OVERVIEW OF MODE CLEANER STATUS

o History

› mode cleaner installed and rough-aligned, May '99; roughly 6 months of in-vacuum operation to date

› commissioning plan was written ahead of time

- ~80% completed at LHO
- some tasks planned for first occurrence at LLO

o Successes

› locks easily, and for long periods of time (days); control signals have plenty of headroom

› length & frequency control servo: unity gain and cross-over frequencies tuned close to their design values

› wavefront sensor-based alignment servo works

› cavity finesse/linewidth is right (FWHM = 7.4 kHz)

› mode matching is good; fractional reflected power is 3%

› *Q's* of the drumhead mode (28.2 kHz) for all three optics are high, meet requirement: $Q = 3.7 \times 10^5$, 7.8×10^5, 1.3×10^6

› MC length set to within ~100 ppm of desired length; modulation frequency within 100 Hz of resonance (3rd f.s.r.)

› stability of MC output beam direction

Peter Fritschel

MC CHARACTERIZATION

o Problems uncovered

› Scattered 1064 nm light interacting with suspension local sensors; produces oscillations of suspension eigenmodes

- MC lock can not be acquired with full input power; but can be turned up following lock acquisition at low power
- solutions being pursued:
  - modulation/demodulation of the local sensor LED/PD
  - new local sensor design that is shielded from 1064 nm light (geometry + filter)

› PSL frequency noise: phase stability of PSL VCO is compromised by servo; redistribution of filtering is req'd

o Further performace characterization and integration work

› length–alignment coupling

› RF amplitude modulation at the MC output

› characterization of alignment system

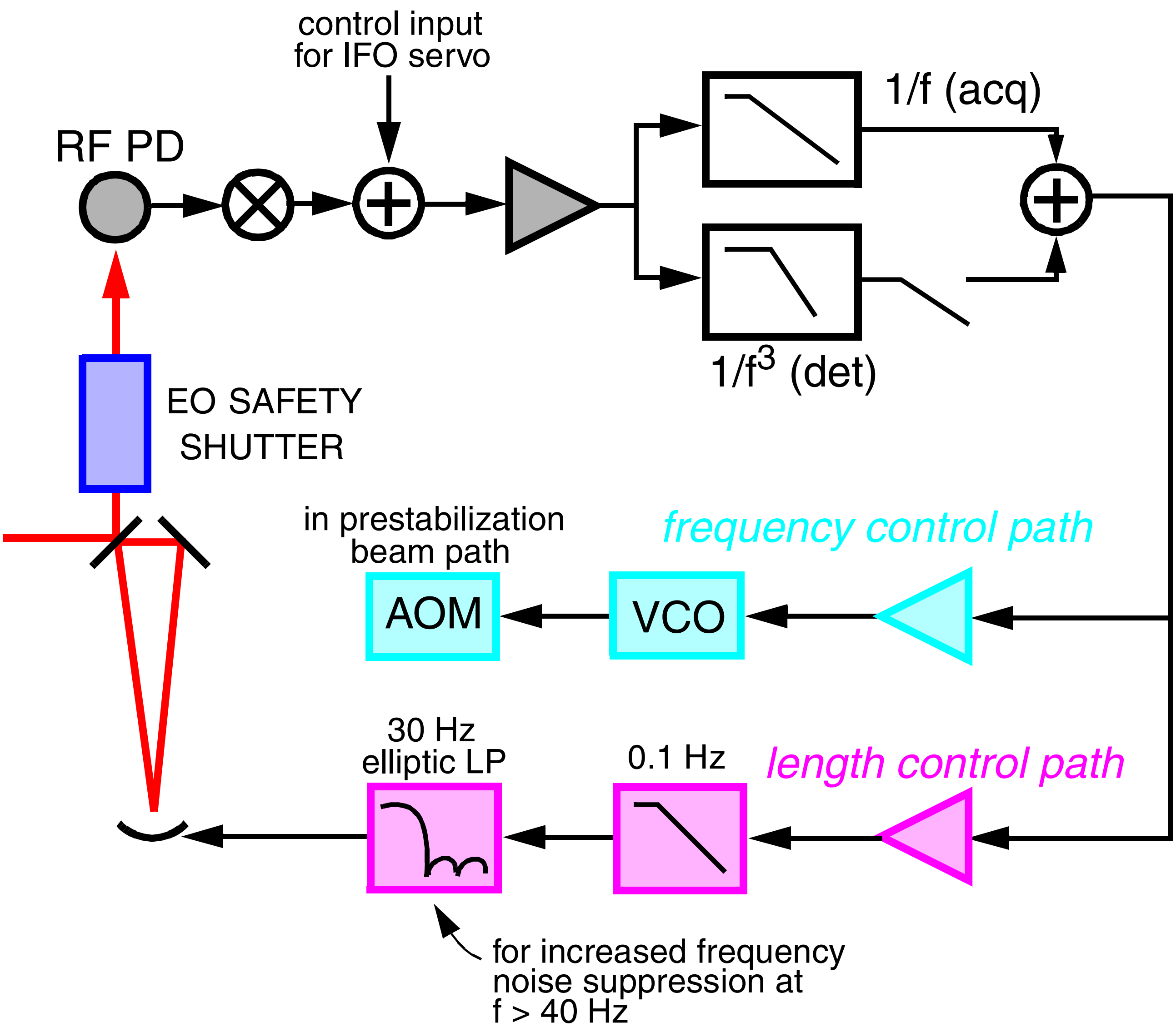
› beam pointing fluctuations in the GW band

