PSL Final Design Review

LIGO–G990021–00–D

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PSL Highlights

Caltech

- Simultaneous operation of frequency stabilization, PMC, intensity stabilization and tidal servos.
- Automated lock acquisition of the frequency stabilization servo.

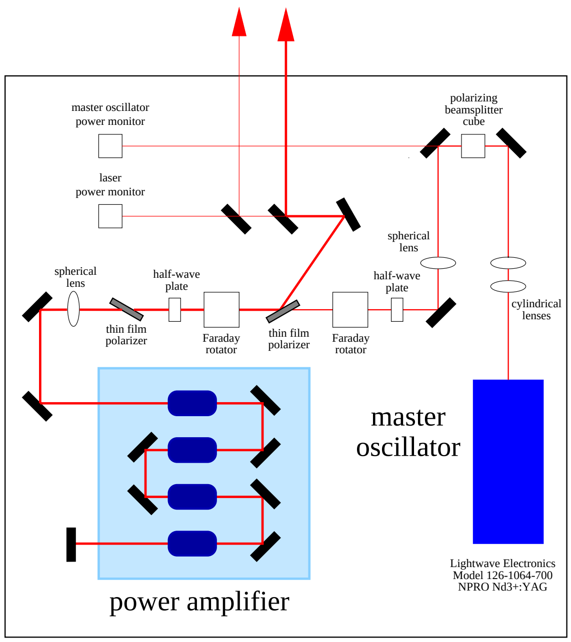
LHO 2k IFO PSL

- In-the-loop frequency noise levels consistent with design requirements.
- Measured intensity noise levels at the **IOO** input close to specification.
- Stabilized output power of $\sim 8\,\mathrm{W}$, close to the $8.5\,\mathrm{W}$ requirement.
- Automated lock acquisition of the PMC servo.
- Continuous operation for a period greater than 30 days, without loss of lock for the frequency stabilization servo.

126 MOPA Laser

Laser Features

The laser is a master-oscillator-power-amplifier configuration.



Three primary actuators are provided with the laser:

- Fast — a PZT.
- Slow — a TEC bonded to the NPRO crystal.
- AC Current Adjust — allows modulation of the diode current.

The laser installed in the LHO 2k IFO PSL is 126 MOPA #102.

Laser Performance

Free-running Intensity Noise

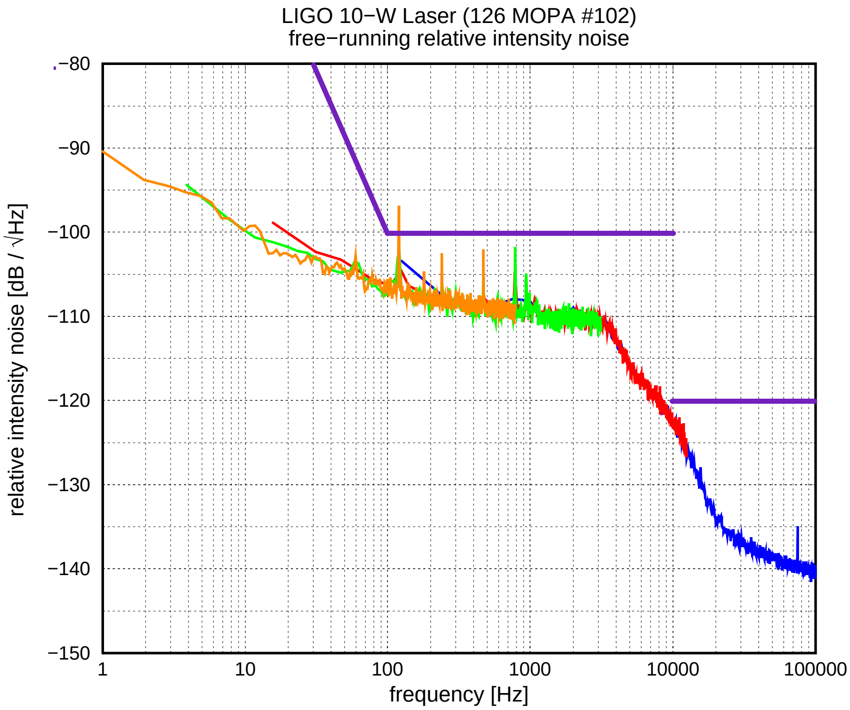


Figure 1: Free-running intensity noise measured for 126 MOPA #102. The measurement was conducted at Caltech.

All lasers delivered, to date, conform to specifications.

Laser Performance (cont.)

Free-running Frequency Noise

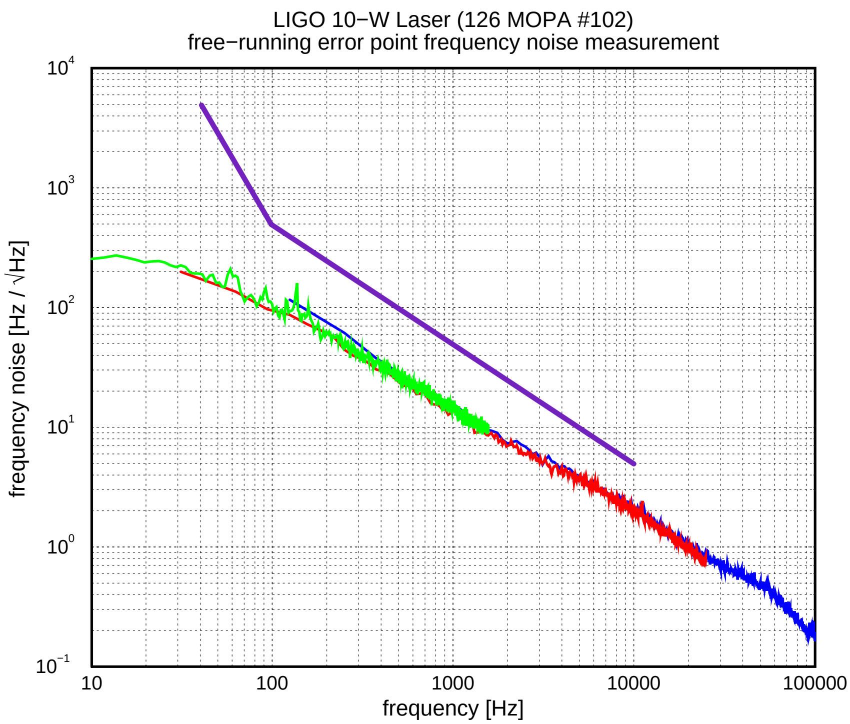


Figure 2: Free-running frequency noise measured for 126 MOPA #102. The measurement was conducted at Caltech.

Both the Alpha-1 and #102 lasers conform to specifications. Other lasers were not characterized owing to the nature of the measurement.

PSL Design Changes

The only design change for the PSL, relates to the implementation of the intensity stabilization.

AC Current Adjust Actuator

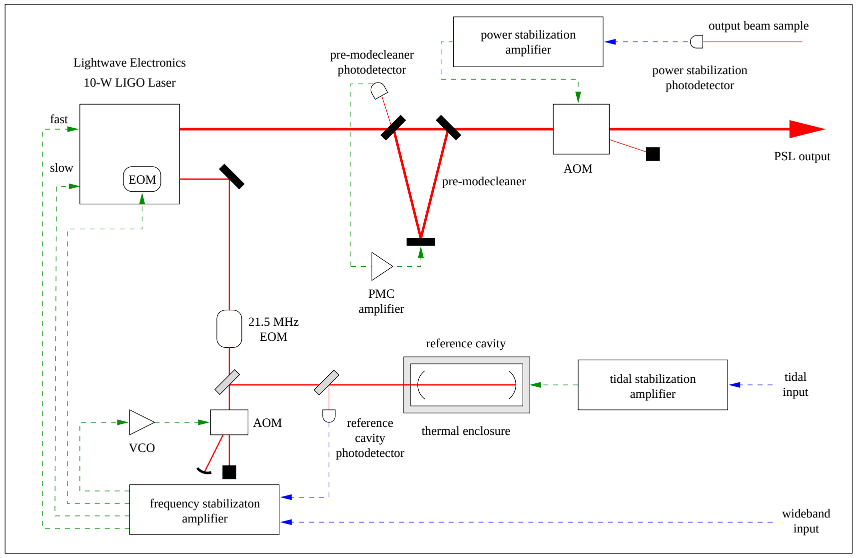
The original strategy for intensity stabilizing the laser envisaged using feedback control to the power amplifier pump diode current, through the AC current adjust actuator.

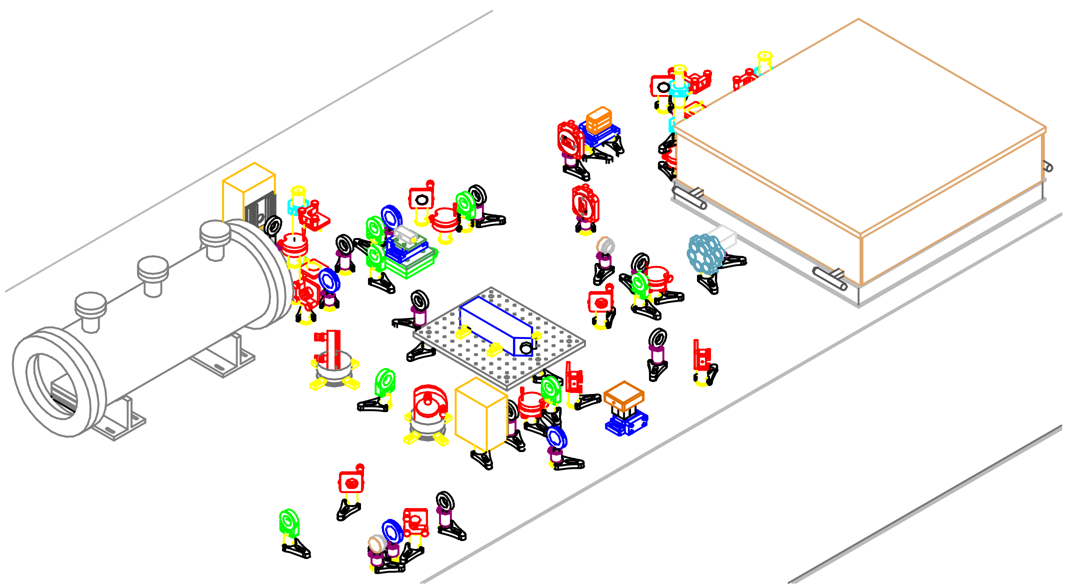
Extra poles were present in the transfer function, making the design of a stable feedback control servo difficult.

