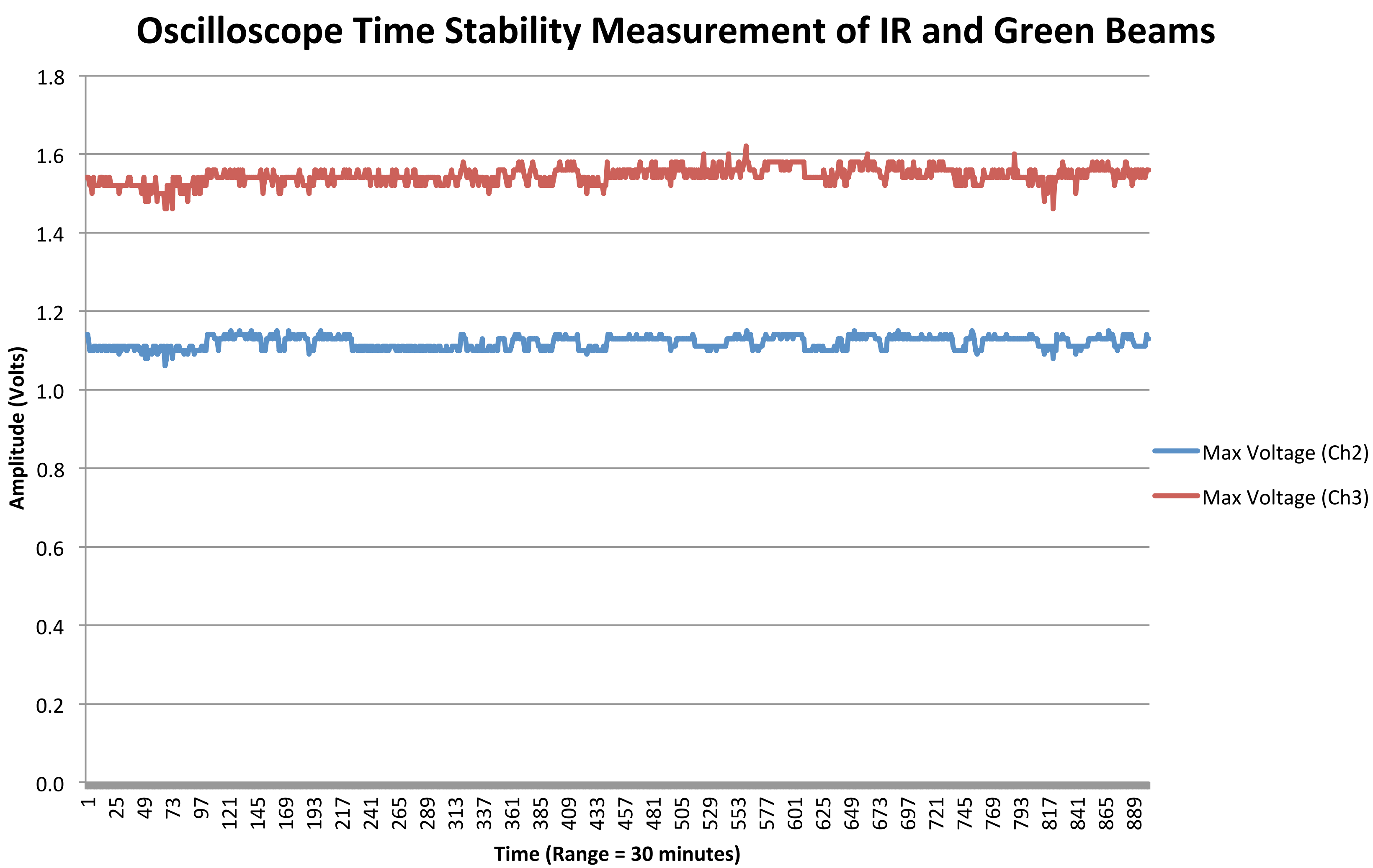
Integrating over time means the integral term will grow with time so long as the error signal is nonzero. Even once the error signal zeroes out, the control signal will remain nonzero, but stable.


Measurement of Green Power Intensity Over Time
Power (Watts)
0.025
0.02
0.015
0.01
0.005
0
1 102 203 304 405 506 607 708 809 910 1011 1112 1213 1314 1415 1516 1617 1718 1819 1920 2021 2122 2223 2324 2425 2526 2627
Time (range = 45 minutes)


Time Stability of the IR Beam (transmitted)
Power (Watts)
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
1 46 91 136 181 226 271 316 361 406 451 496 541 586 631 676 721 766 811 856 901 946 991 1036
Time (range = 25 minutes)

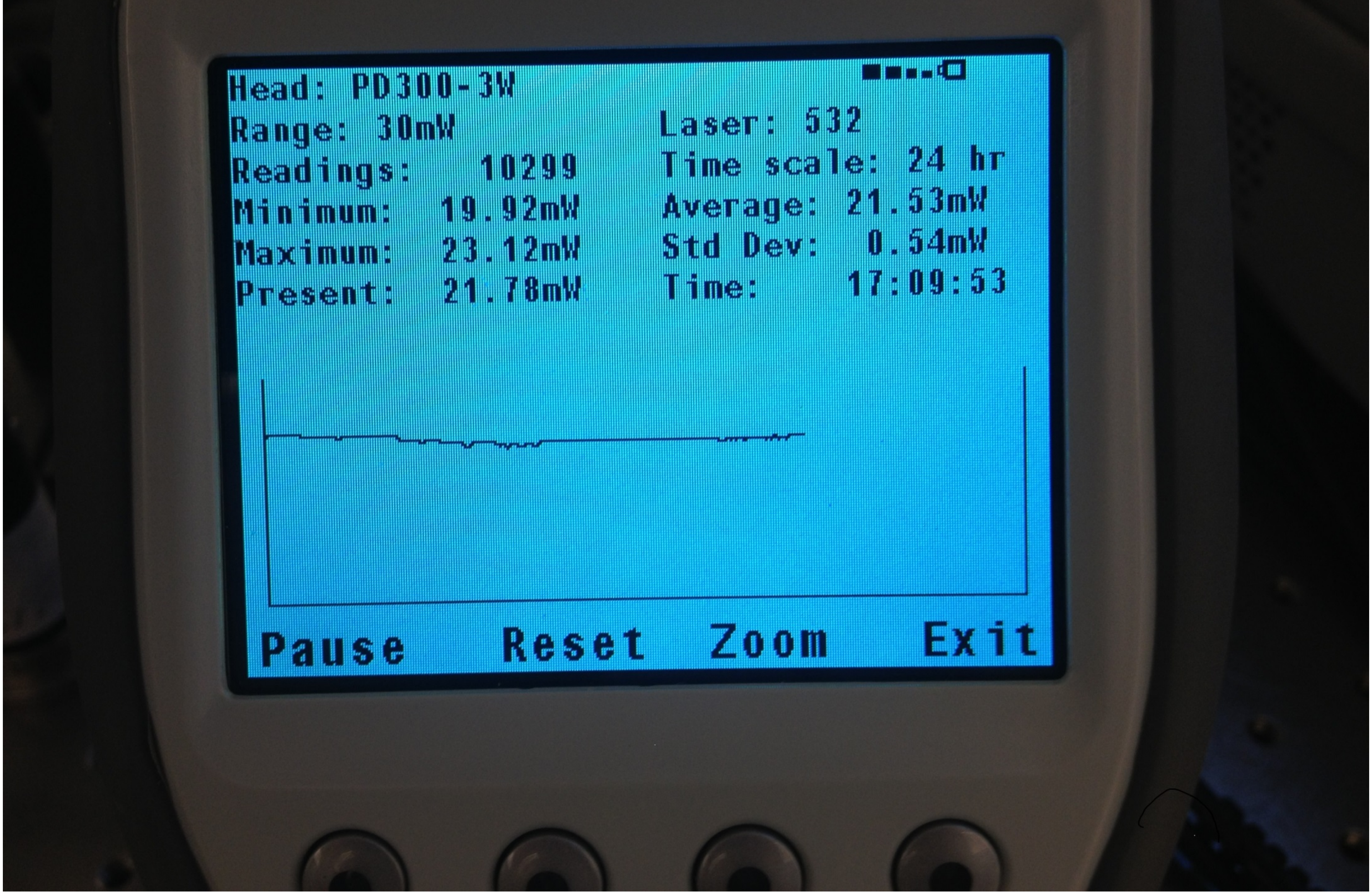

45 Minute Scan of Green Beam Power Distribution
Frequency
2000
1500
1000
500
0
0.01 0.012 0.014 0.016 0.018 0.0191 0.0193 0.0195 0.0197 0.0199 0.0201 0.0203 0.021 0.023
Power (Watts)
Frequency


Time Stability of IR Beam (Transmitted)
Frequency
1000
800
600
400
200
0
0 0.0001 0.0002 0.0003 0.0004 0.0005 0.0006 0.0007 0.0008 0.0009 0.001 0.0011 0.0012 0.0013 0.0014 0.0015 0.0016 0.0017 0.0018
Power (Watts)