› implement power stabilization of MC output

› automatic locking procedure

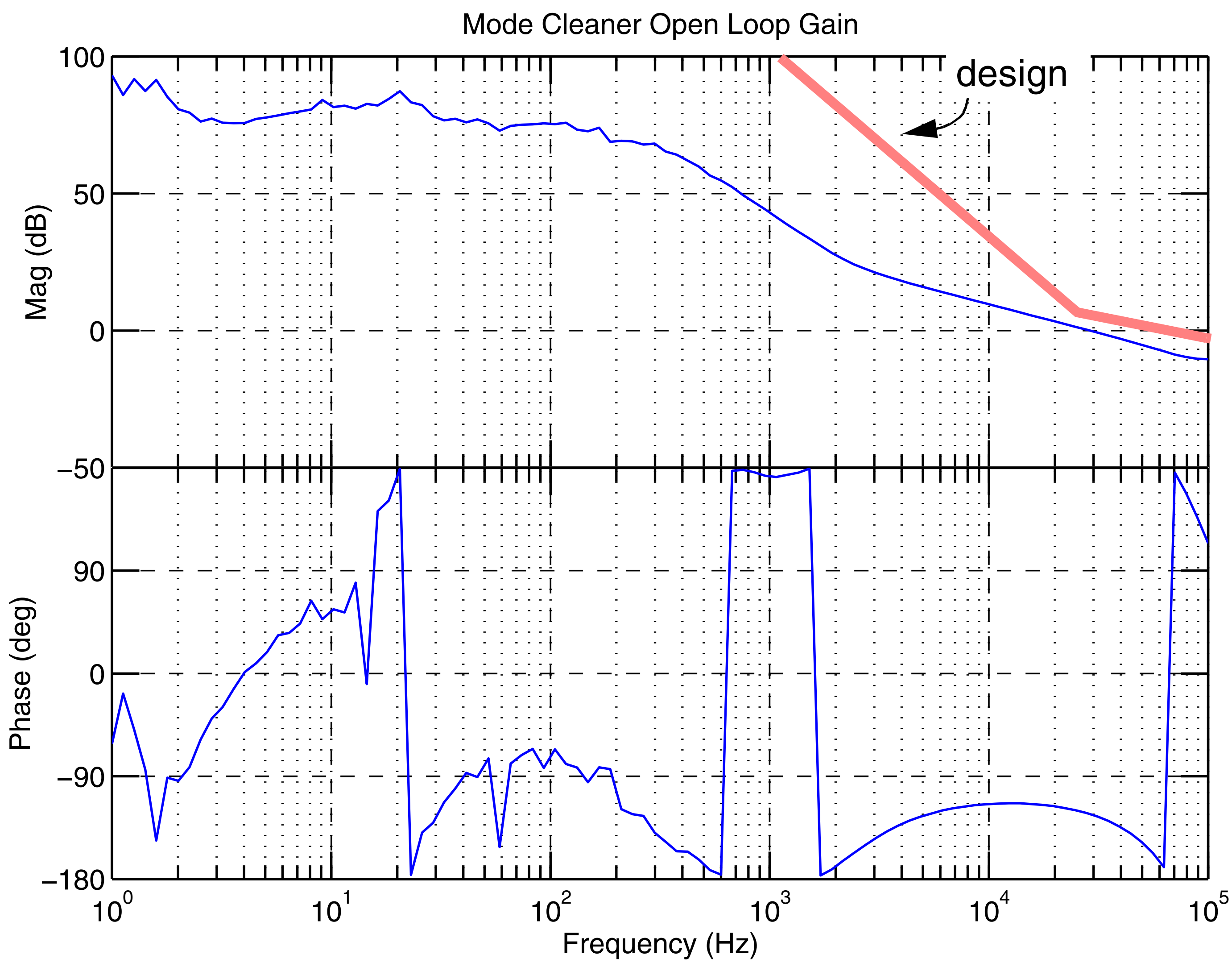
› characterization of MC output frequency noise

MODE CLEANER SERVO



- loop unity gain frequency ~100 kHz
- frequency path – length path crossover: 3–5 Hz
- frequency suppressing gain at 100 Hz: ~80 dB

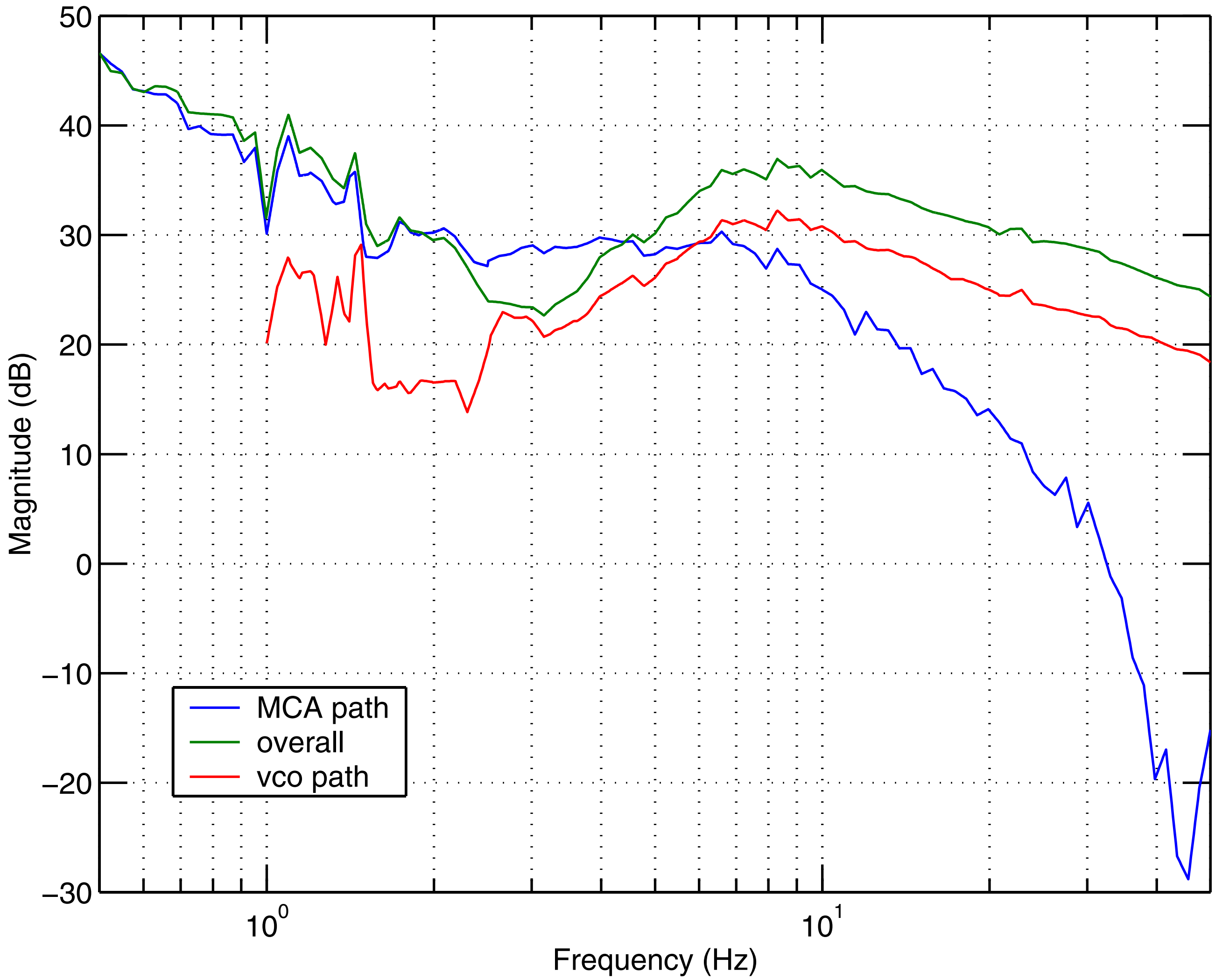
LOOP GAIN MEASUREMENT



- unity gain frequency currently limited by electronics (& low power)