Acousto-optic Modulator

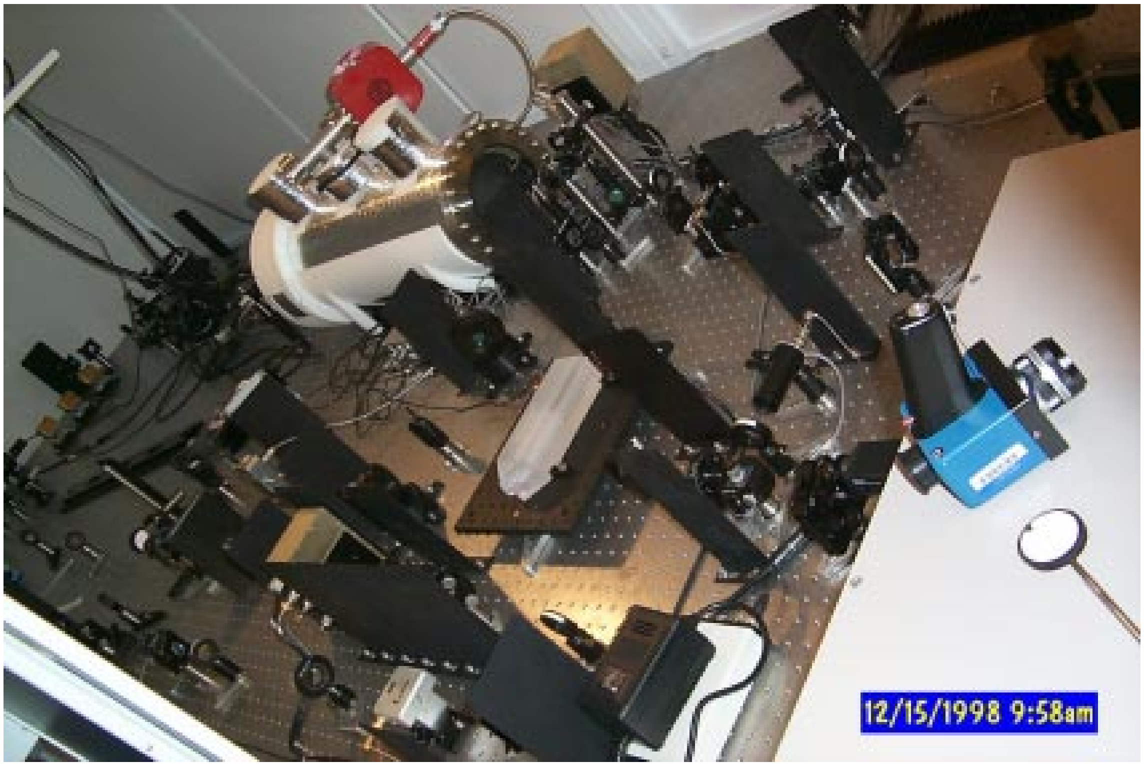
The new strategy uses an AOM for regulating the intensity.

PSL Optical Layout





PSL Optical Layout (cont.)



Frequency Stabilization

Reference Cavity

The reference cavity, reference cavity vacuum chamber and vibration isolation stack are nominally identical to that used on the PNI.

PSL Modulation Frequency

The modulation frequency used is 21.5 MHz for both interferometers.

Wideband Frequency Control Input

Design Requirement

PSL shall provide a wideband frequency control input for frequency correction signals from the **IOO** modecleaner servo. The interface parameters for the PSL Wideband Frequency Control Input are specified below.

Frequency Response:

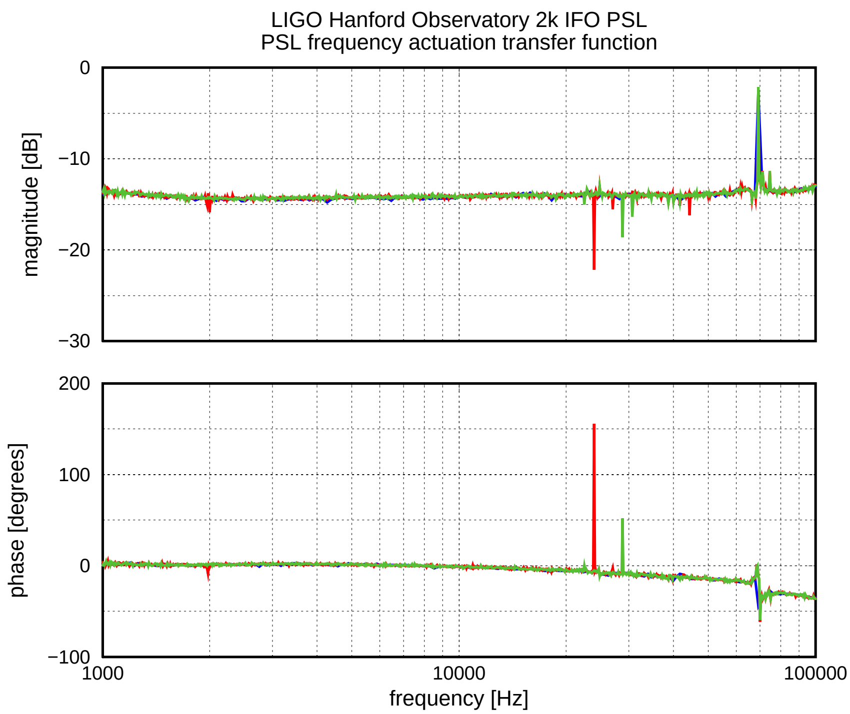
Magnitude:

DC to 100 kHz: Flat within 2 dB

$f > 100$ kHz: $< (f/100\,\text{kHz}) \times$ (average response below 100 kHz)

Phase: Phase lag at 100 kHz, $\phi < 20°$

Result

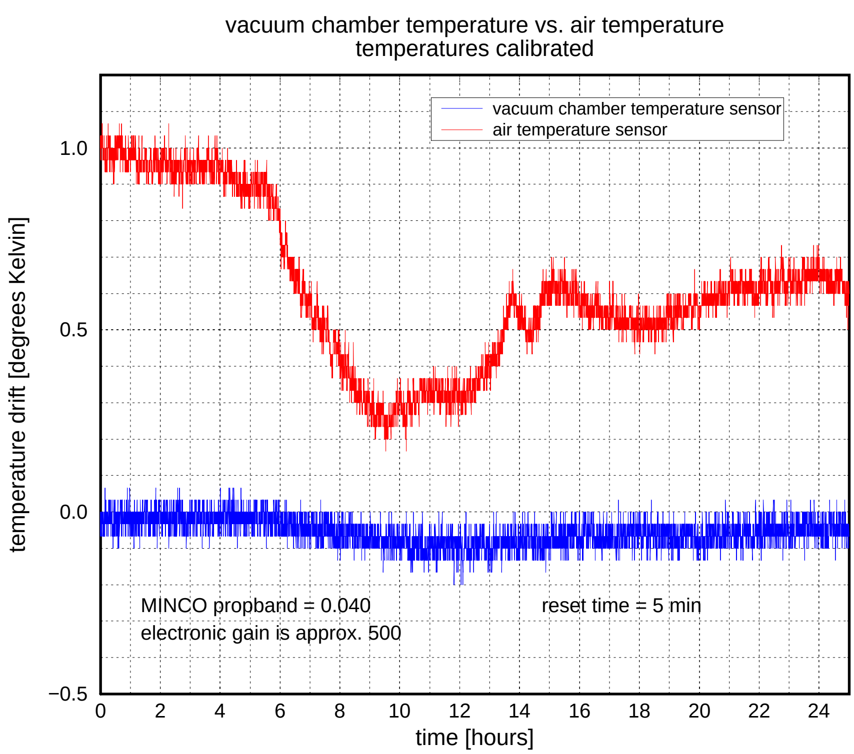


Tidal Correction Frequency Control Input

Two important time constants have been measured:

- τ_{heat}, the time taken for the reference cavity vacuum chamber to respond to a step input from the heater.
- τ_{rad}, the time taken for the laser frequency to respond to a step input from the heater.

Temperature Stabilization



Frequency Fluctuations

Design Requirement

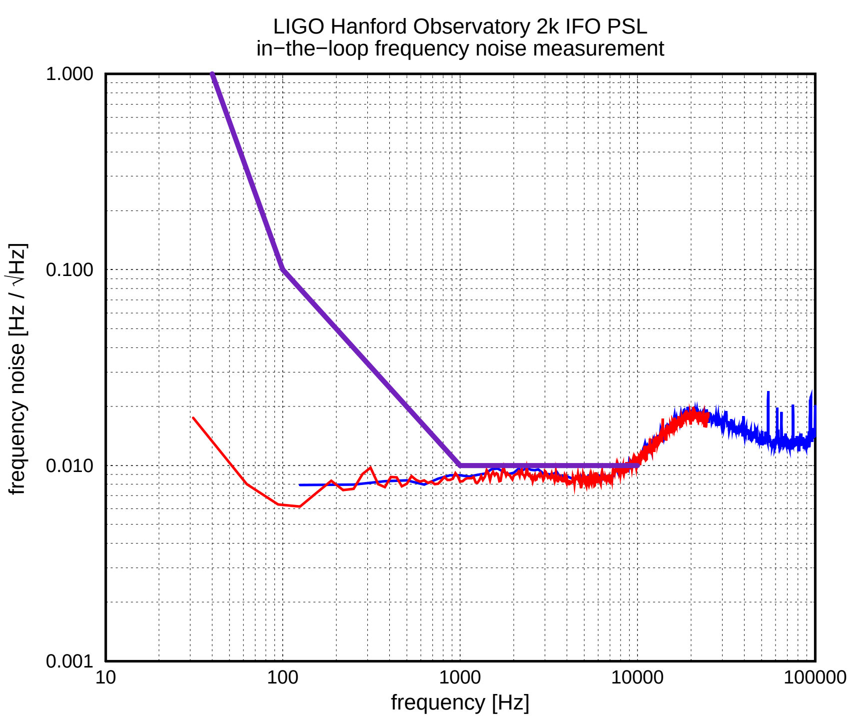
The amplitude spectral density of the frequency fluctuations at the input to the **IOO** shall be as specified in Table 1, below.