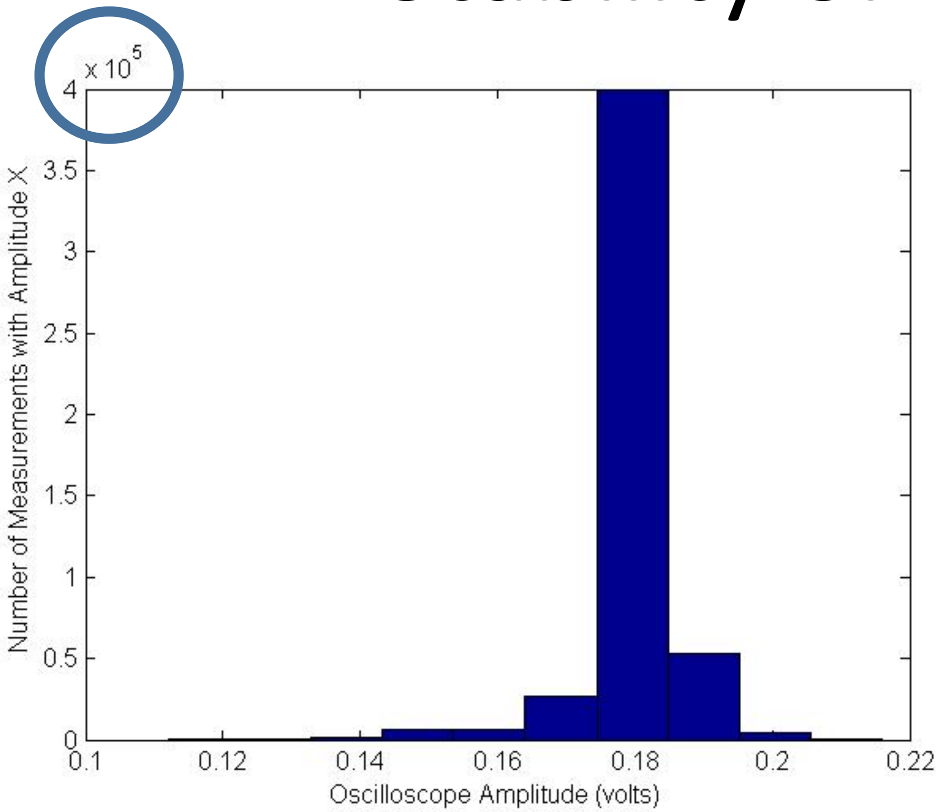


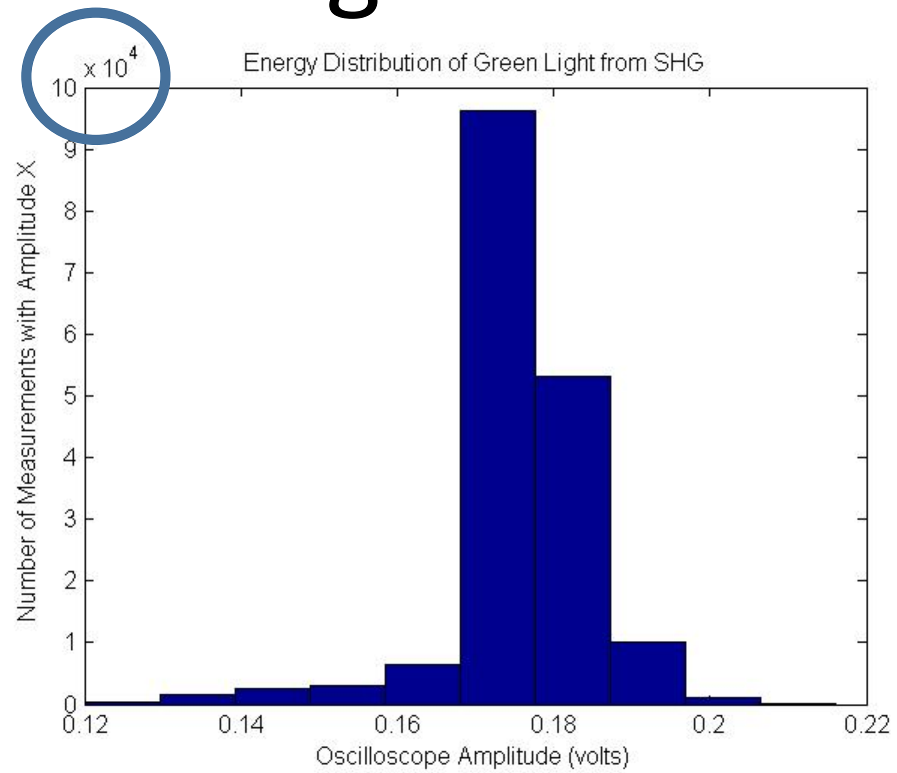
Oscilloscope Time Stability Measurement of IR and Green Beams
Amplitude (Volts)
Time (Range = 30 minutes)
Max Voltage (Ch2)
Max Voltage (Ch3)

Longest Observed Lock Held = 17 hours



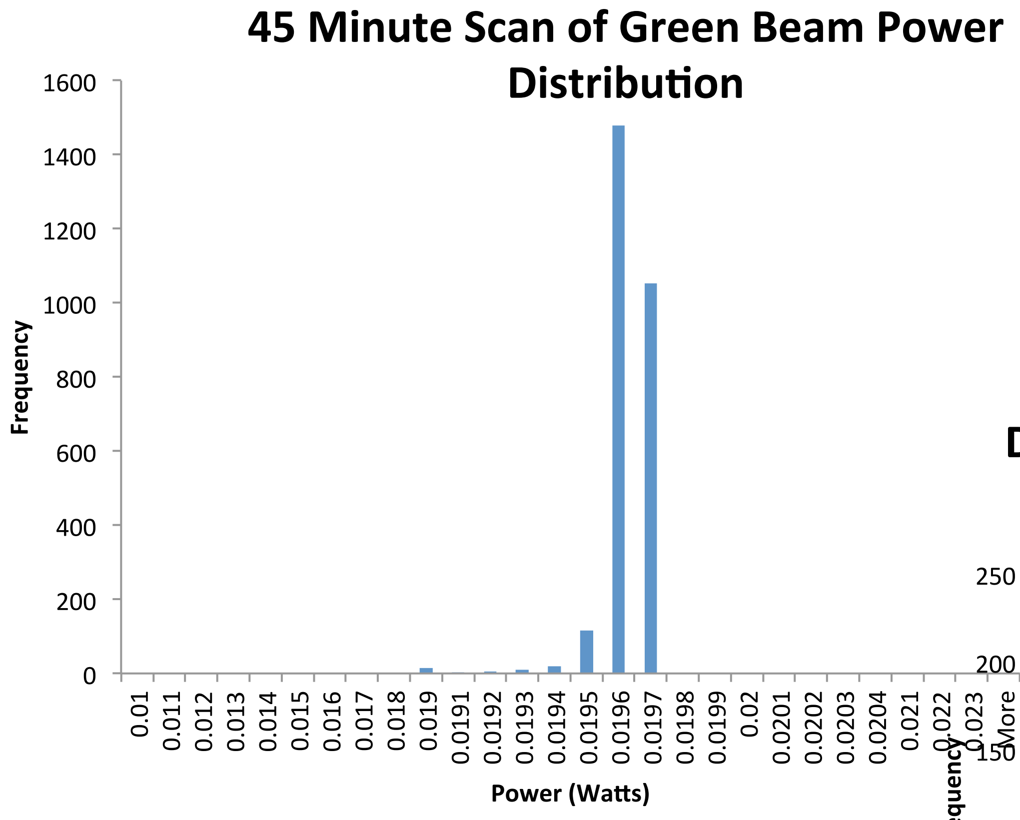
Stability of Green Light





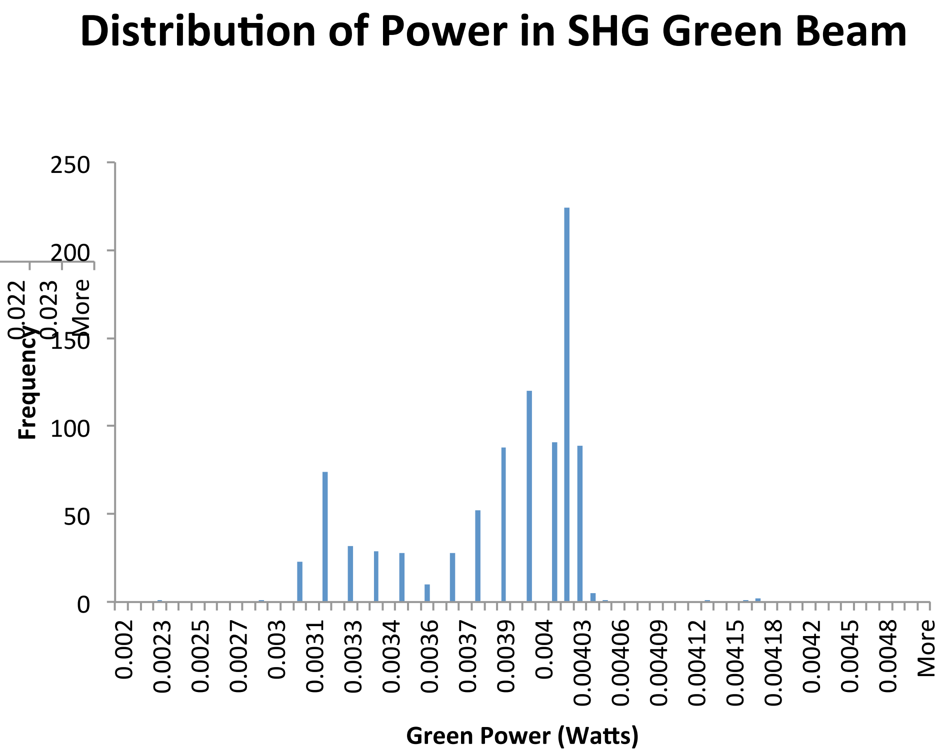
A good servo lock confirms minimal spread in the green light intensity