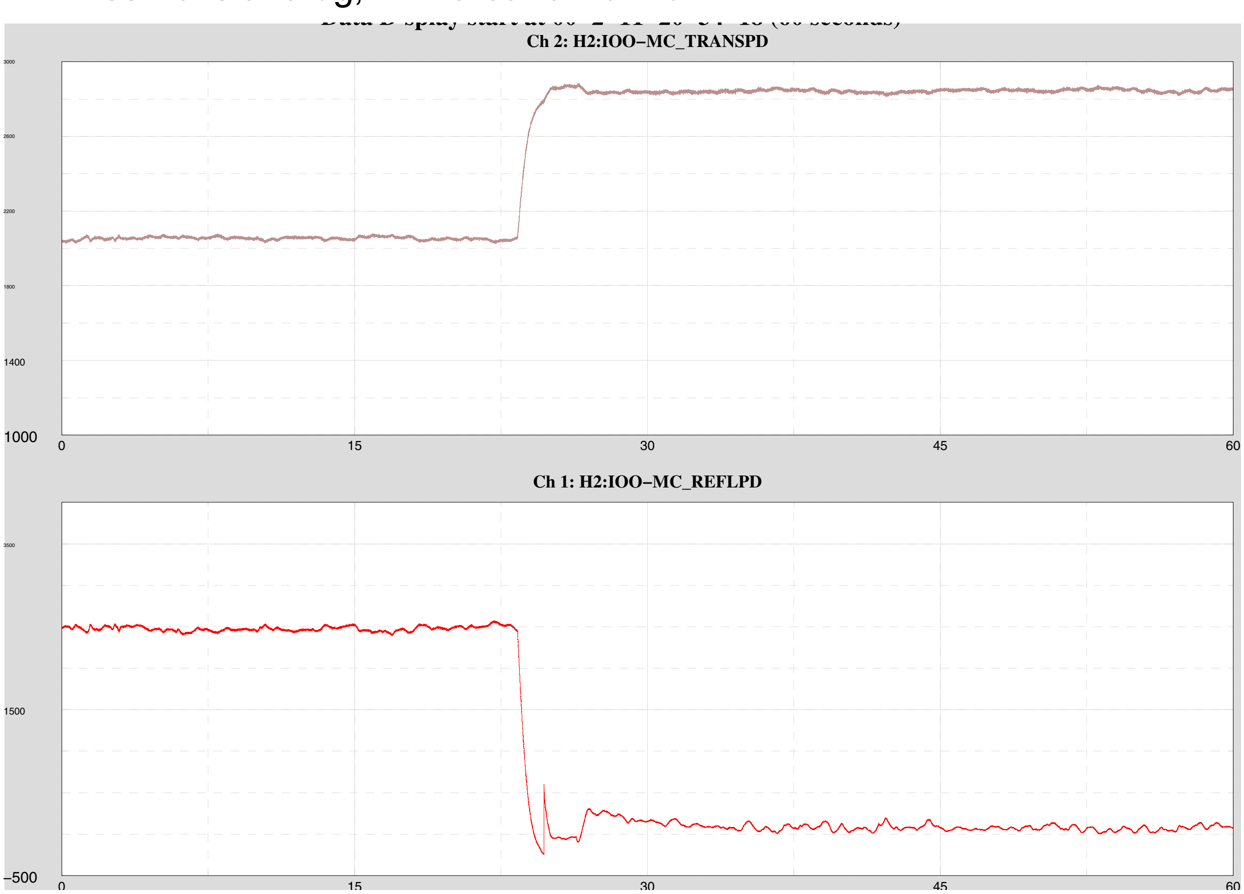
MC LENGTH-PSL FREQUENCY CROSSOVER

- difficult to measure because of high loop gain
  - operate in p-polarization, lower overall gain