Frequency Range	Allowed Frequency Fluctuations
40 Hz to 100 Hz	$< 0.1 \times (100\,\mathrm{Hz}/f)^{2.5}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$
100 Hz to 1 kHz	$< 0.1 \times (100\,\mathrm{Hz}/f)\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$
1 kHz to 10 kHz	$< 1.0 \times 10^{-2}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$

Table 1: Allowed PSL output beam frequency fluctuations.

Result

The in-the-loop frequency noise measurement obtained from the LHO 2k IFO PSL.



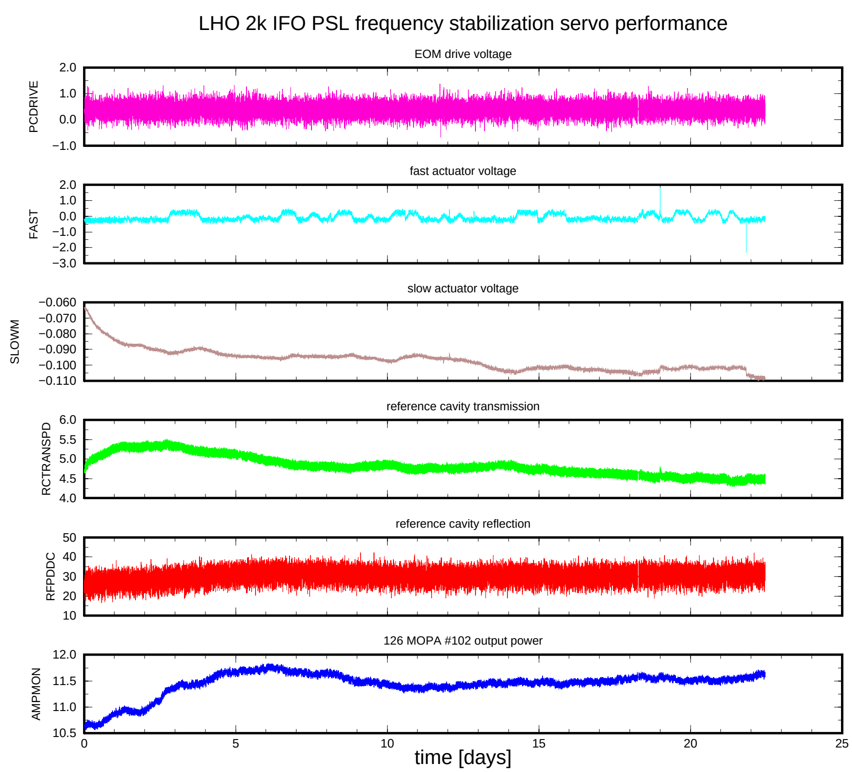
Frequency Stabilization Servo Performance

Design Requirement

The PSL shall be designed to operate continuously without loss of 'lock' (even for short times) for 40 hours, during normal seismic conditions (90 % percentile **TBD** by **SYS** for either site).

Result

Performance monitoring of the LHO 2k IFO PSL frequency stabilization servo. The recorded monitoring was for a period of ∼22 days, however the PSL remained in lock for a longer period of time.



Power Stabilization

Power stabilization is divided into three categories:

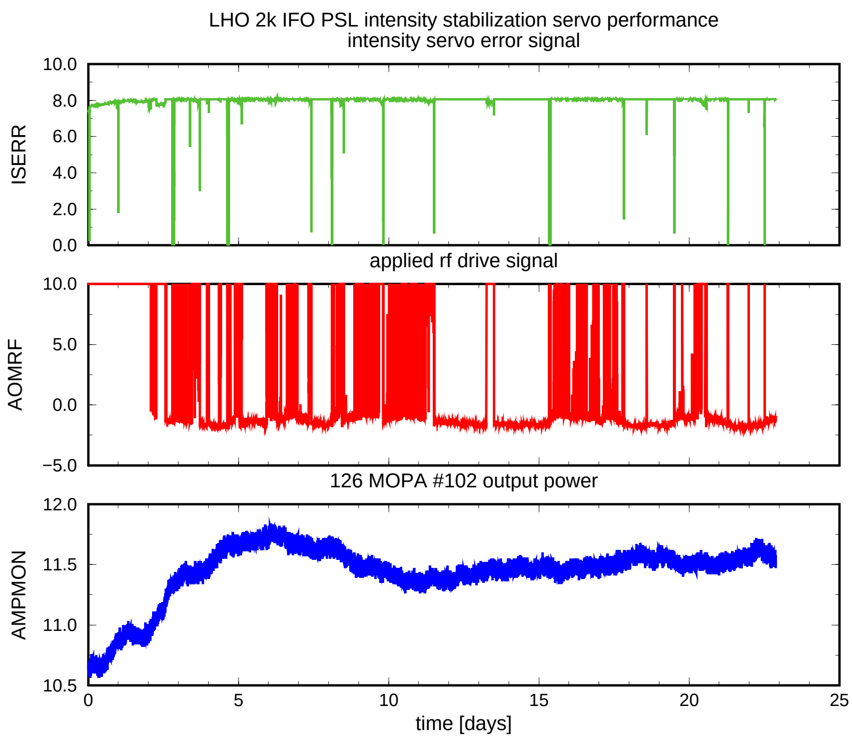
- Low-frequency power fluctuations.
- Fractional light power fluctuations in the GW band.
- Shot-noise limited power fluctuations.

The first two are implemented via the use of an AOM as an intensity modulator. The third, requires the use of a passive cavity, the PMC.

Design Requirement

The low-frequency variations in the PSL output power shall be less than 1 % peak-to-peak over any 24-hour period.

Result

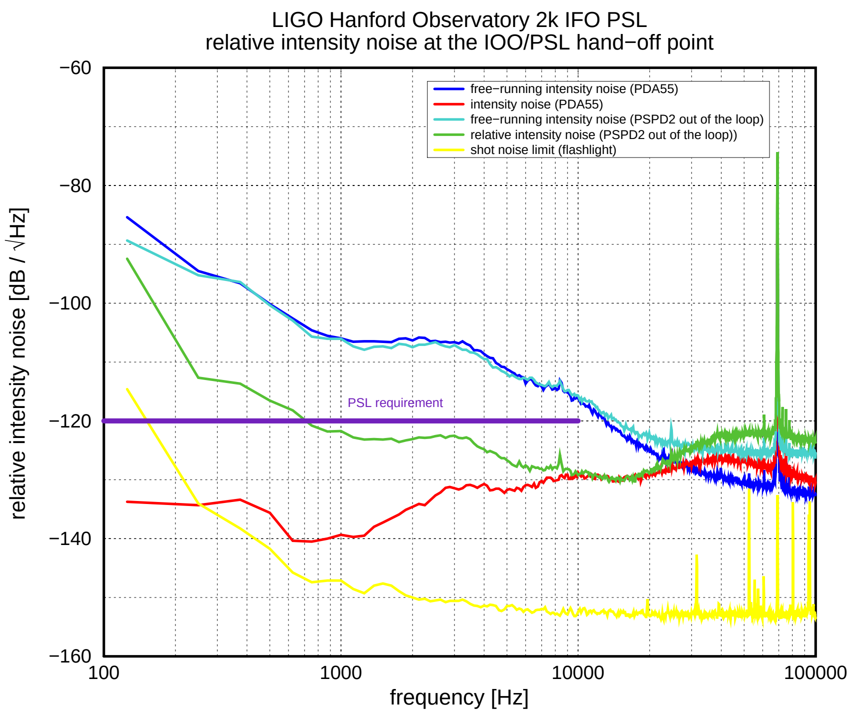


Power Stabilization (cont.)

Design Requirement

The amplitude spectral density of the fractional light power fluctuations at the input to the **IOO** shall be $\delta P(f)\,/\,P < 10^{-6} 1\,/\,\sqrt{\text{Hz}}$ for $100\,\text{Hz} < f < 10\,\text{kHz}$ and rising as $f^{-3/2}$ for $40\,\text{Hz} < f < 100\,\text{Hz}$.