Test with Ophir Power Meter

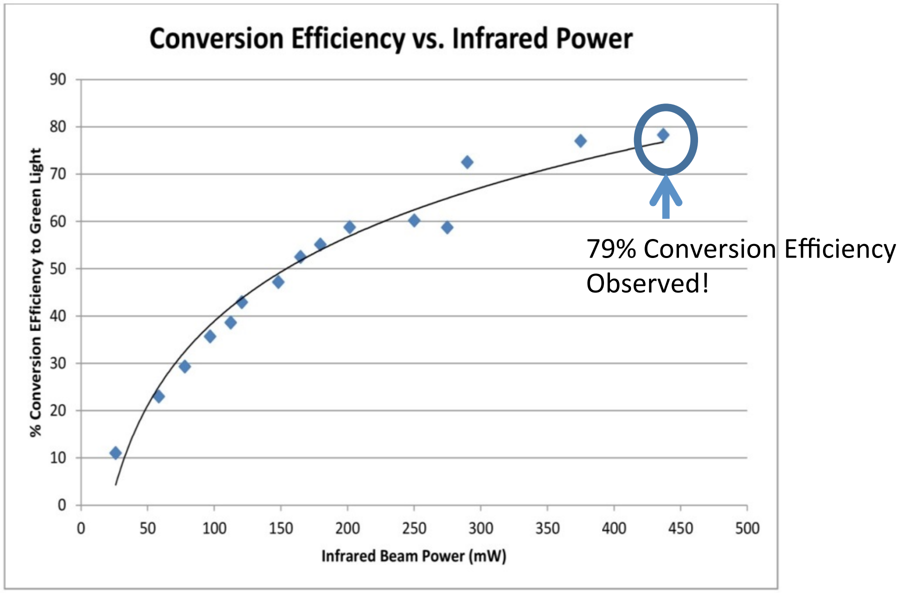


Time Range ~ 1 hour

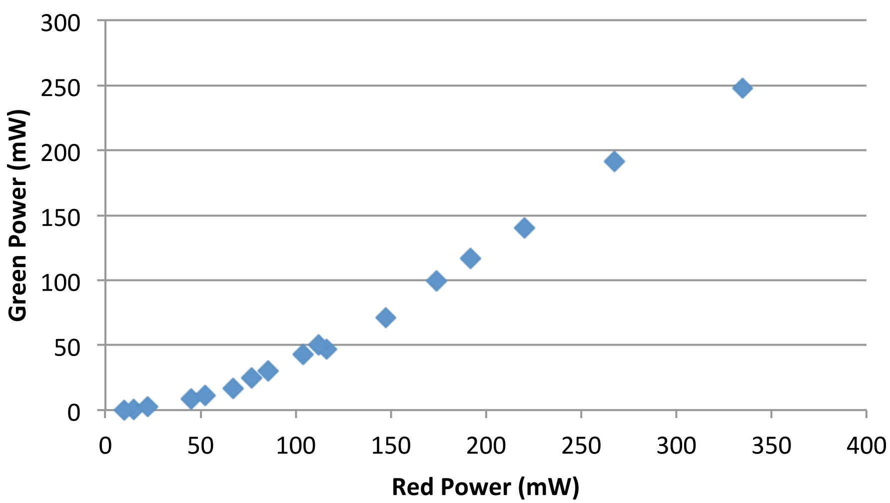
If the lock is not good and the resonance drifts, then the power is 'jumpy'

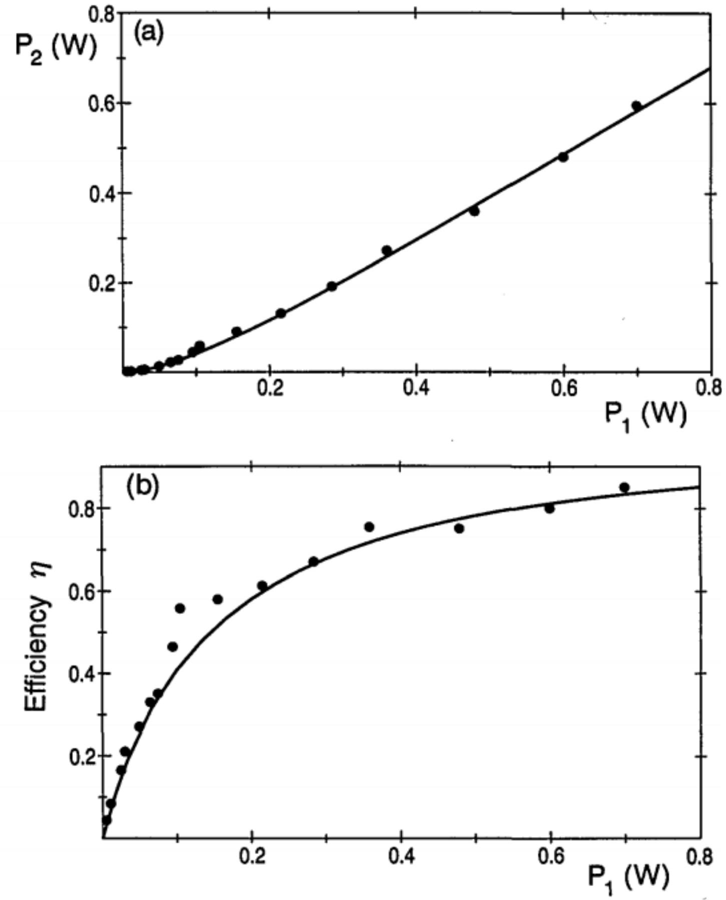


Conversion Efficiency vs. Input Power



Output Green Power as a Function of Input Infrared (mW)





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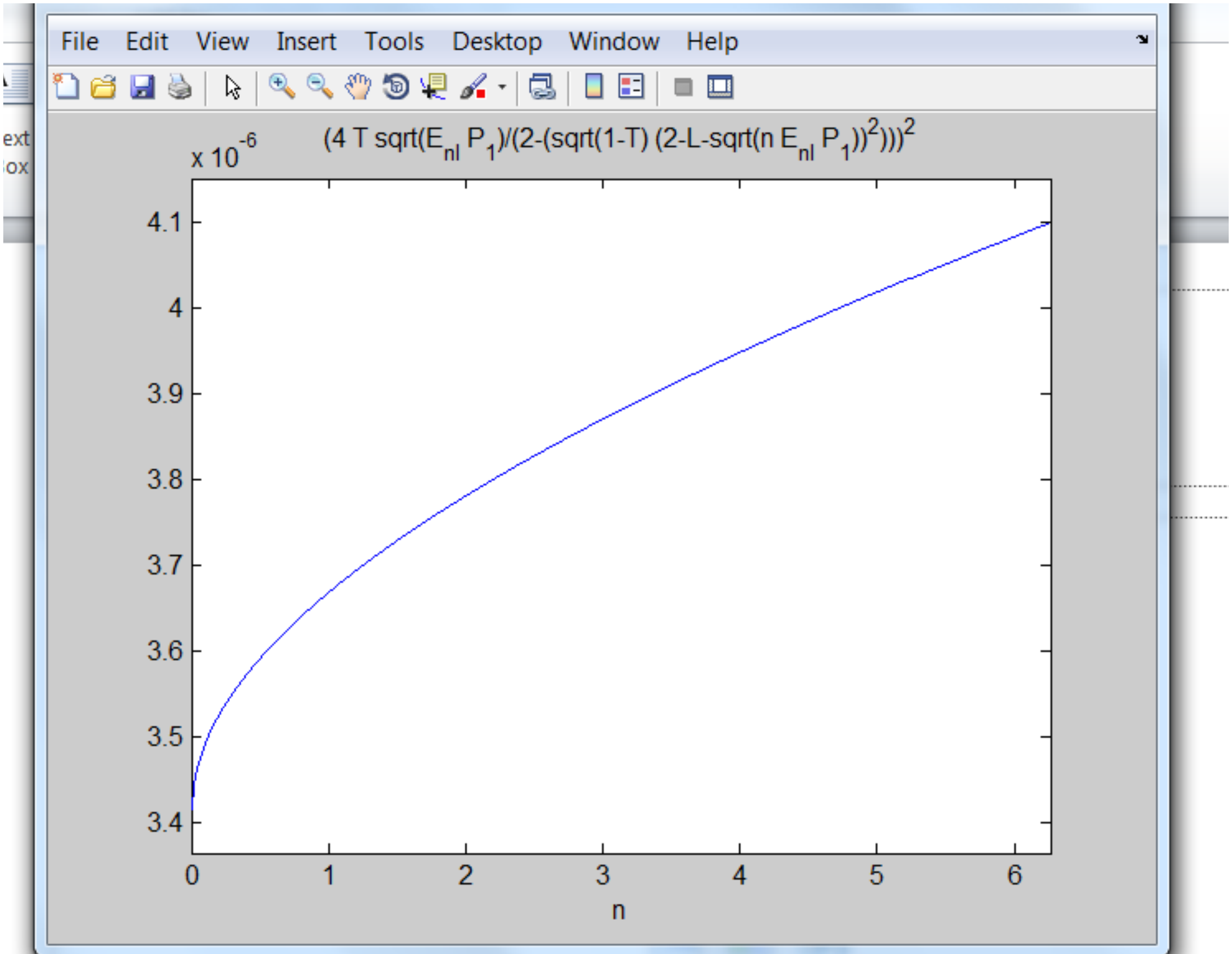
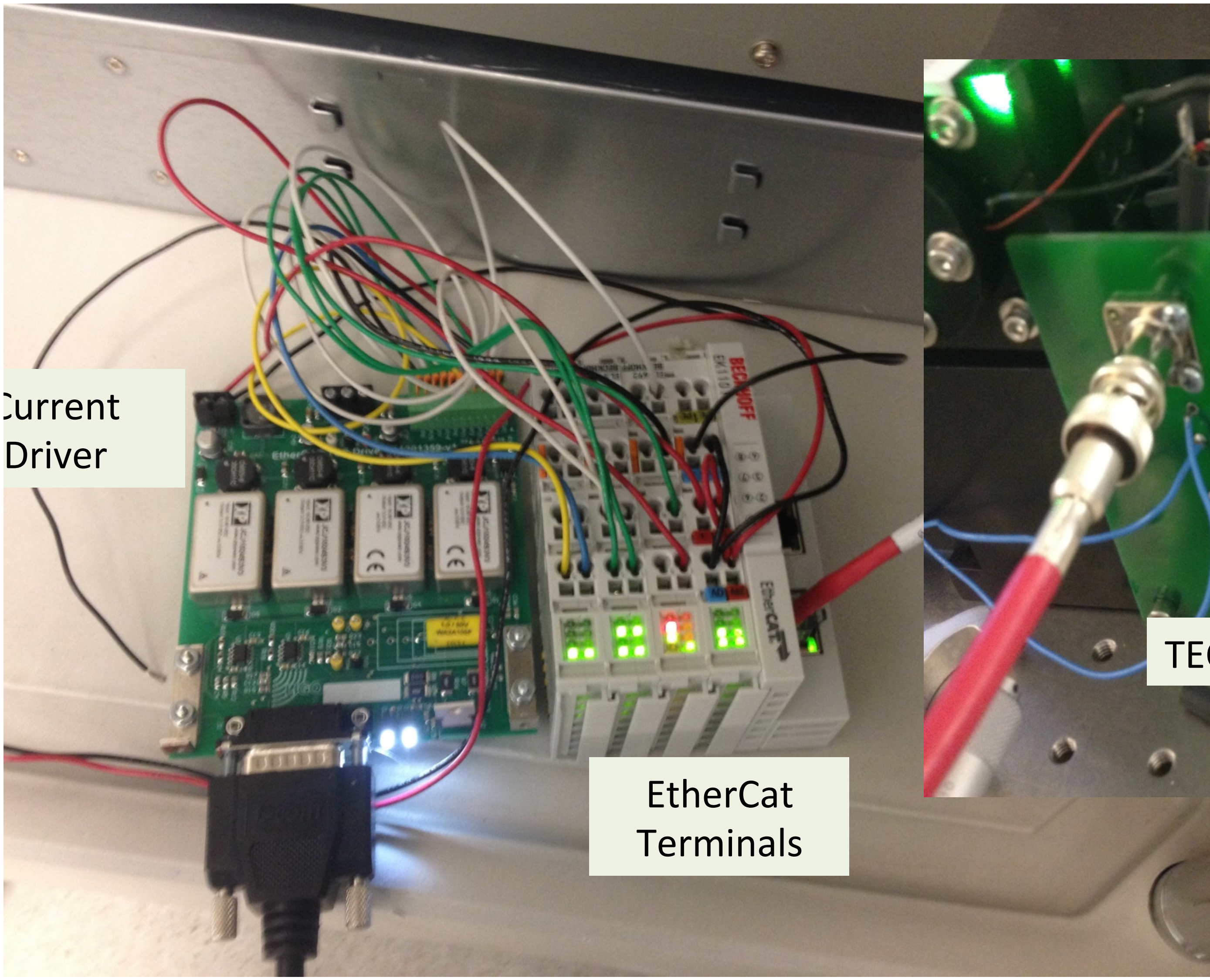
$$P_{2\omega} = \eta_{SHG} P_{\omega}^{2}$$ At Low Power