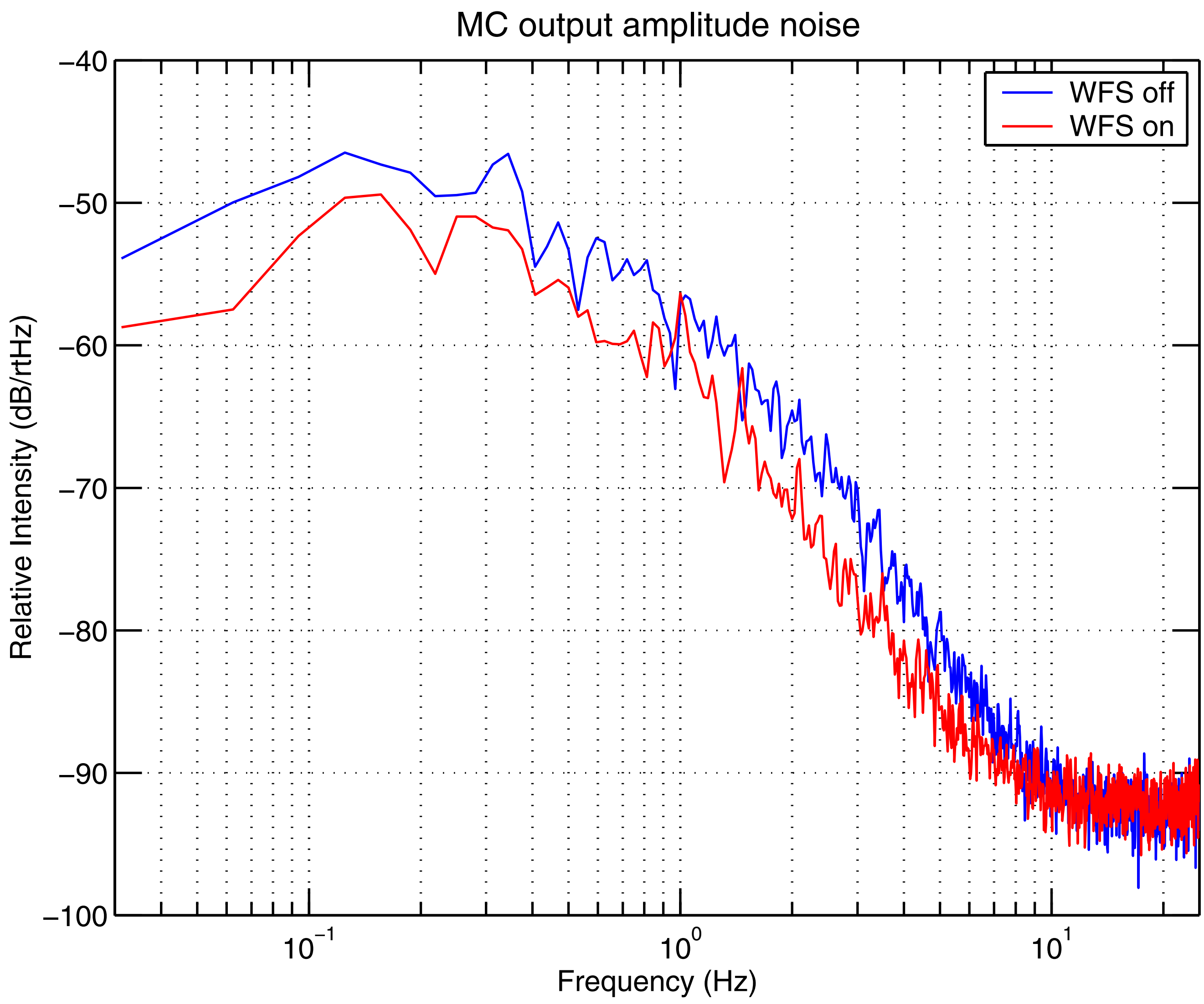


Alignment Control

- **2 wavefront sensors control the 4 d.o.f.**
- **Input beam direction is servoed to the mode cleaner cavity axis**
  - mode cleaner axis more stable than the input beam
  - alignment scale: beam divergence angle is 200 μrad; relative stability of ~10 μrad required
  - fluctuations are small; servo functions to find optimal alignment and compensate for drifts
  - servo is analog, with a bandwidth of ~1 Hz



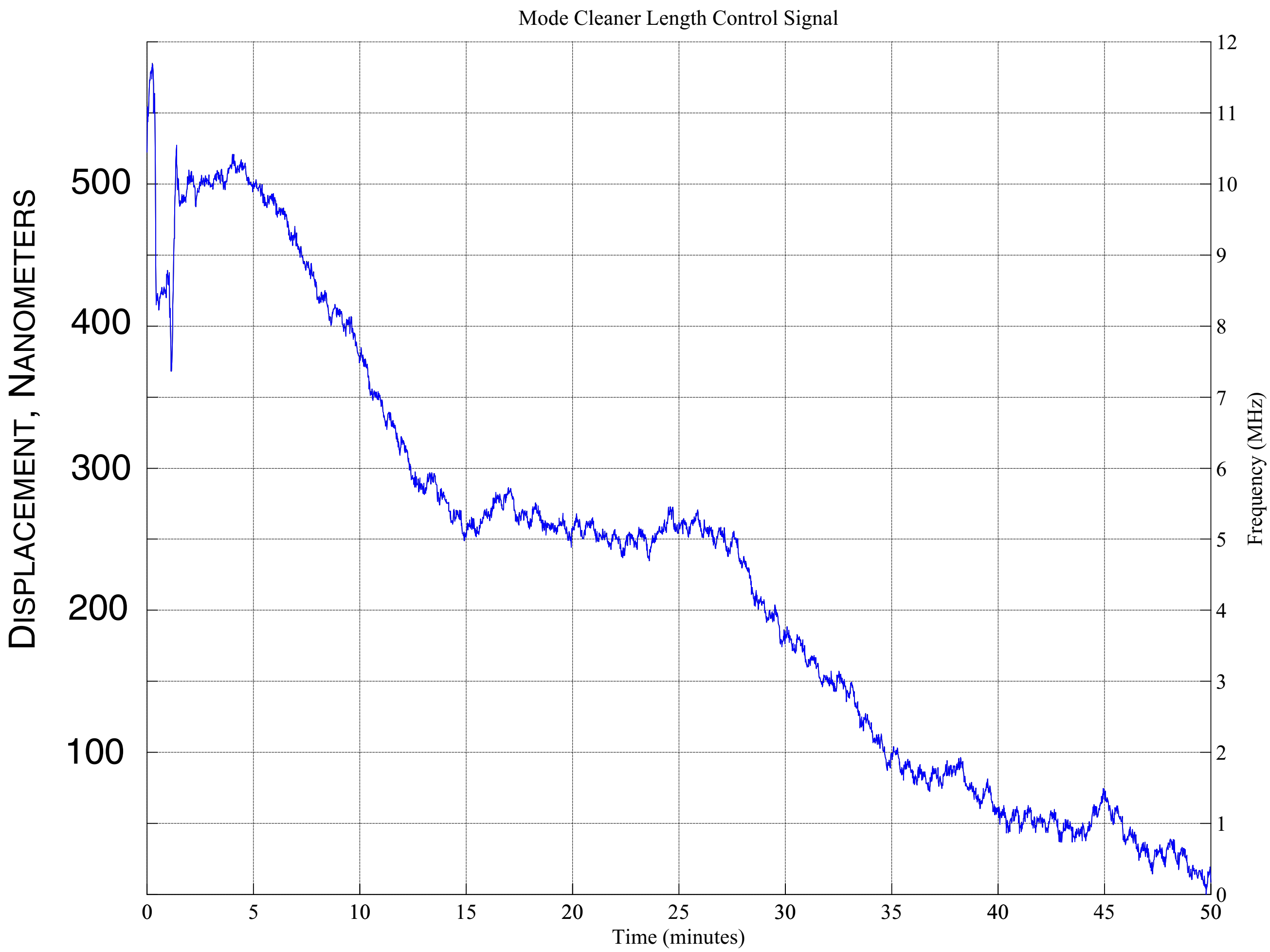
ALIGNMENT CONTROL, CONT'D



LOCK ACQUISITION & STABILITY

- o Lock typically acheived with no bypass gain & lower overall gain
- o WFS alignment servo can be left on during acquisition
- o Electro-optic shutter operation
  - › must detect ~15% of input power to reach req'd shot noise sensitivity
  - › when unlocked, ~1W headed toward photodetector
  - › EO shutter closes quickly when MC falls out of lock; lets through an adjustable level of power (few percent) for locking
  - › when MC locks, shutter opens when trigger PD passes a threshold and stays there for more than some delay time (1 sec)
- o Remains locked for ~1 day (looses lock only when PMC falls out?)