Result

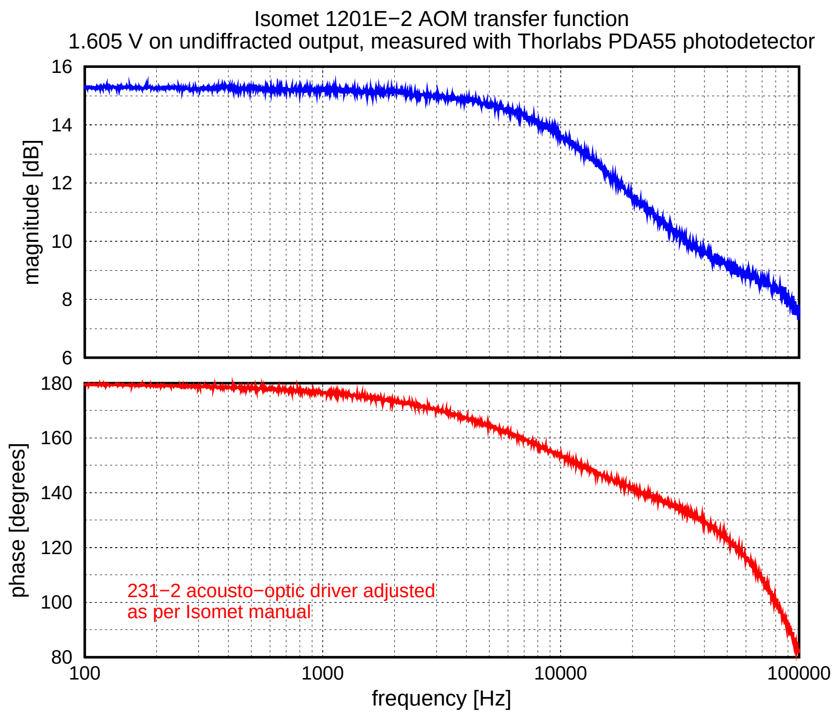


The LHO 2k IFO PSL does not meet the power fluctuation specification at the **COC** input and the reason is the response of the AOM.

Power Stabilization (cont.)

It should be noted that no experience with the intensity stabilization AOM was obtained prior to installation. As such, the results obtained do not illustrate any optimization of the intensity stabilization servo.

AOM Transfer Function



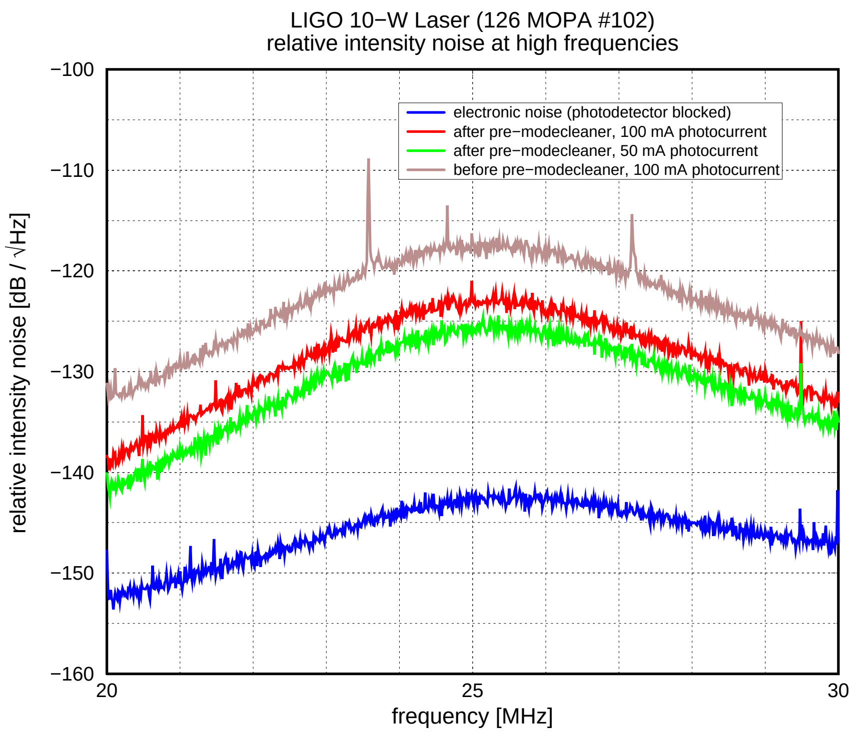
The unexpected roll off of the AOM limited the bandwidth of the intensity stabilization servo. Whilst the servo gain could be increased, this resulted in oscillation peaks at high frequencies.

Shot-noise Limited Power Fluctuations

Design Requirement

The amplitude spectral density of relative power fluctuations in the output beam of the PSL, measured at the input to the **IOO**, at frequencies above 24.5 MHz and 29.5 MHz (the modulation frequencies of the sidebands used for gravity wave detection for the 4-km and 2-km interferometers, respectively), shall be less than 1.005 times the shot noise limit for 600 mW of laser light. (This is the expected power level at the dark port of the interferometer).

Result



Shot-noise Limited Power Fluctuations (cont.)

The intensity noise N_L before the PMC is 6 dB higher than that after the PMC.

$$N_L = 2\ N_{PMC}. \tag{1}$$

The measurement implies that the light after the PMC is shot noise limited.

$$N_{PMC} = N_{SN}. \tag{2}$$

The intensity noise has contributions from shot noise N_{SN} and the laser's technical noise N_T, given by

$$N_L = \sqrt{N_T^2 + N_{SN}^2} \tag{3}$$

Simplification and re-arranging terms yields

$$N_T = N_{SN}\ \sqrt{3} \tag{4}$$

The output power of the laser is 10 W, which is 67 times greater than the detected power of 150 mW. The technical noise scales as the power incident on the photodetector and the shot noise scales as the square root of the power incident on the photodetector. Scaling of the results obtained at 150 mW suggests that the technical noise from the laser is 14 times the shot noise of 10 W.

The design requirement is

$$N_{600\,\mathrm{mW}} < 1.005\ N_{SN\ 600\,\mathrm{mW}}. \tag{5}$$

The ratio laser power and the sampled power, gives the requirement on the technical noise from the laser to be

$$N_{T\ 10\,\mathrm{W}} = \sqrt{\frac{10}{0.600}}\ \sqrt{1.005^2 - 1}\ N_{SN10\,\mathrm{W}}. \tag{6}$$

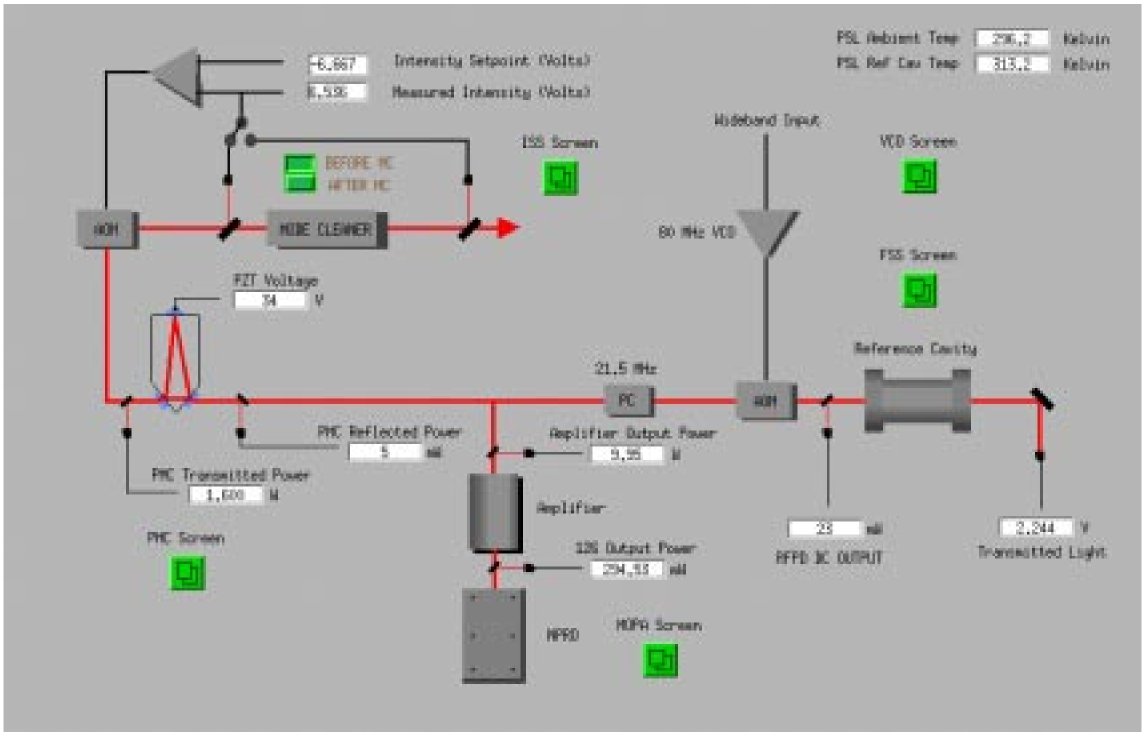
The technical noise needs to be 0.41 times the shot noise limit for 10 W. Comparison of the experimental result, with the calculated result suggests that the technical noise needs to be filtered by a factor of ~ 35.

This degree of filtering requires a bandwidth of 714 kHz.