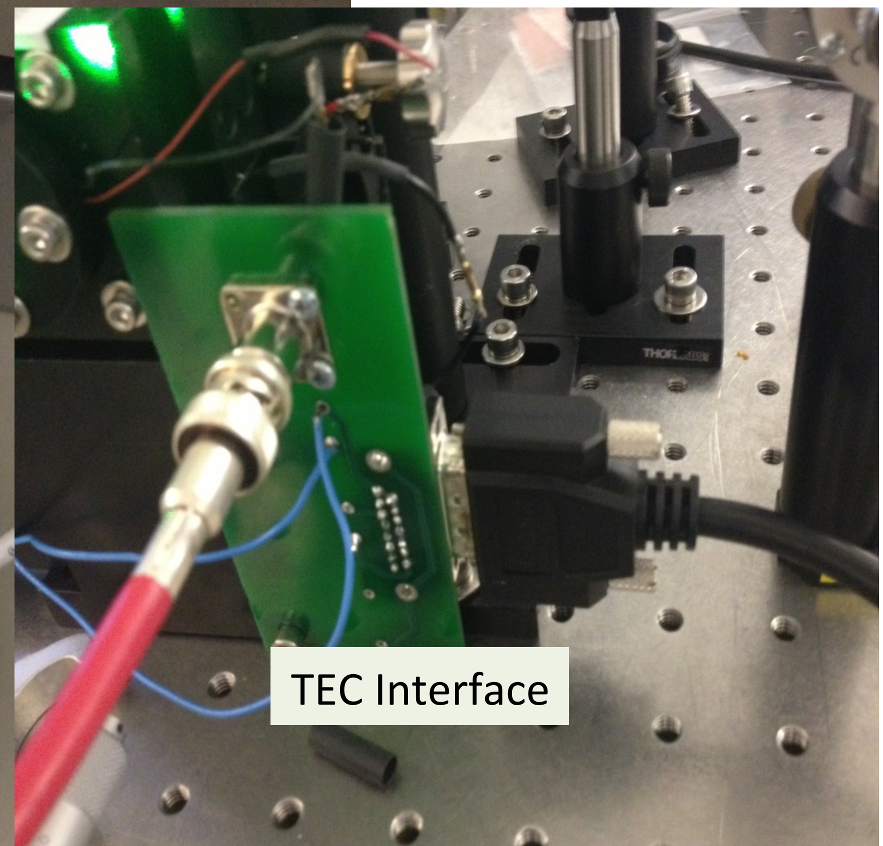
$$P_{2\omega} = P_{\omega} \tanh^{2} \sqrt{\eta_{SHG} P_{\omega}} \qquad (Including\ pump\ depletion)$$

$$\sqrt{\eta} = \frac{4T\sqrt{E_{\mathrm{NL}}P_1}}{[2 - \sqrt{1 - T}(2 - L - \sqrt{\eta E_{\mathrm{NL}} P_1})]^2}$$