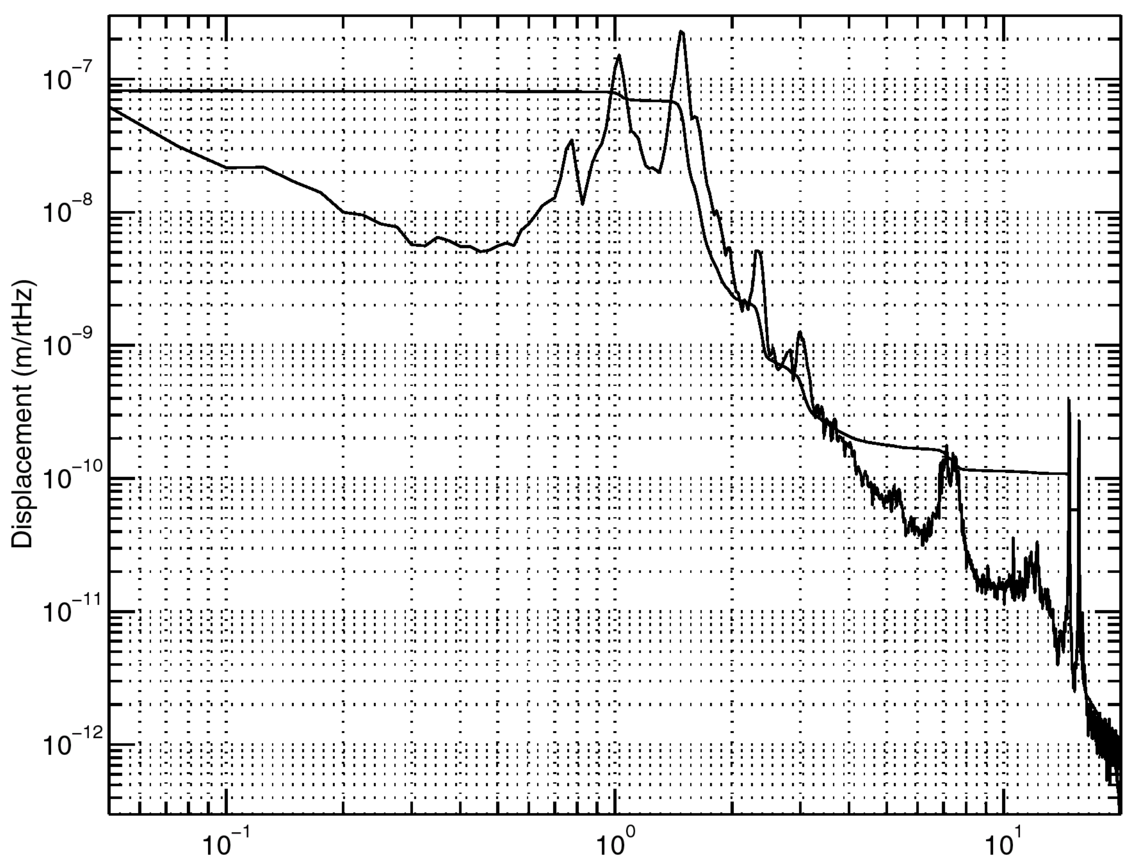
LONG TERM DRIFT



› Recent data shows drift rate of 15 nm/min, and is much smaller than the frequency drift implied by the PSL reference cavity temperature drift

Integration with Interferometer (2km cavity)

- **Frequency stabilization feedback to the mode cleaner to be tried on 2km cavity**
  - › additive offset to mode cleaner error signal
  - › mode cleaner length correction signal
- **MC length fluctuations produce relatively large frequency fluctuations** **(100x arm length ratio)**



1 nm
→ 20 kHz

Revisions for next servo module

- o Resonant gain stage (Q~10) at the first stack mode (1.5 Hz) in the MC length path
- o Notch filter at the SOS vertical mode (15 Hz) in the PSL/VCO control path
- o Elliptic low-pass filter in MC length path will be switchable (IN/OUT)
- o Low-pass filtering in the PSL/VCO path will be moved into the VCO module to preserve the VCO chip's phase noise
- o New variable gain stage with wide bandwidth, low noise
- o Will use LSC demodulation board, so that both I & Q phases are available
- o DAQ channel outputs will have appropriate signal conditioning

w2k mode cleaner characterization measurements

- MC length
- MC cavity linewidth
- MC transmission
- MC output beam stability
- Internal Q's of MC mirrors