User Interface

Top Level PSL

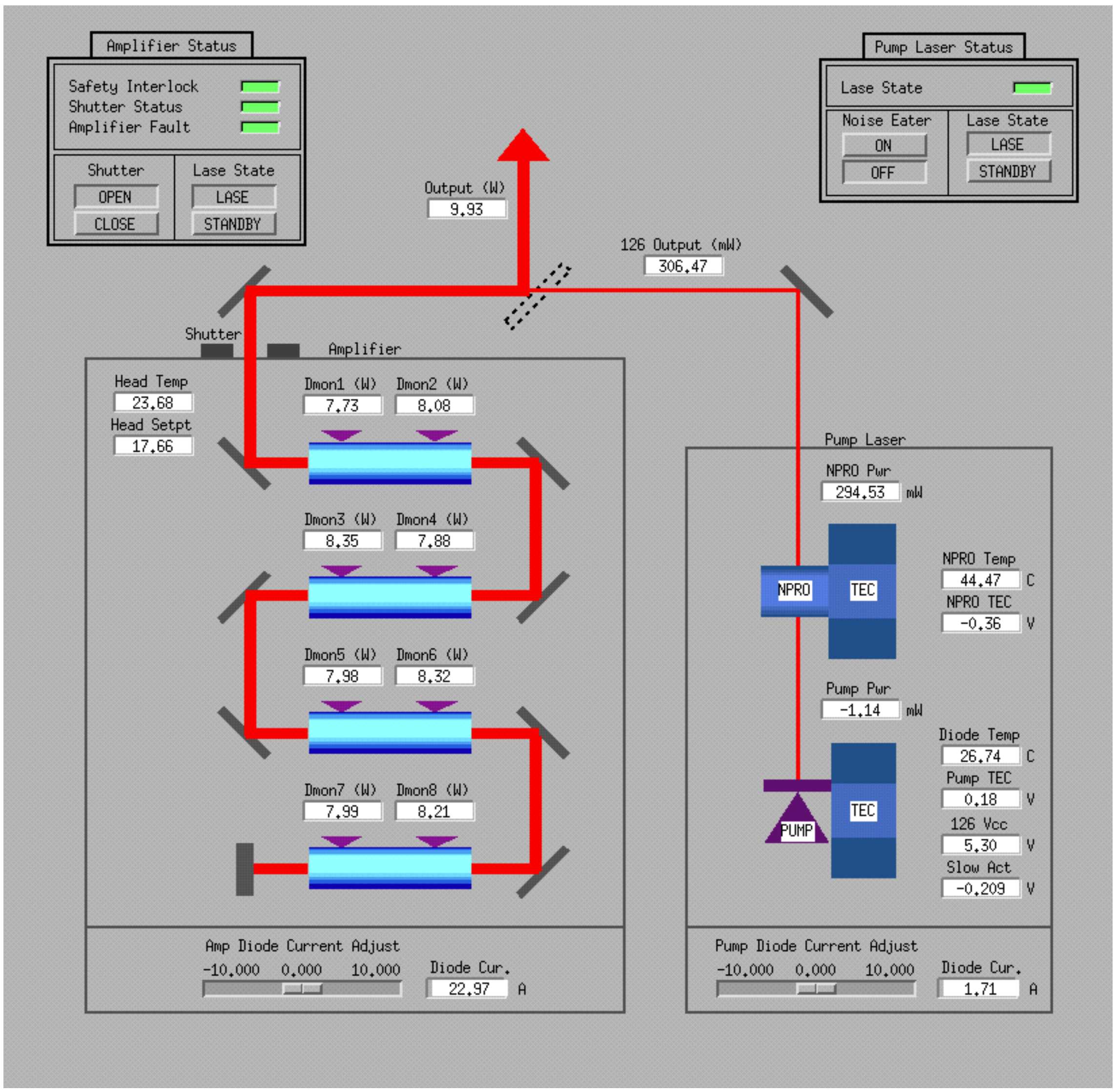
The operator should be able to tell the status of the PSL "at a glance".



User Interface (cont.)

MOPA

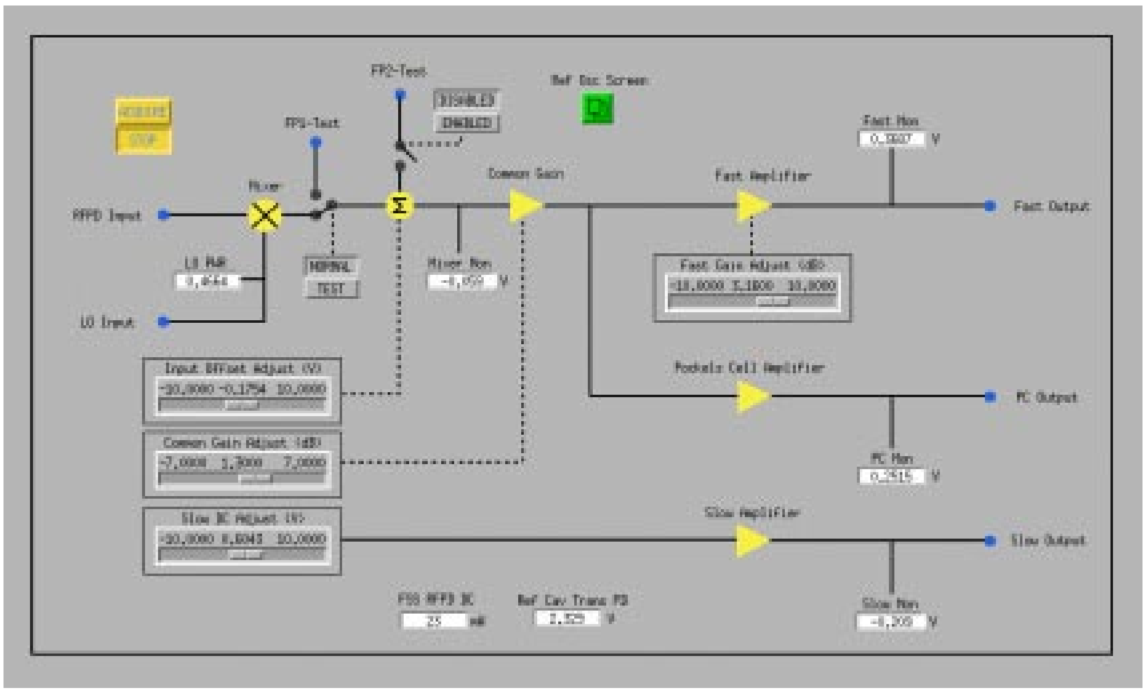
Control the status of the 126 MOPA Laser via four buttons and two sliders. Various signals are displayed. The beam animates to indicate the current lase status.



User Interface (cont.)

Frequency Stabilization Servo

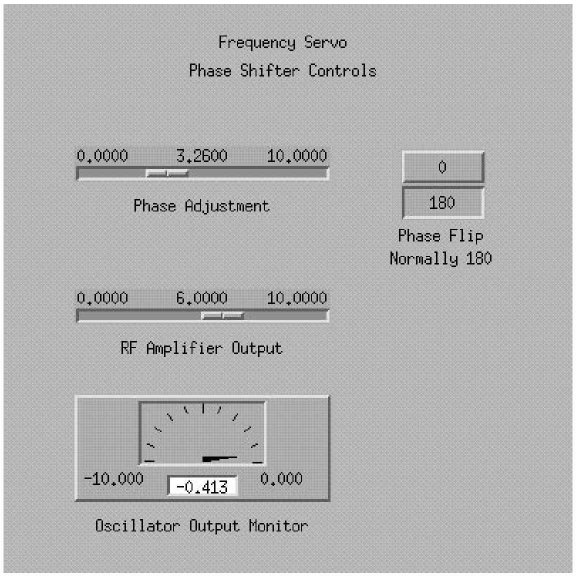
Control all the settings for the frequency stabilization servo.



User Interface (cont.)

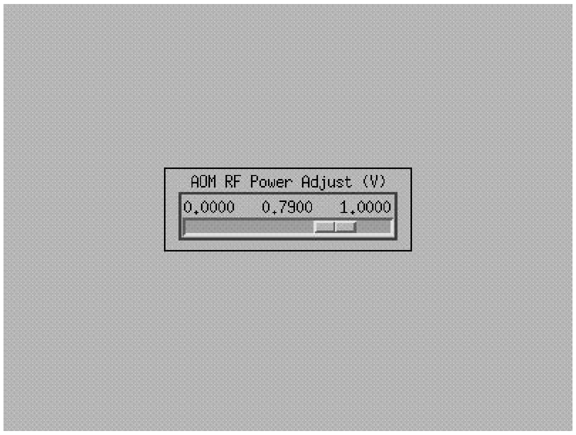
Phase Shifter

Adjustment of phase and rf power.



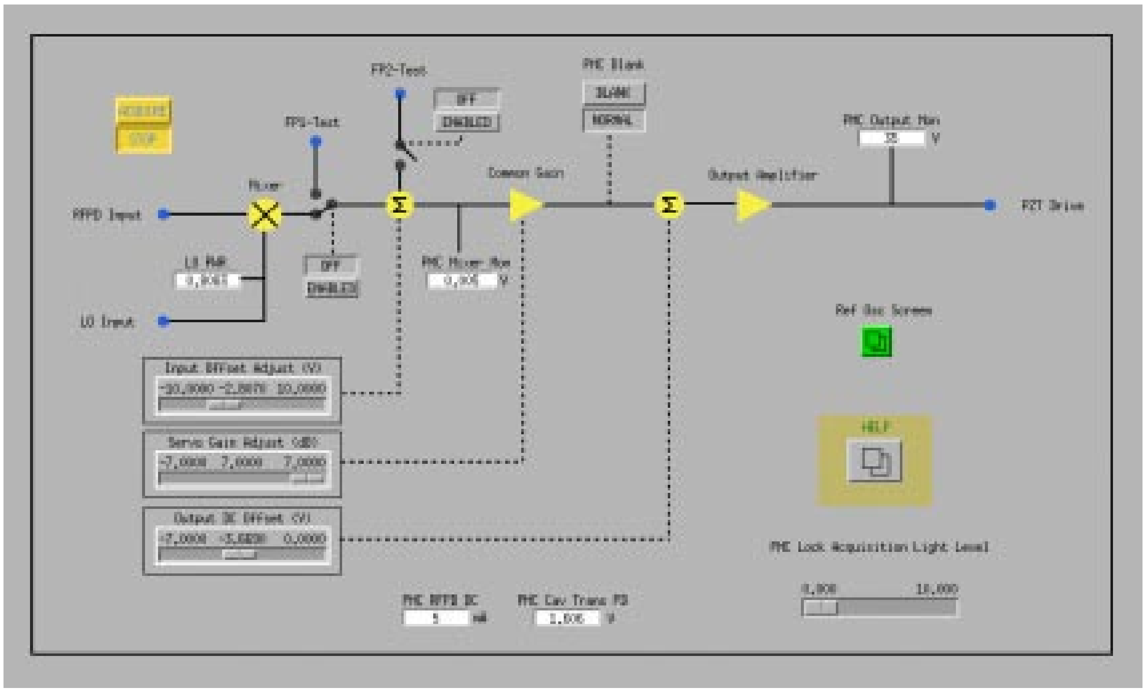
VCO

Adjustment of rf power for maximum diffraction efficiency.