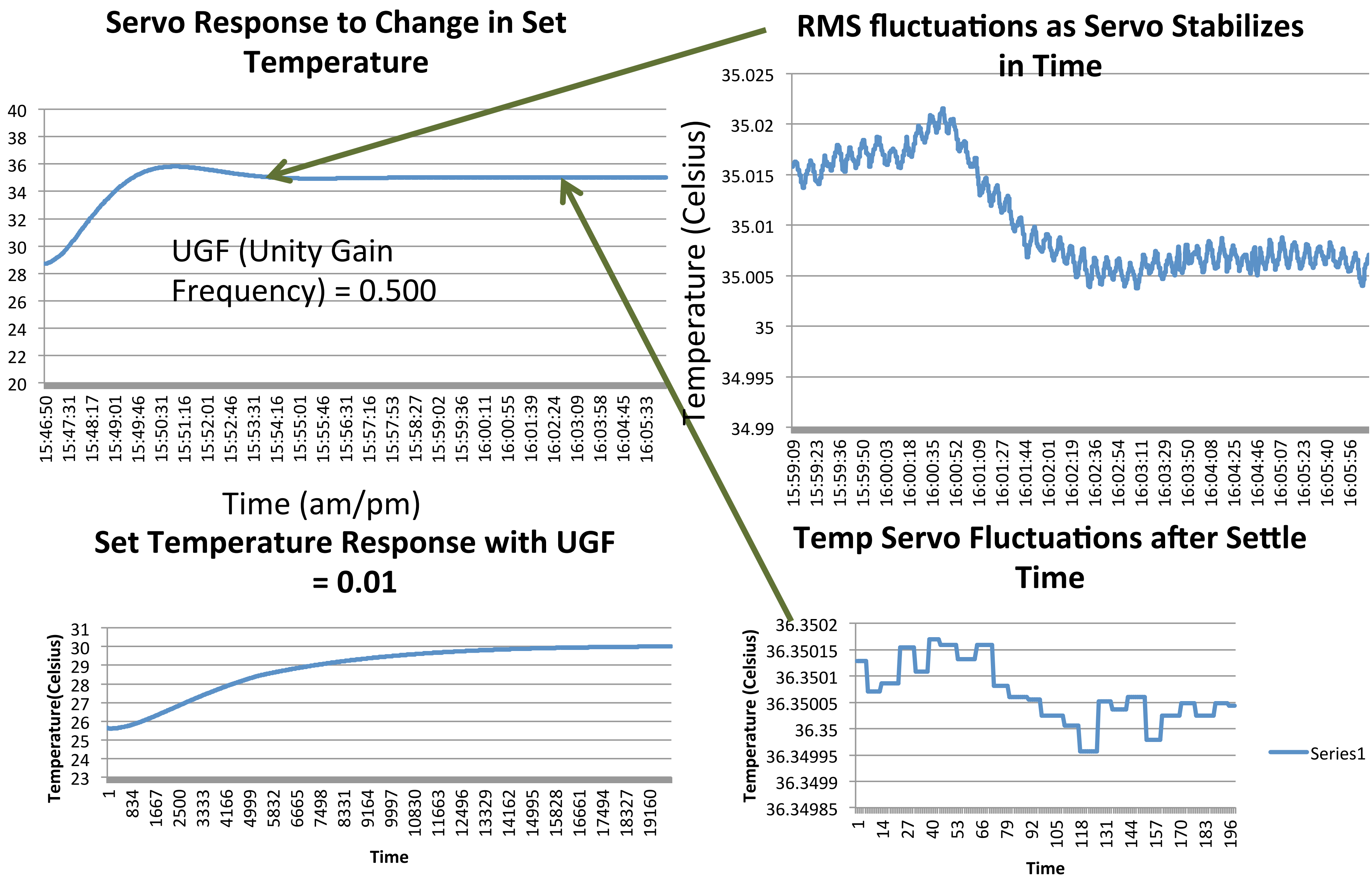


New Temperature Controller implemented with Beckhoff electronics



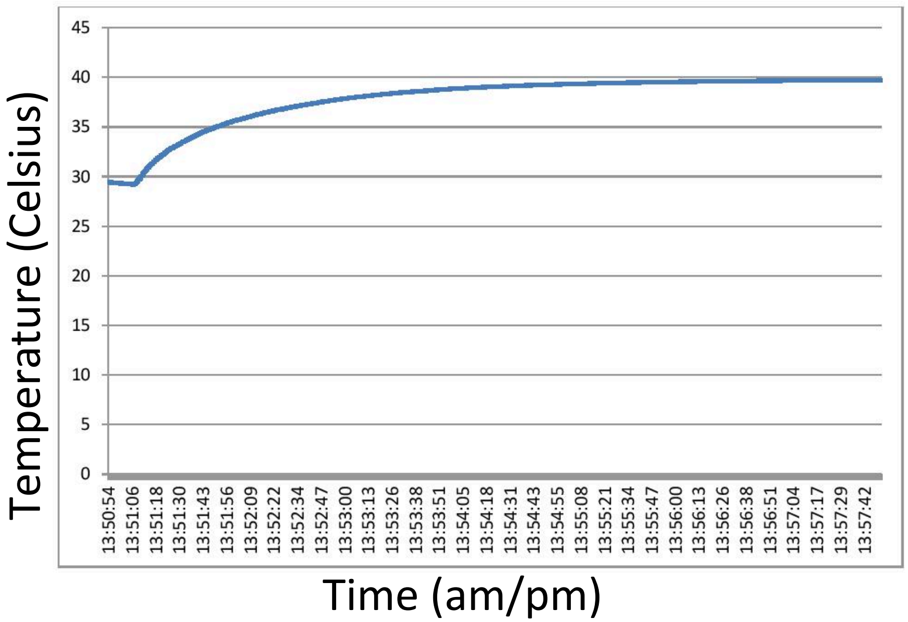


Servo Characterization (in Time Domain)



Unit Step Response

Unit Step Response of Temperature Servo in Time



Laplace Transform (time domain <-> frequency domain)

$$\Gamma(s) = \int_0^\infty \gamma(t)e^{-st}dt = \int_0^\infty e^{-st}dt = \frac{1}{s}$$

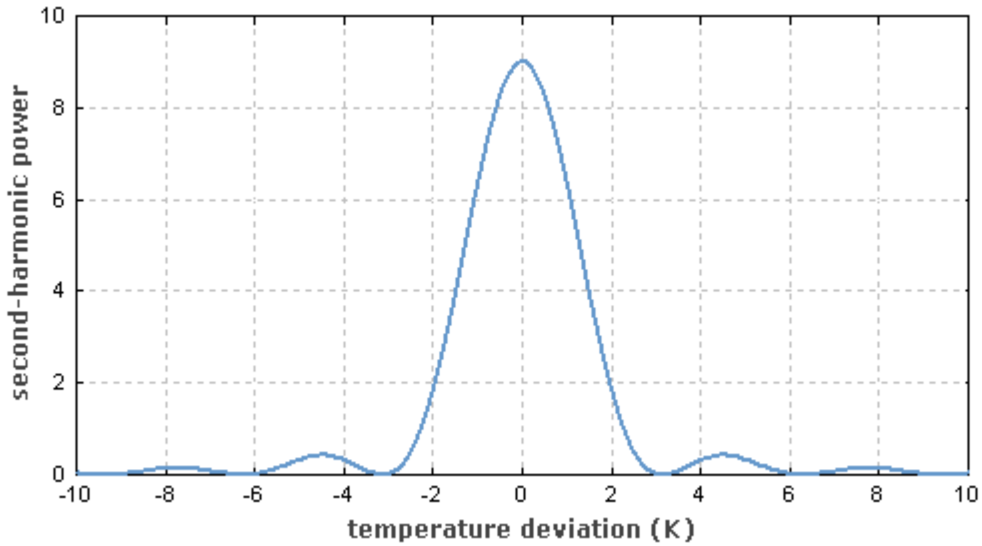
$$H(s) = \frac{bs+c}{s+a}$$

$$H(0) + (H(\infty) - H(0))e^{\frac{-t}{\tau_0}}$$

Take inverse Laplace Transform of convolution of the unit step function and the transfer function:

$$Y_{conv} = \frac{1}{s}H(s) = (\frac{1}{s})\frac{bs+c}{s+a}$$

Phase Matching of Green and Red by Temperature Tuning



Phase Matching Curve

$$k_{sig} = \frac{\omega_{sig}}{c_0} n(\omega_{sig}) = \frac{(2\omega)}{c_0} n(2\omega)$$

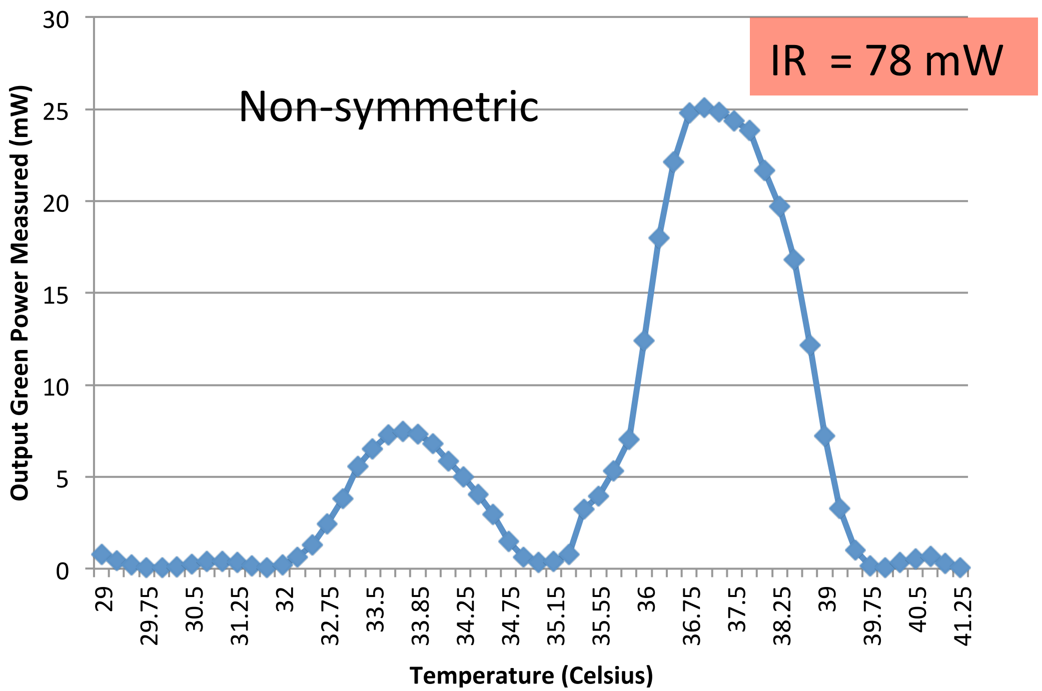
$$k_{pol} = 2\,k = 2\frac{\omega}{c_0} n(\omega)$$

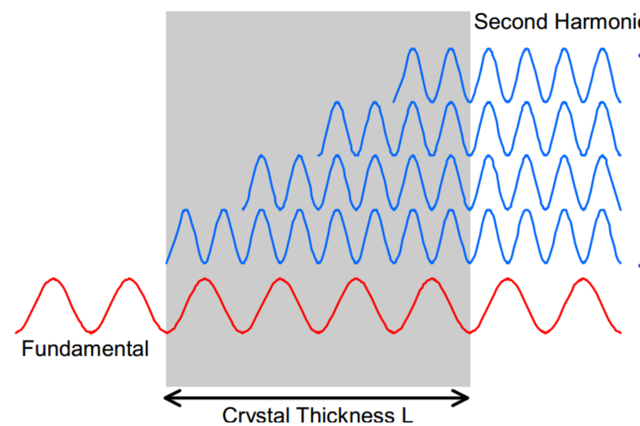
Phase (mis)matching equation:

$$\Delta k(\lambda) = \frac{4\pi}{\lambda}\left[n(\lambda) - n(\lambda/2)\right]$$

$$I_{sig}(L) \propto (L/\lambda)^2 \operatorname{sinc}^2(\Delta k\, L/2)$$

Boyd, *Nonlinear Optics*





Questions?

References

[1] Erick Black. Notes on pound drever hall technique, 1998. accessed 8/15/2013.

[2] Robert Boyd. *Nonlinear Optics*. Elsevier, Inc., 2008.

[3] Erik Cheever. Unit response, 2013. accessed 8/15/2013.

[4] Michiel Dood. Second harmonic generation. *Huygens Laboratorium*, 2006.

[5] Eugene Hecht. *Optics*. Addison-Wesley Publishing Company, 2001.

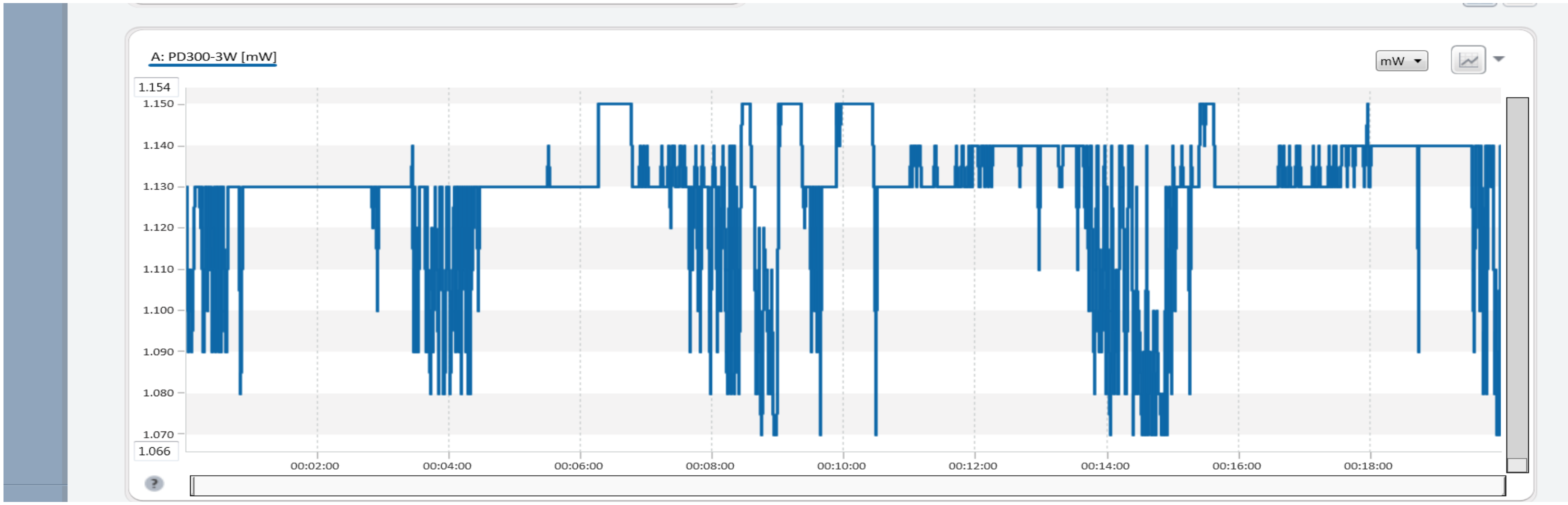
[6] Tony F. Heinz Jerry Dadap, Jie Shan. Theory of optical second harmonic generation from a sphere of centrosymmetric material: Small particle limit. *Journal of the American Optical Society B*, 2004.