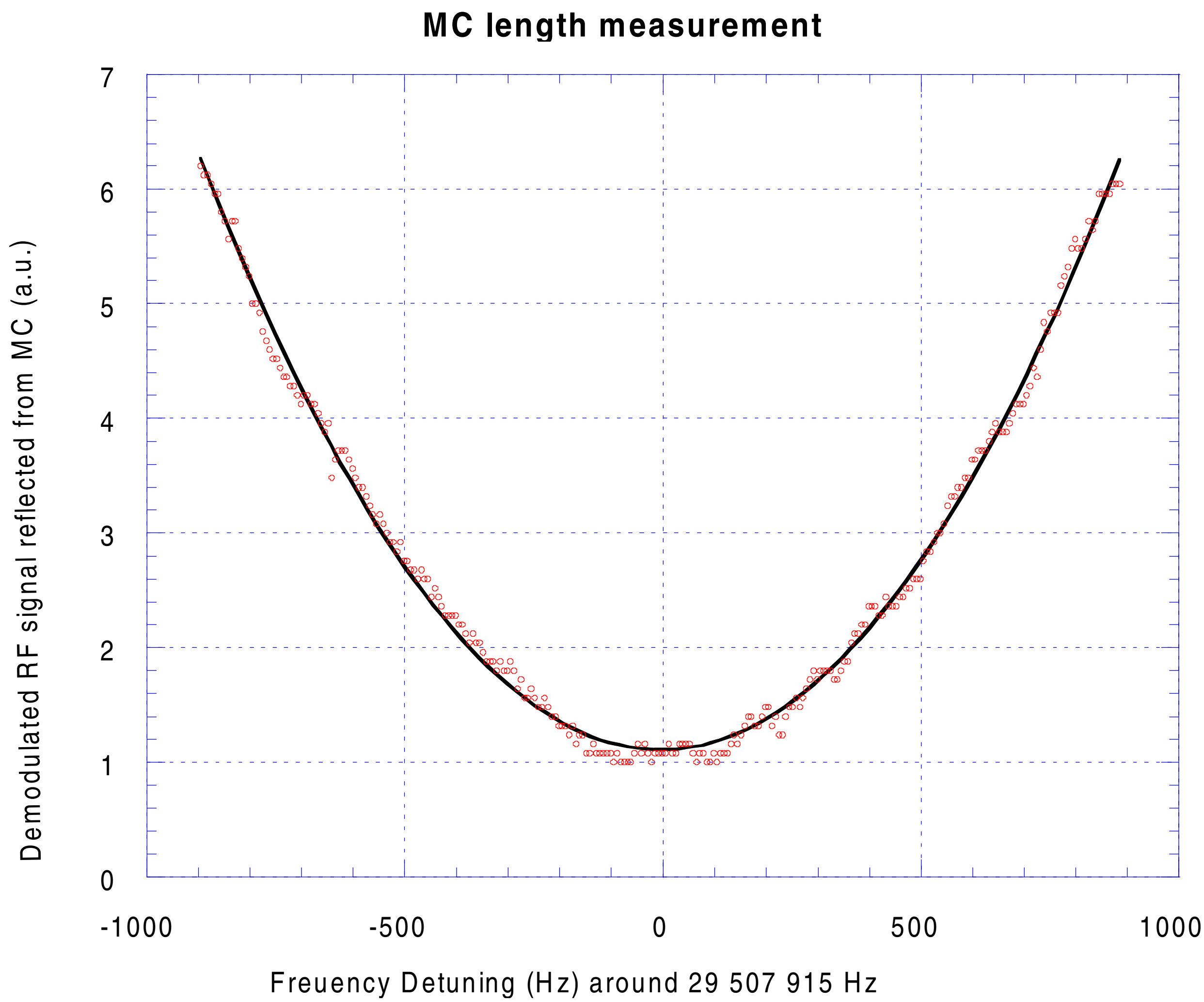
MC length measurements

- Method: RF resonant sideband detuning
  - ››add resonant sideband, f = 3 FSR
  - ››sweep the modulation frequency
  - ››measure the demodulated reflection
  - ››find the minimum f_0

$$L_{mc} = 3c / 2f_0$$

MC length measurements (cont'd)

- Data Plot



MC length measurements
(cont'd)

- Results

f_0 = 29 507 915 ± 100 Hz

L_{mc} = 15.239595 m ± 50μm

(L_{design}= 15.240 m)

- Technical notes
  - to improve S/N
    - Dither carrier frequency at a rate of ~ 1kHz
    - Measure demod signal with lock-in
  - MC length measurements
    - after the installation
    - after length adjustment in air
    - final in-vacuum measurement
  - RFAM at MC output
    - sensitive to MC length and RF frequency mis-match

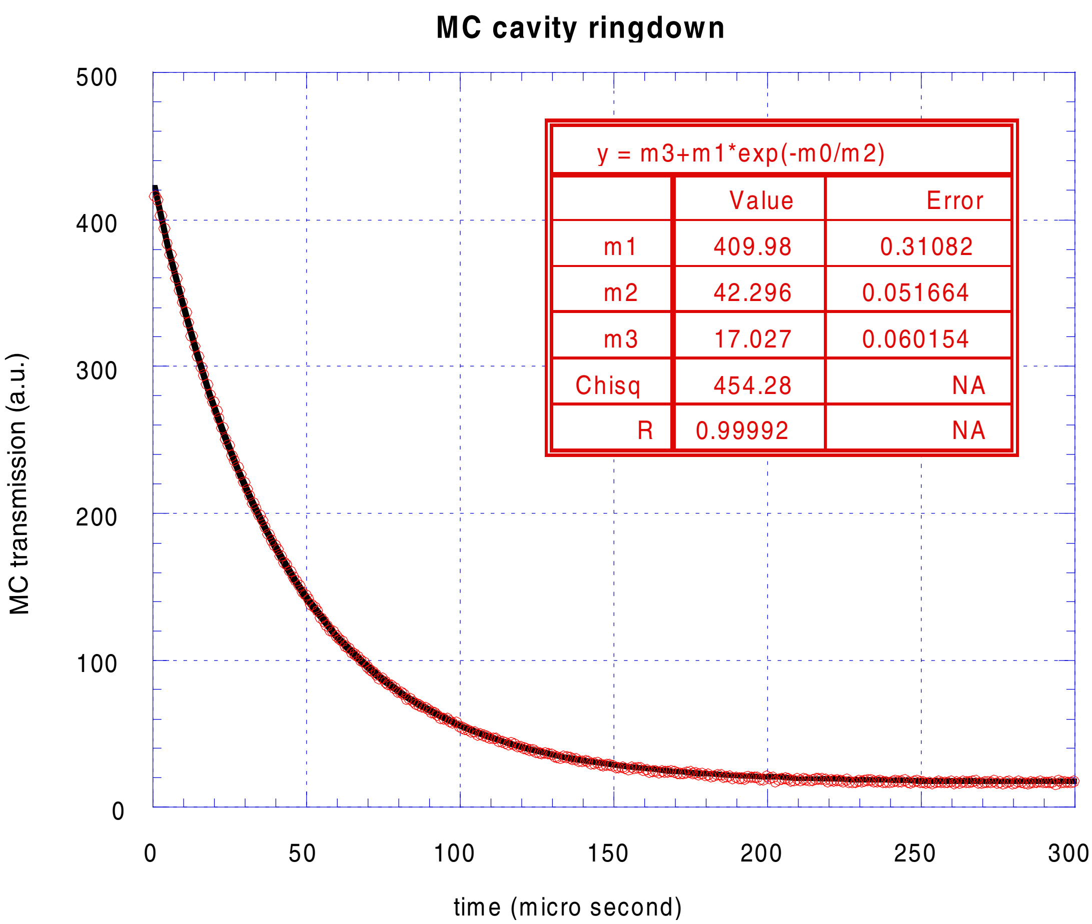
MC cavity linewidth measurements

- Methods
  - Ringdown/up
    - Square wave modulation of input power using AOM

      Modulation depth 10%
    - Measure MC output power with fast PD
    - Determine (average) ringdown/up time constant τ
    - Cavity linewidth Δf (FWHM) = $1/\pi\tau$
  - Transfer function
    - Using AOM to modulate laser power
    - Measure output/input power transfer function
    - Determine pole frequency f_p
    - $\Delta f = 2f_p$

MC cavity linewidth measurements(cont'd)