User Interface (cont.)

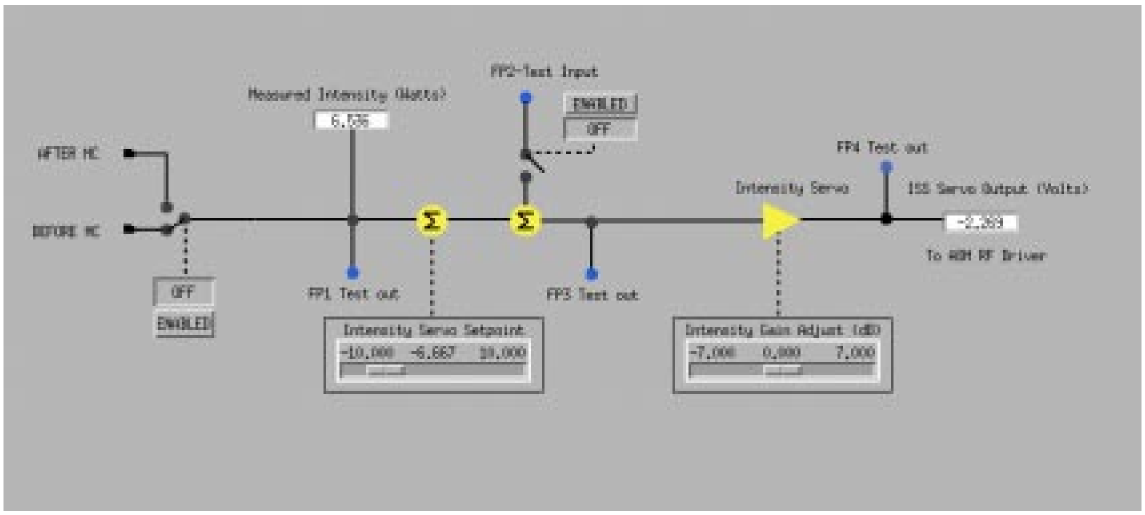
PMC Servo



User Interface (cont.)

Intensity Stabilization Servo

Adjustment of stabilized intensity setpoint and selection of photodetector.



Performance Monitoring

Signals Monitored

EPICS Name	Description
PSL-126MOPA_AMPMON	126 MOPA output power from the internal power monitor
PSL-126MOPA_126MON	NPRO output power from the internal power monitor
PSL-126MOPA_DS1	diode monitor 1
PSL-126MOPA_DS2	diode monitor 2
PSL-126MOPA_DS3	diode monitor 3
PSL-126MOPA_DS4	diode monitor 4
PSL-126MOPA_DS5	diode monitor 5
PSL-126MOPA_DS6	diode monitor 6
PSL-126MOPA_DS7	diode monitor 7
PSL-126MOPA_DS8	diode monitor 8
PSL-126MOPA_HTEMP	head temperature
PSL-FSS_RFPDDC	reference cavity "visibility"
PSL-FSS_LODET	frequency servo local oscillator power
PSL-FSS_PCDET	EOM drive
PSL-FSS_FAST	fast voltage monitor
PSL-FSS_PCDRIVE	EOM voltage monitor
PSL-FSS_RCTRANSPD	reference cavity transmission monitor
PSL-ISS_AOMRF	rf drive to the intensity stabilization AOM
PSL-PMC_RFPDDC	PMC "visibility"
PSL-PMC_LODET	PMC servo local oscillator power
PSL-PMC_PMCTRANSPD	PMC transmission monitor
PSL-PMC_PCDRIVE	35.5 MHz oscillator
PSL-PMC_PZT	high voltage drive to the PMC PZT
PSL-FSS_MODET	21.5 MHz oscillator output power monitor
PSL-PMC_MODET	35.5 MHz oscillator output power monitor
PSL-FSS_MINCOIN	tidal servo error voltage
PSL-FSS_MINCOOUT	reference cavity heater control voltage
PSL-FSS_RMTEMP	IOO / PSL optical table enclosure temperature
PSL-FSS_RCTEMP	reference cavity temperature
PSL-FSS_MIXERM	frequency servo mixer monitor
PSL-FSS_SLOWM	slow voltage monitor
PSL-ISS_ISERR	intensity servo error point
PSL-PMC_PMCERR	PMC servo error point

PSL Implementation Issues

There are perhaps two issues that are currently outstanding with the PSL.

Placement of the ISS AOM

Currently the intensity stabilization AOM is placed after the PMC. This was done to facilitate the implementation of various diagnostic modes. The location of the intensity stabilization AOM may impact the diagnostic modes.

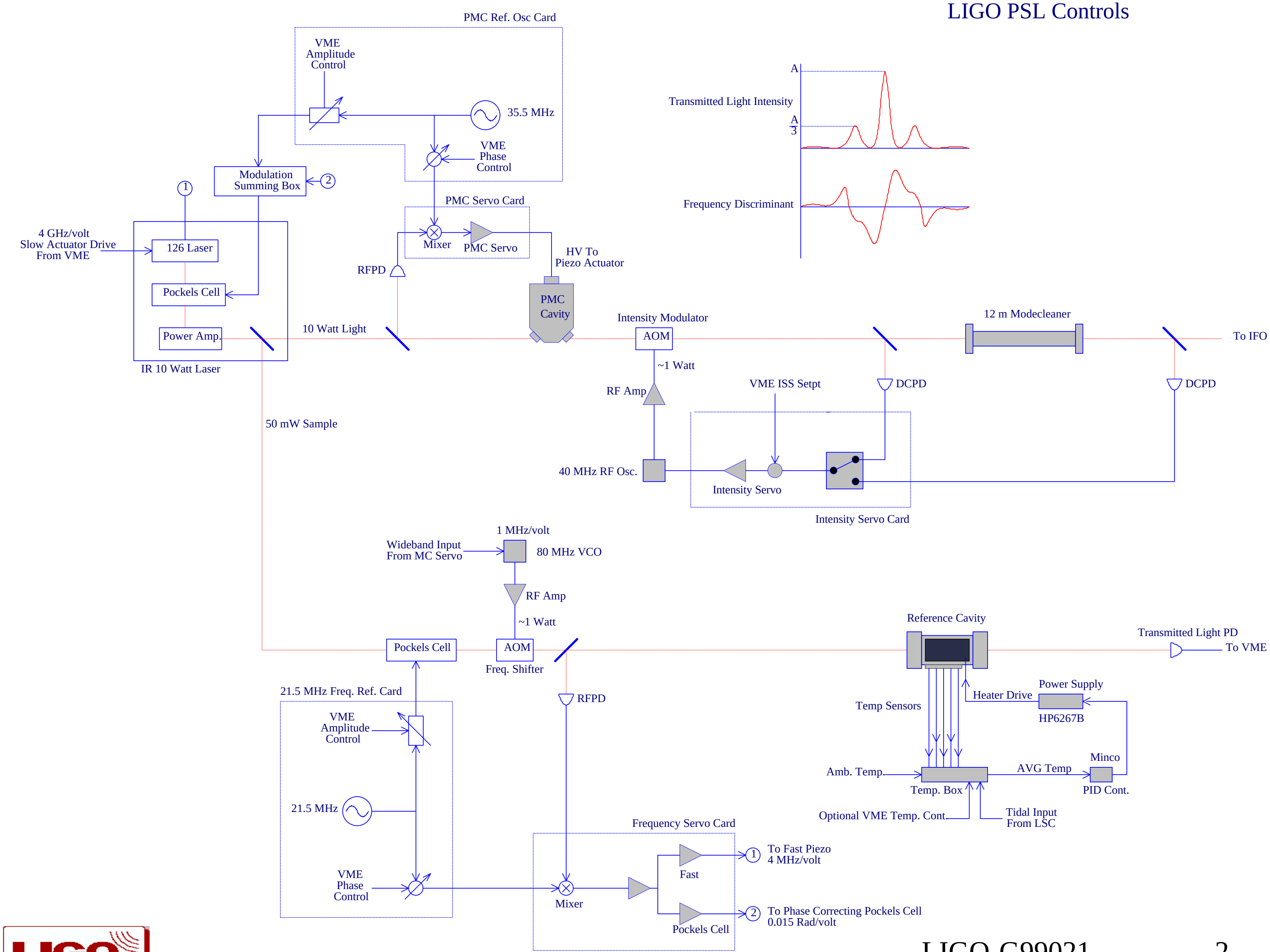
PMC Bandwidth

The current PMC bandwidth was calculated based on the assumption that the master oscillator was shot-noise limited out at 25 MHz. Measurements show that there is insufficient filtering at 25 MHz and so a smaller bandwidth cavity is required.