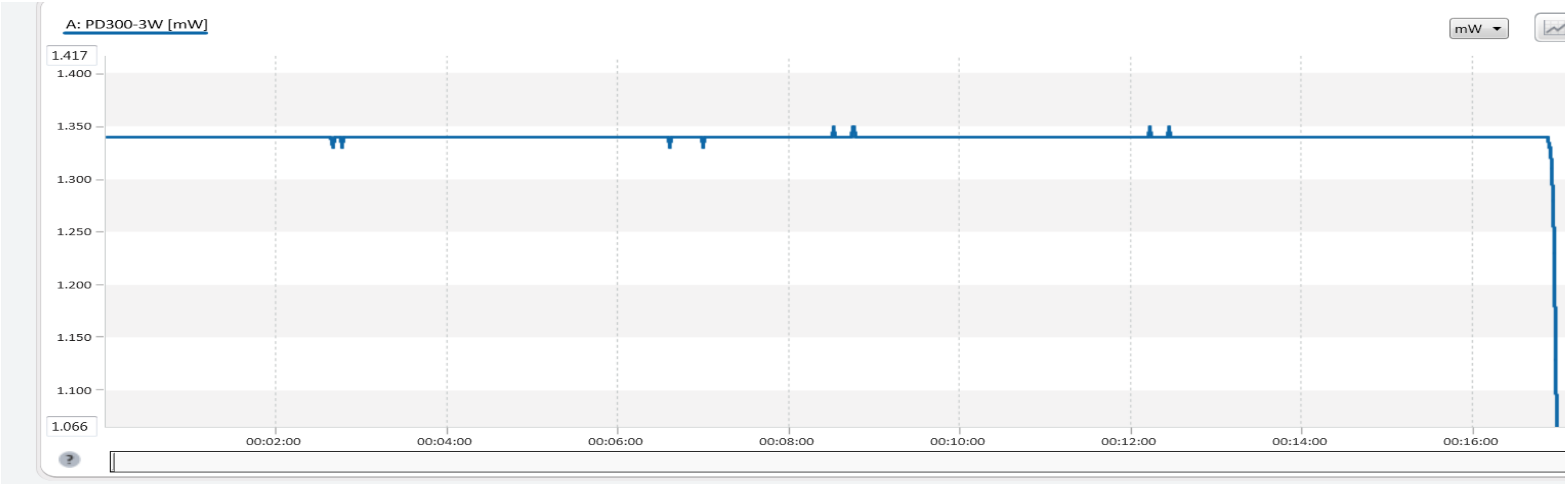
[7] M Nickerson. An introduction to pound drever hall laser frequency locking. *American Journal of Physics*, 2001.

[8] Rudiger Paschotta. Rp photonics encyclopedia: Noncritical phase matching, 2013. accessed 8/15/2013.

[9] Anthony Siegman. *Lasers*. University Science Books, 1986.