- Ringdown Measurement



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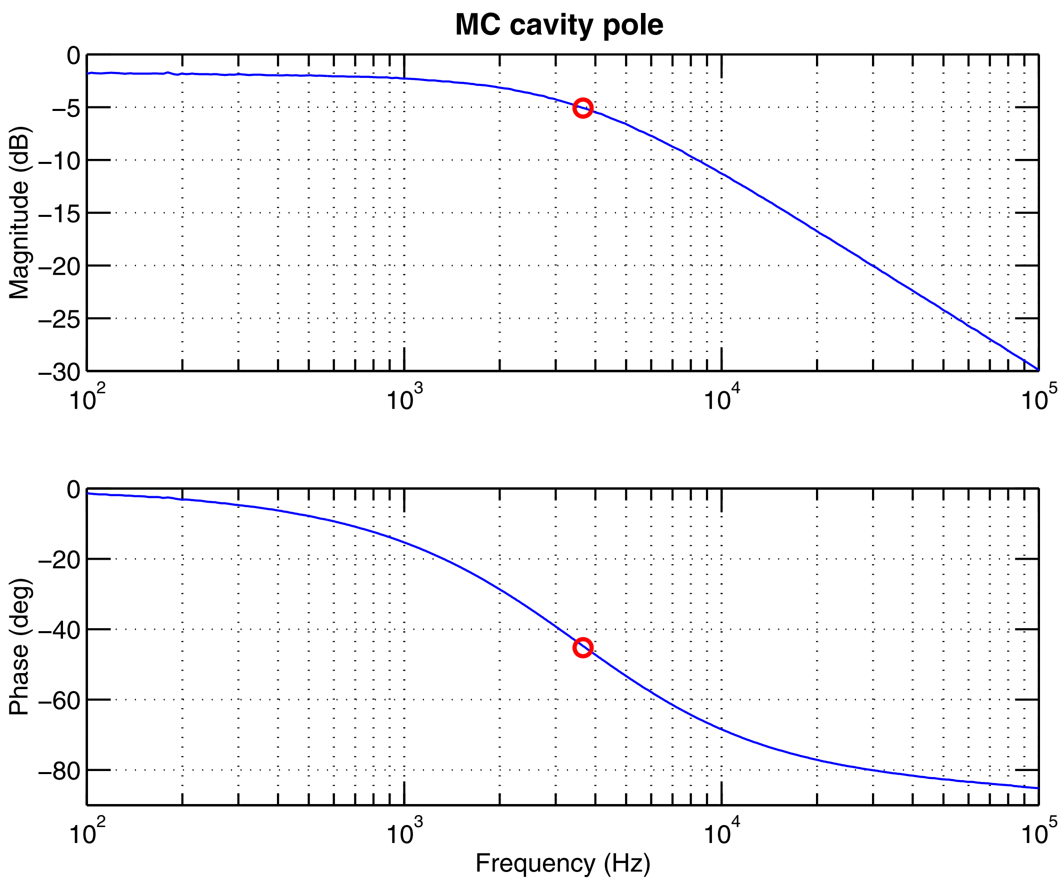
MC cavity linewidth measurements(cont'd)

- Transfer Function measurement



MC cavity linewidth measurements(cont'd)

- Measurement Results

Table 1: Cavity Linewidth

Method	Ringdown/up	X-function	Average
Δf (kHz)	7.24	7.38	7.31

- Estimate Losses of the Cavity
  - Finesse from linewidth measurement

$$F = \mathrm{FSR}/\Delta f = 1346$$

  - Total round trip loss

$$\delta = 2\pi / F = 4668 \text{ ppm}$$

  - Measured mirror transmission

$$T_{mc1,3} = 2255 \text{ ppm},\ T_{mc2} = 10 \text{ ppm}$$

  - Other losses in the cavity

$$\delta - (T_{mc1} + T_{mc2} + T_{mc3}) = 148 \text{ ppm} \rightarrow 49 \text{ppm/mirror}$$

MC Transmission

Input I_i = 124 ± 1% mW, Output at AS I_o= 0.632 ± 1% mW

Table 2: Transmission/Reflection of all optical elements in the beam path

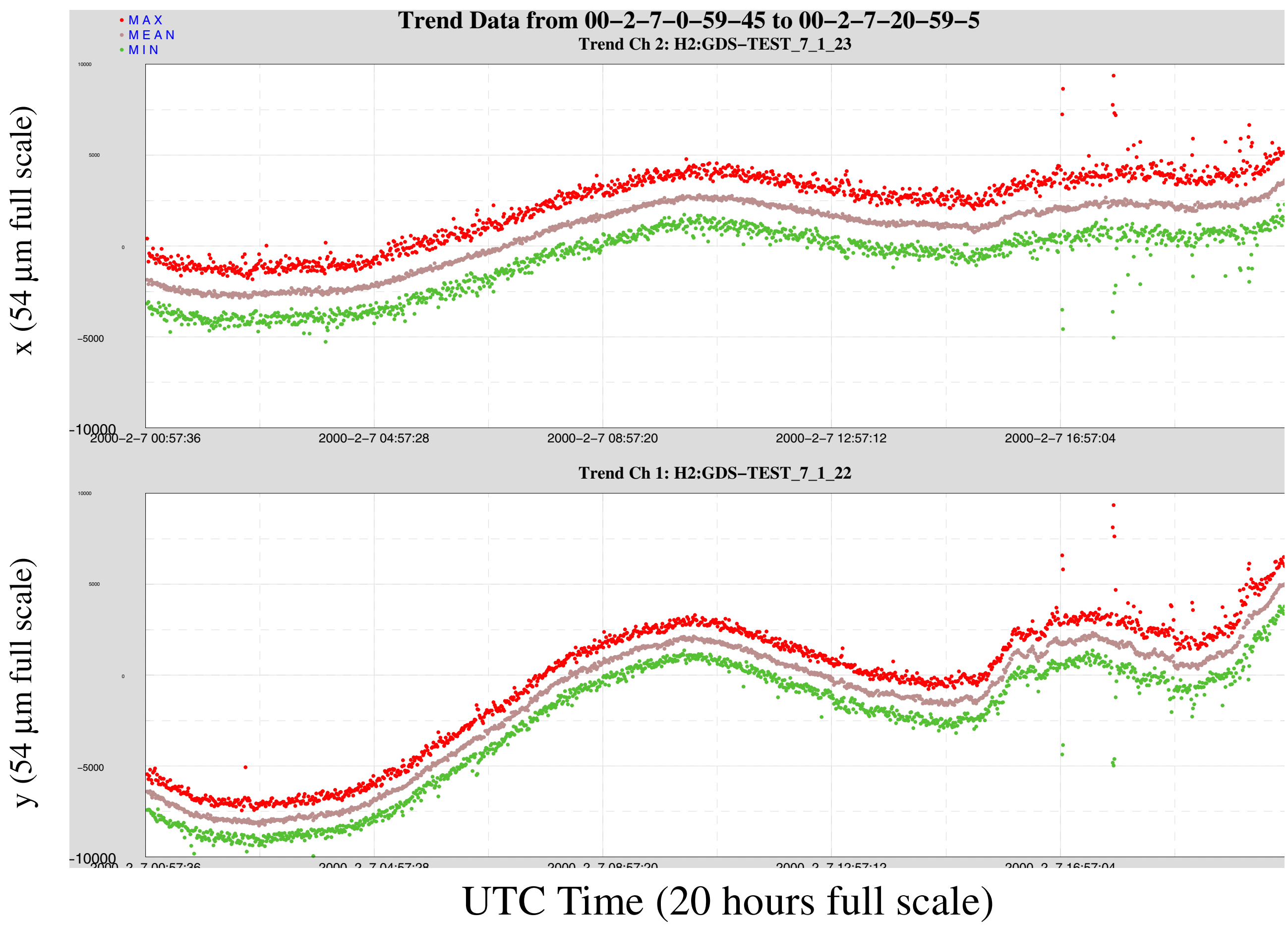
Optics	Transmission/ (Reflection)	Errors
Input viewport	0.98	1%
SM1	0.995	0.1%
Faraday Isolator	0.90	1%
SM2 and MMTs	0.999	-
RM	0.025	4%
BS (T)	0.50	-
ITMy	0.97	-
BS (R)	0.50	-
APS and SMs	0.99	1%
Output viewport	0.99	1%
Total(T)	**0.00521**	**4.5%**