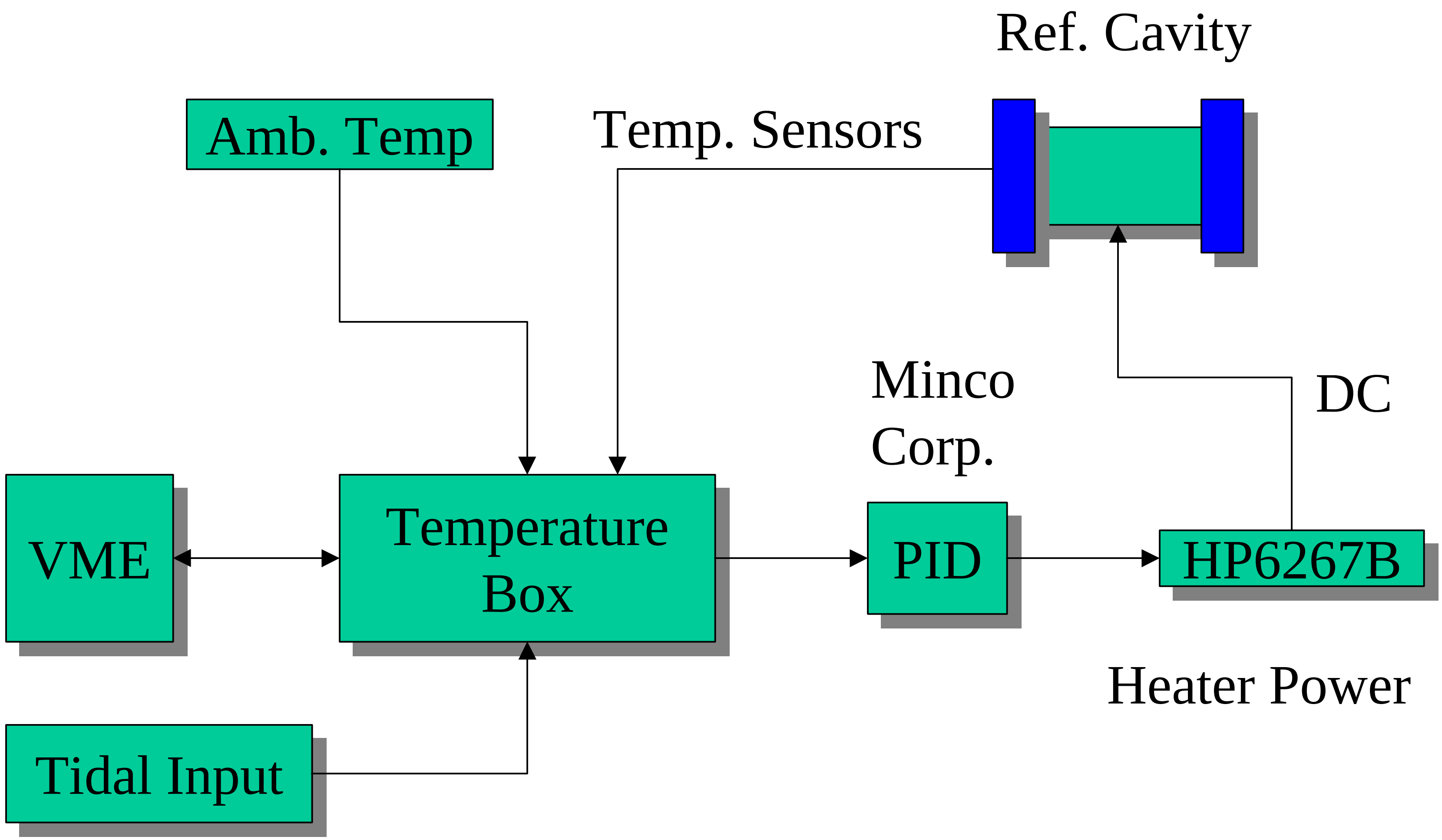
IR PSL CDS DESIGN

- Scope
  - This review covers the final topologies used in the design of the CDS portion of the LIGO IR PSL
- Organization of Presentation
  - Subsystems integrated diagram
  - Body of presentation
    - » Individual subsystem topology
    - » Transfer functions

LIGO PSL Controls



Tidal Servo


Ref. Cavity
Amb. Temp
Temp. Sensors
Minco
Corp.
DC
VME
Temperature
Box
PID
HP6267B
Heater Power
Tidal Input

Tidal Servo Transfer Function

- Dynamic Range
  - To meet the 400 µm p-p range requirement of LIGO-F970088-00-D, a 30 MHz p-p adjustment is needed in laser frequency
  - 30 MHz p-p corresponds to ~ 200 mK p-p reference cavity temperature change.
  - Nominal stability in "temperature control" mode should be about 20 mK p-p

Tidal Servo Transfer Function (cont'd)

- Frequency Response
  - Time constant of prototype measured to be about 1 hour
  - Loop response characteristics readily modifiable in the commercial PID controller
  - Gain of tidal input is configurable

Tidal Servo construction

- Vacuum chamber components
  - Custom built velcro attachable heater and insulation
  - Heater power limited by power supply to 120 watts (40 VDC and 13 ohm heater resistance)
  - 4 temperature probes averaged across the surface of the cavity for regulation
  - 1 independent probe for outside loop measurement of cavity temperature

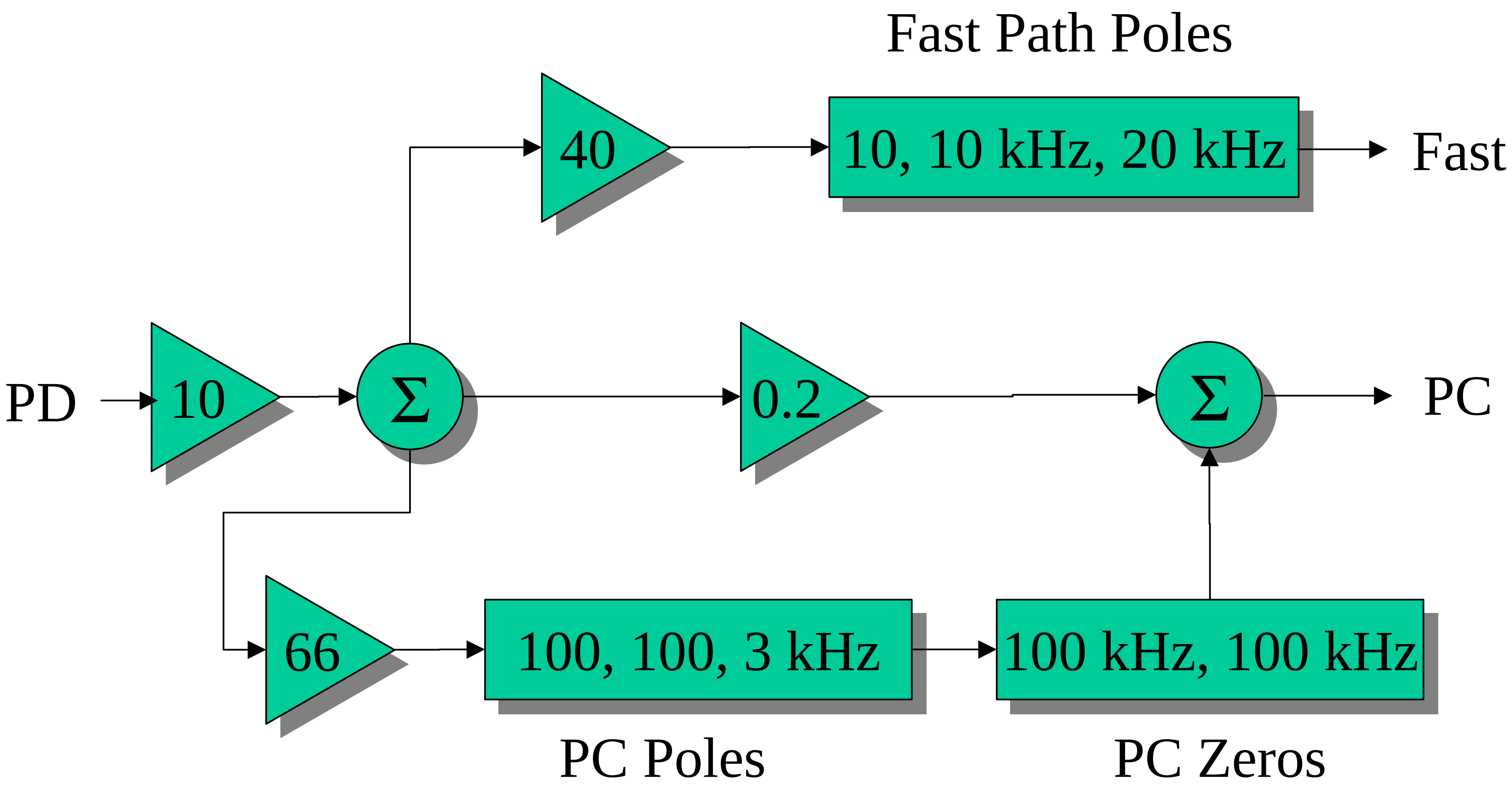
Tidal Servo construction (cont'd)

- Miscellaneous components
  - Ambient temperature probe
  - Optional VME setpoint
  - Linear DC supply chosen for noise reasons