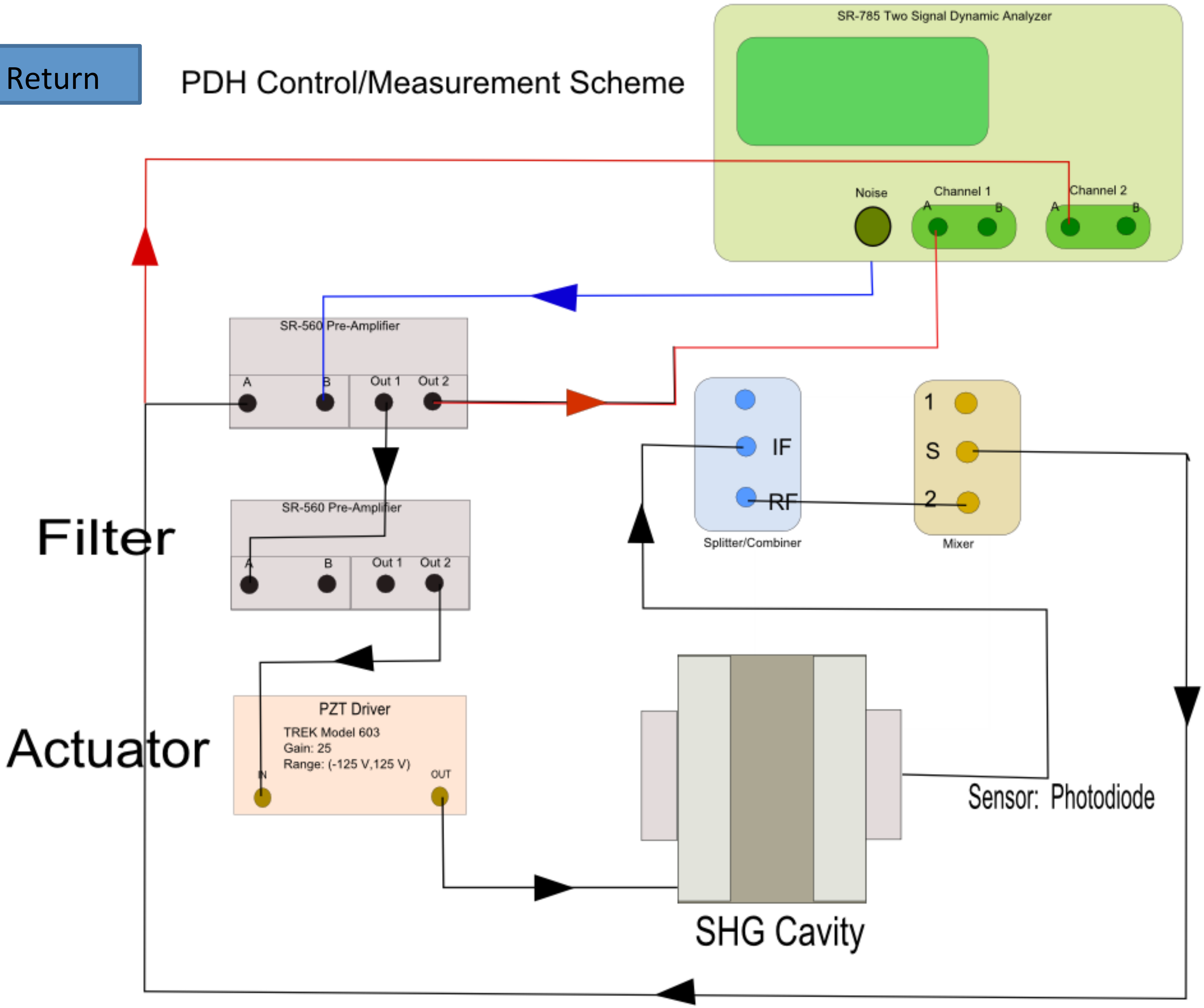
Temperature Servo Introduces Noise

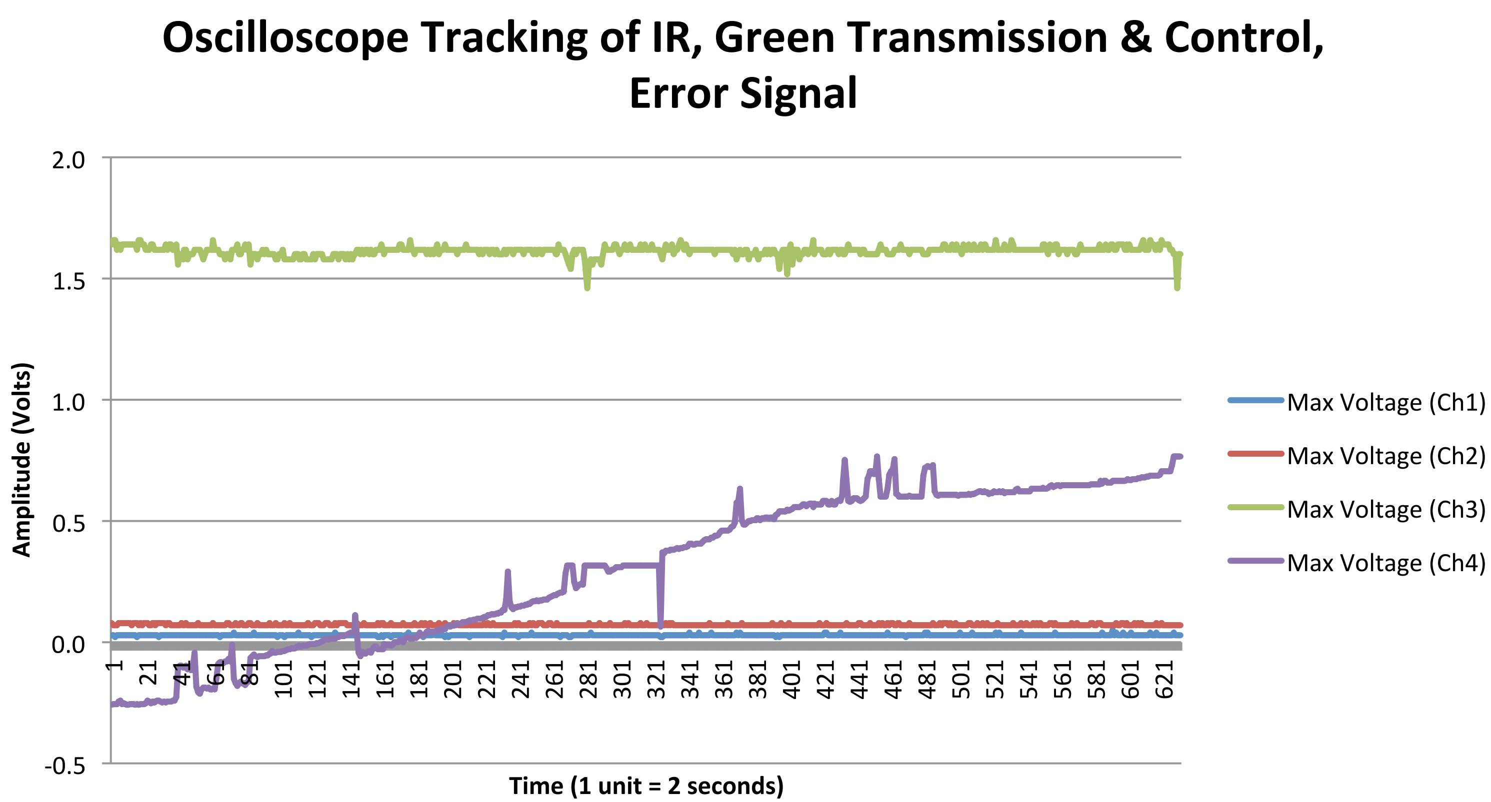




Return

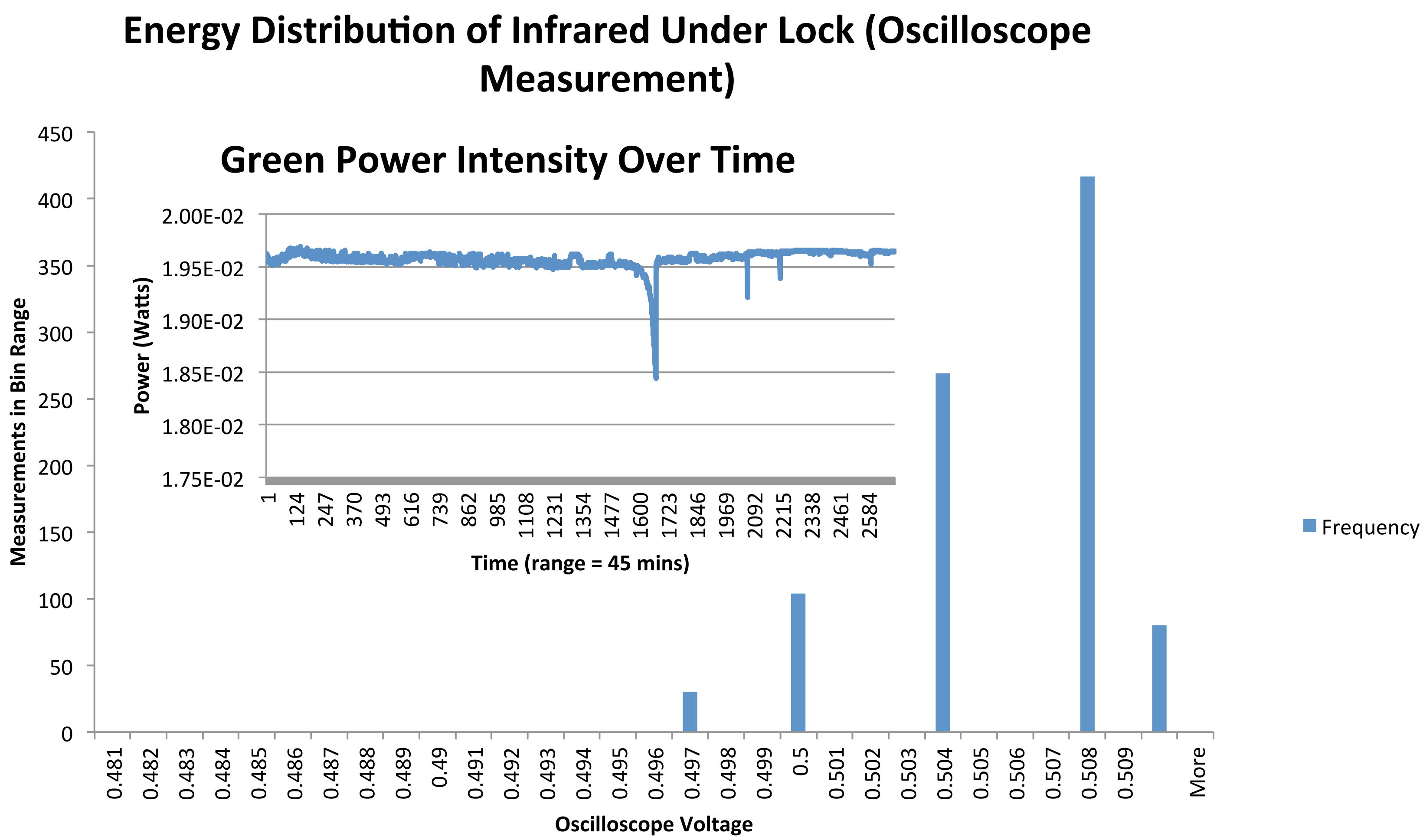
PDH Control/Measurement Scheme



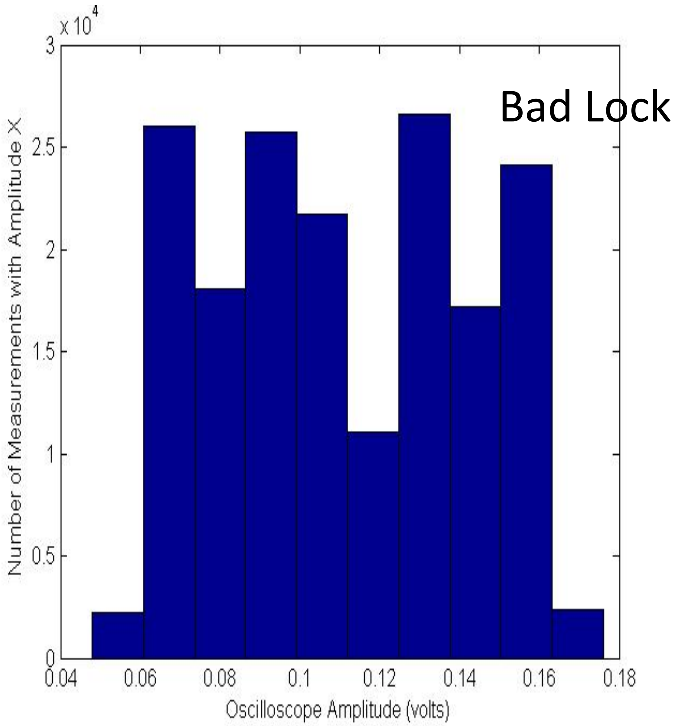


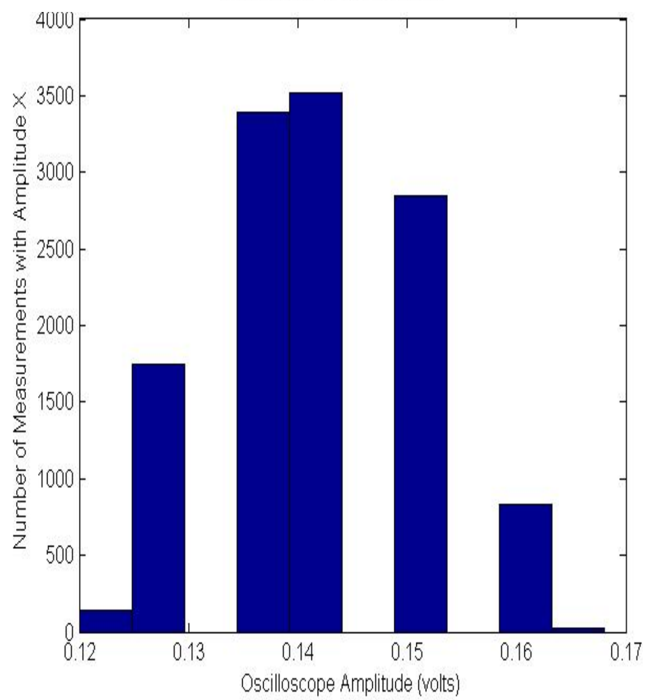
Oscilloscope Tracking of IR, Green Transmission & Control, Error Signal
2.0
1.5
1.0
0.5
0.0
-0.5
Amplitude (Volts)
1 21 41 61 81 101 121 141 161 181 201 221 241 261 281 301 321 341 361 381 401 421 441 461 481 501 521 541 561 581 601 621
Time (1 unit = 2 seconds)
Max Voltage (Ch1)
Max Voltage (Ch2)
Max Voltage (Ch3)
Max Voltage (Ch4)