$$\mathbf{T_{mc} = (I_o/I_i)(1/T) = \underline{0.98 \pm 4.7\%}}$$

MC output beam stability

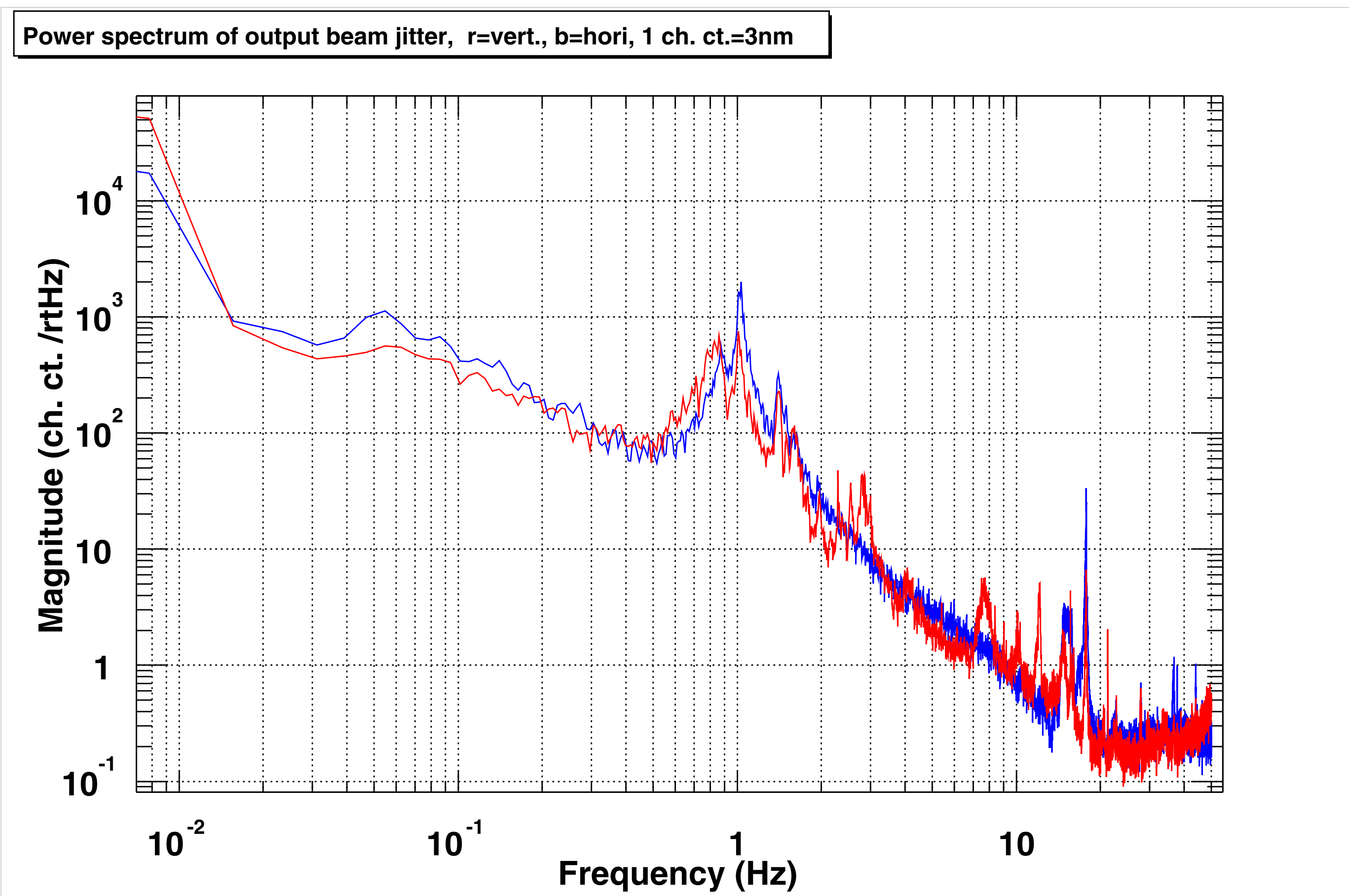
- Long-term fluctuation
  - Measured with QPD placed 6m away from MC waist

Minute-trend data over 20 h, x: horizontal; y: vertical



MC output beam stability (cont'd)

- short term stability
  - Measured with QPD placed 6m away from MC waist



Internal Q's of MC mirrors

- Method
  - ›› excite internal modes by driving MC mirrors with random noise
  - ›› find resonance frequencies f in error signal spectrum
  - ›› set lock-in reference frequency close to the resonance to produce a beat at ~ 1Hz
  - ››turn off noise source, measure ringdown time constant τ
  - ›› $Q=\pi\tau f$

- Results

Table 3: Internal Q's of MC mirrors

Mirrors	Frequency(kHz)	Q (10^6)
MC1	28.233	0.75
MC2	28.199	0.37
MC3	28.233	1.29

Internal Q's of MC mirrors(cont'd)

- Q-measurement data plot