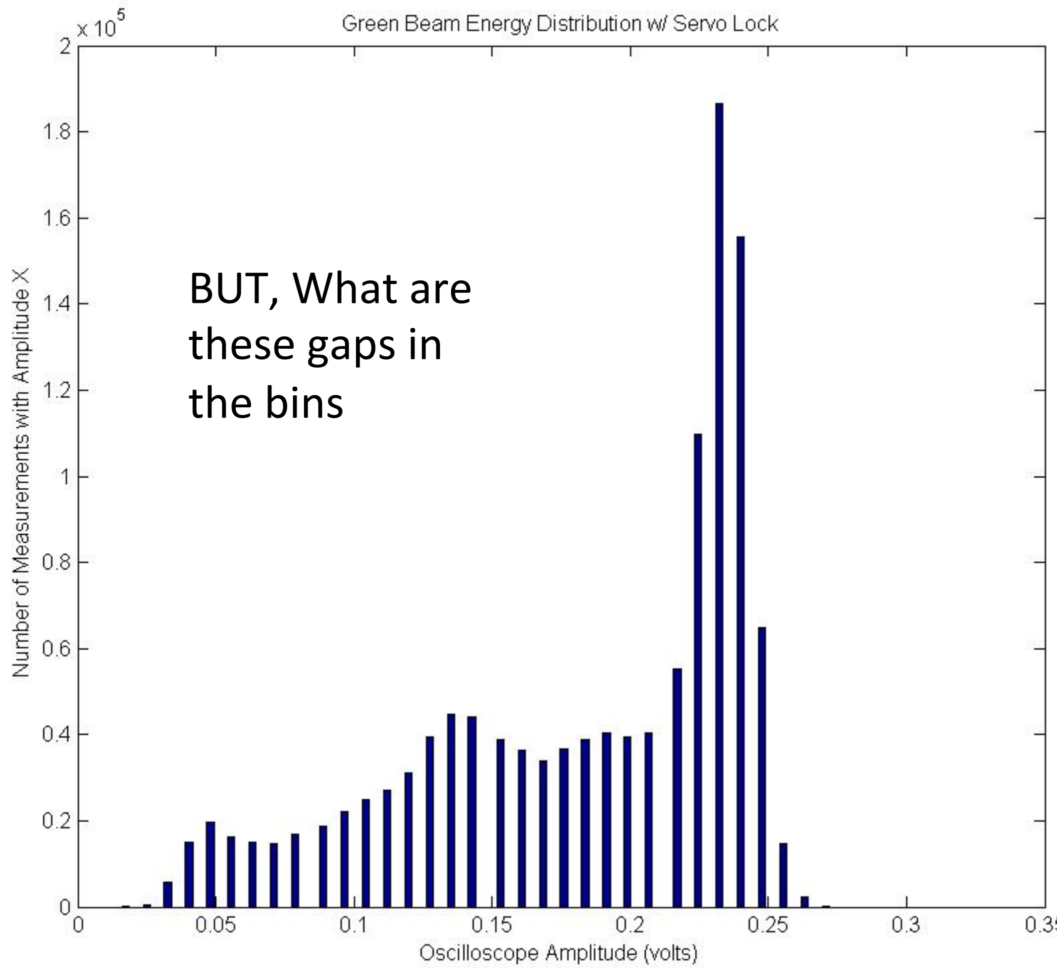
Phenomenon seen again in SHG 2.0

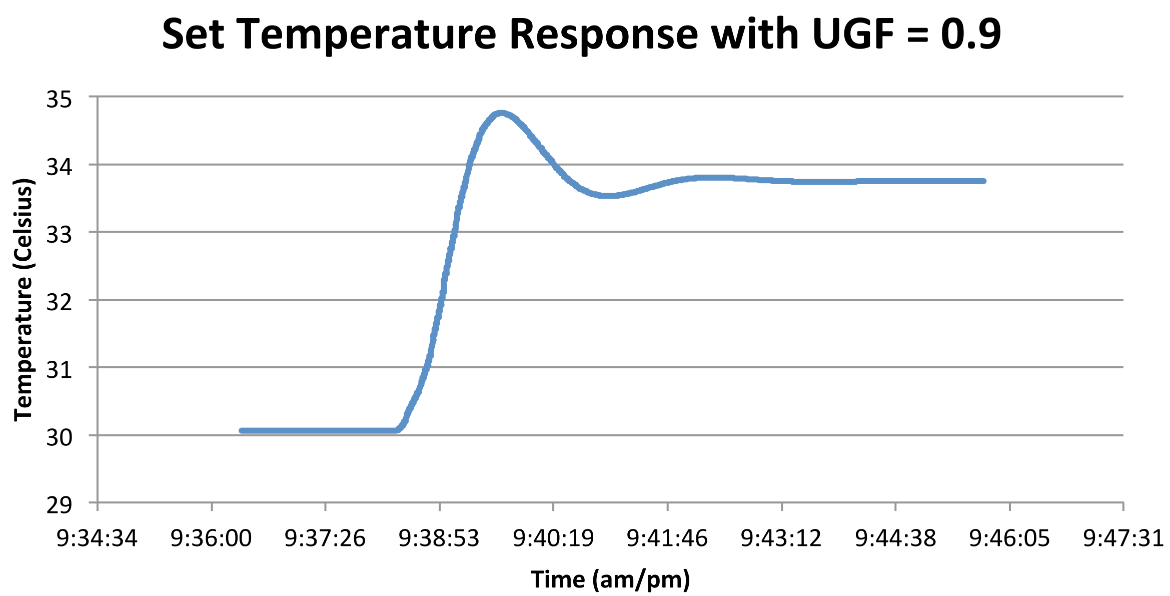


Anomalies in the Distribution

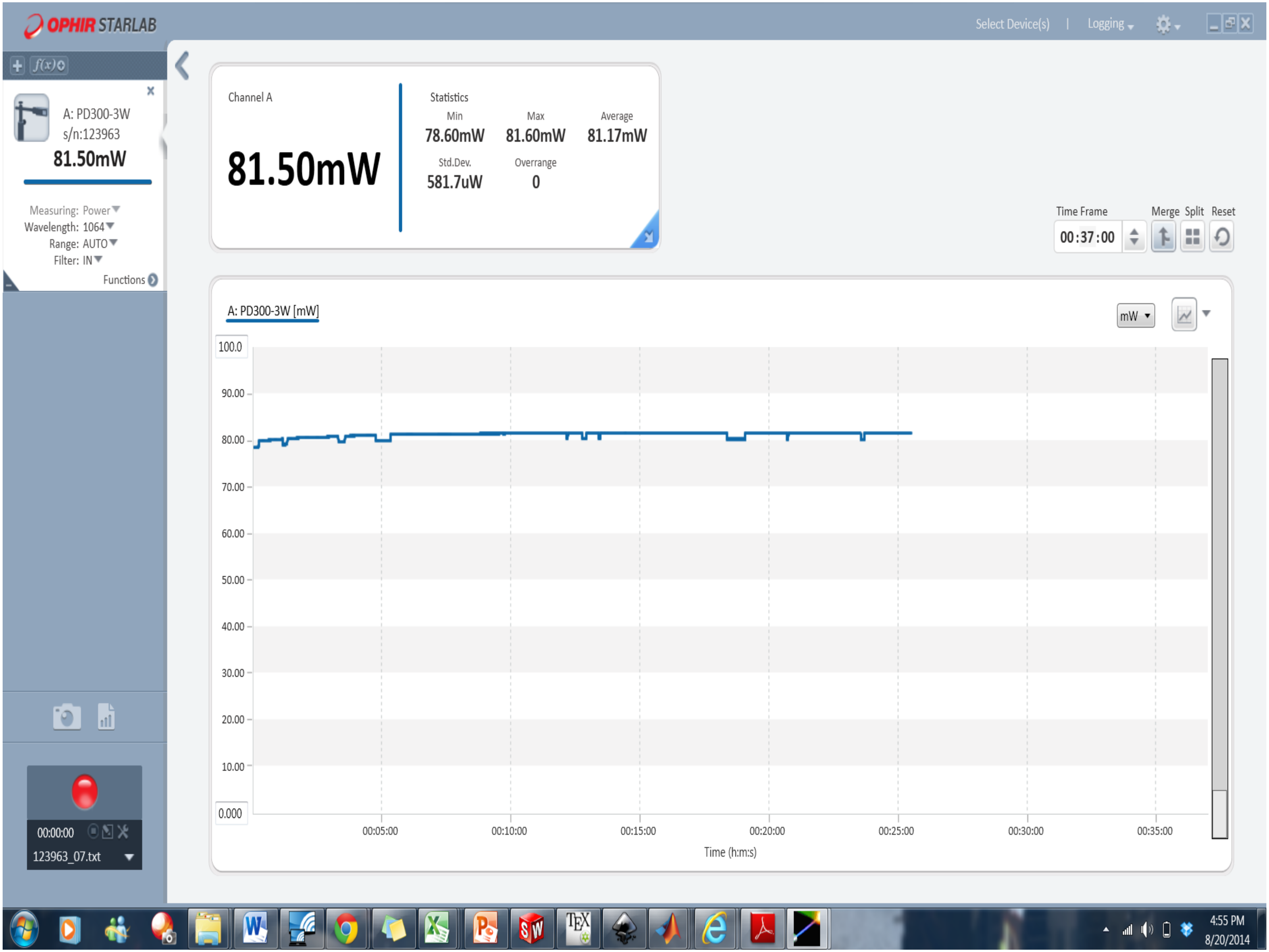








Rise Time: ~60 seconds
Settle Time: ~2 mins
Overshoot: 1 degree Celsius
Peak Time:


OPHIR STARLAB
Select Device(s)
Logging
A: PD300-3W
s/n:123963
81.50mW
Measuring: Power
Wavelength: 1064
Range: AUTO
Filter: IN
Functions
Channel A
81.50mW
Statistics
Min
78.60mW
Max
81.60mW
Average
81.17mW
Std.Dev.
581.7uW
Overrange
0
Time Frame
00:37:00
Merge
Split
Reset
A: PD300-3W [mW]
mW
100.0
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.000
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
00:30:00
00:35:00
Time (h:m:s)
00:00:00
123963_07.txt
4:55 PM
8/20/2014