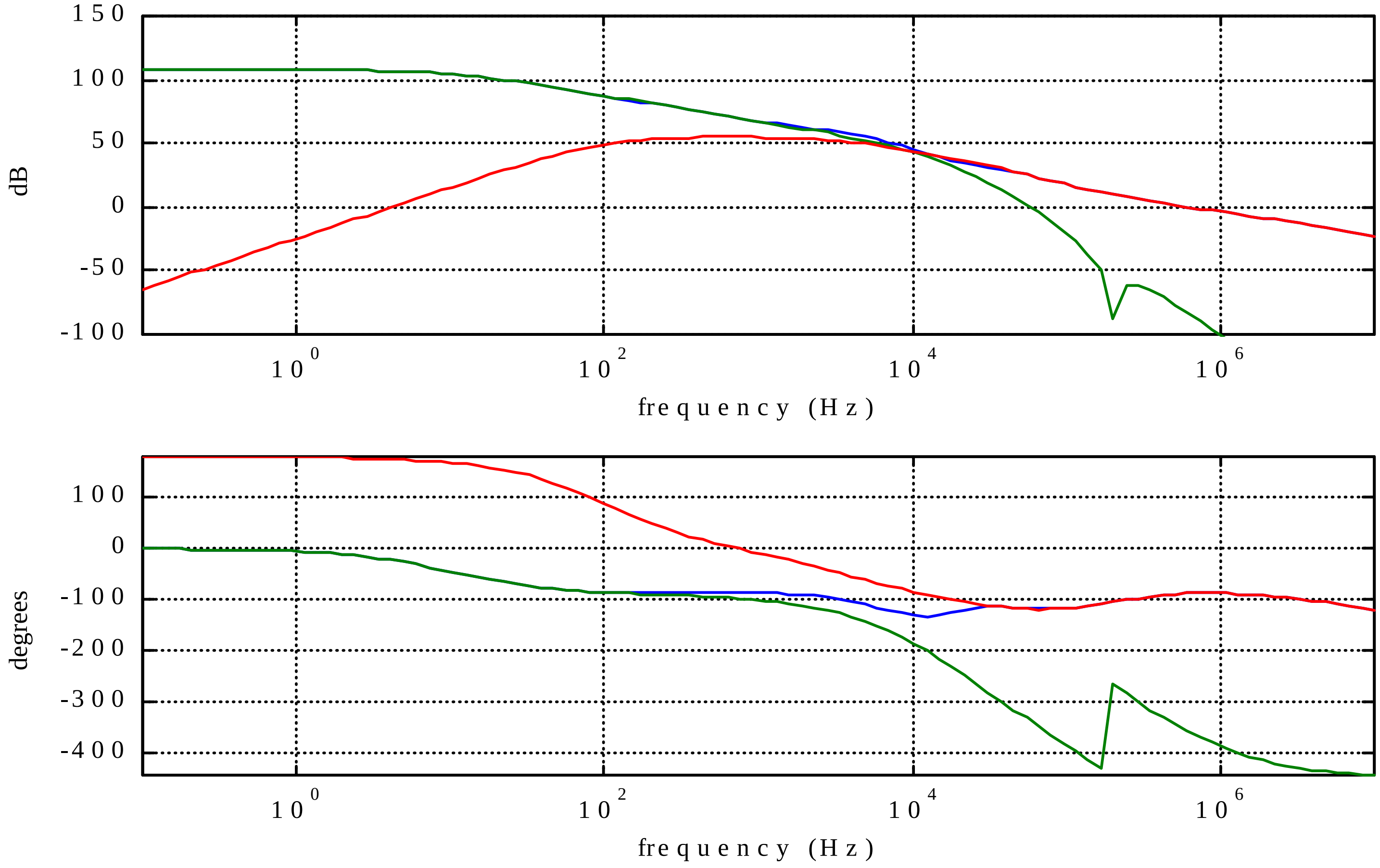
Frequency Servo Transfer Function

- Frequency Response
  - Unity gain frequency of 600 kHz
  - Nominal crossover frequency between piezo and pockels cell of 10 kHz
  - DC gain of 110 dB

FSS Transfer function



FSS Transfer Function (cont'd)



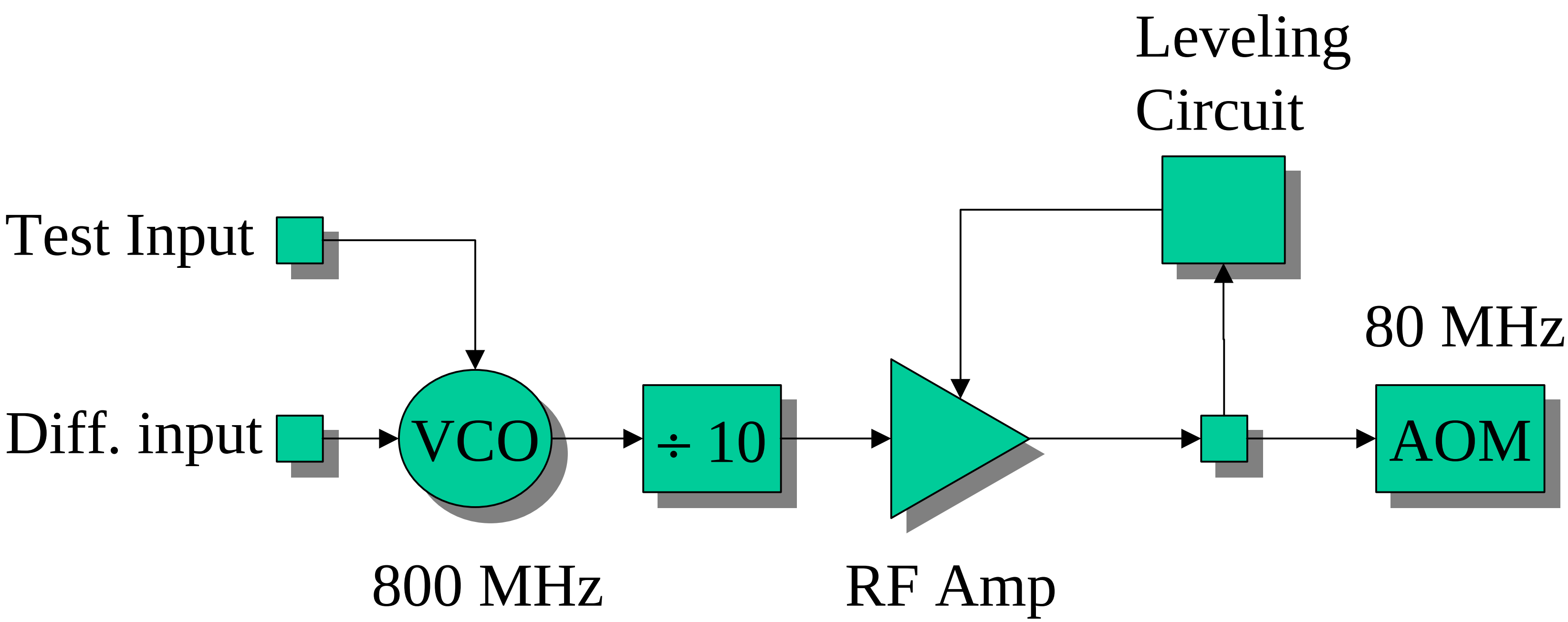
FSS Construction

- Servo Card
  - 6U Eurocard format in dedicated card cage
  - All functions controllable from VME based computer interface
- Actuators
  - Slow thermal and fast piezo actuators supplied with laser
  - External pockels cell used for high frequencies is shared with PMC servo by a summing box

Frequency Shifter (VCO)

- Frequency Response
  - Essentially flat but modified by the response characteristics of the frequency servo and PMC bandwidth
  - Provisions on board to compensate the frequency response of the PSL as an actuator
- Dynamic Range
  - 10 MHz at low frequencies. High frequency range limited by FSS pockels cell response

Frequency Shifter (VCO) Topology



VCO Construction

- Inputs
  - 1 MHz/volt gain on differential inputs
  - All inputs remotely isolable for noise
- Features
  - Configurable AM noise reduction circuit
  - Configurable compensation circuit
  - Remotely controllable modulation index
  - Located on optics table for seismic isolation

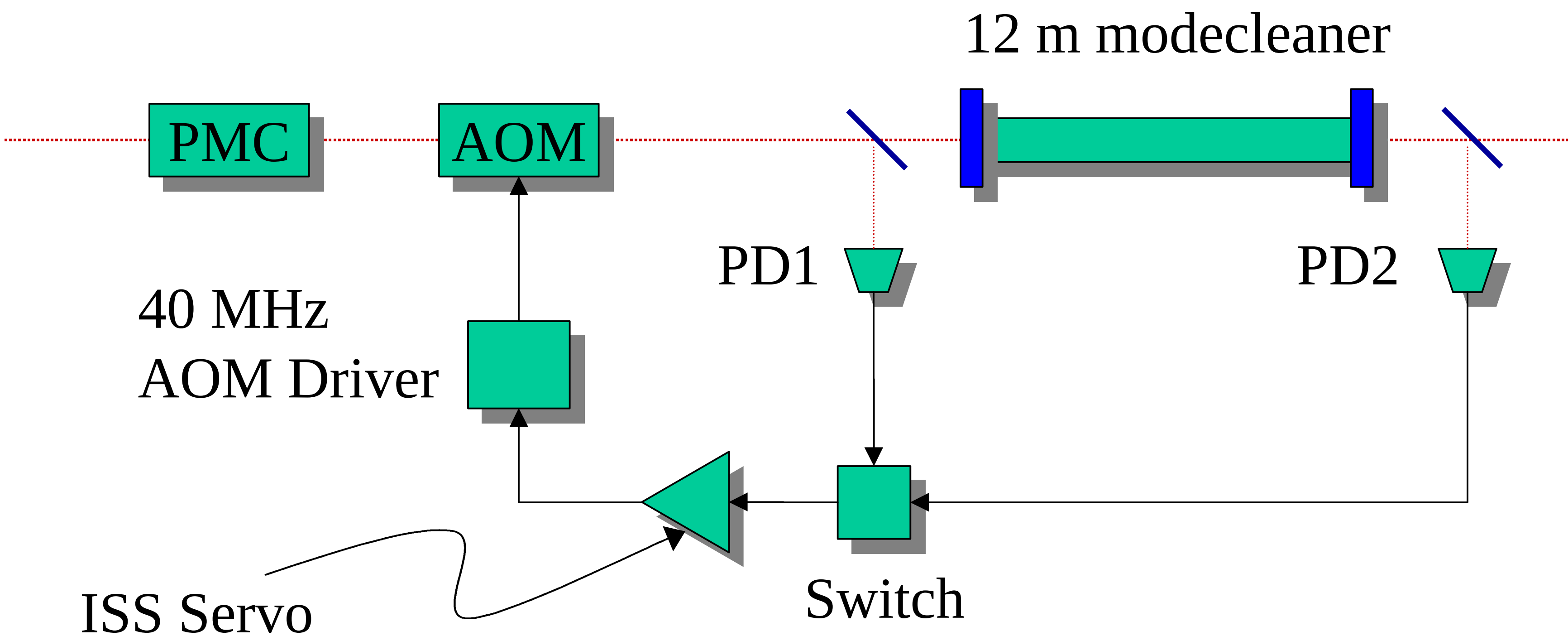
Intensity Servo (ISS)

- Frequency Response
  - Single pole at 10 Hz
  - 4 kHz compensation pole included to mimic mode-cleaner bandwidth
  - Unity gain frequency of ~50 kHz
- Dynamic Range
  - Limited by passive AOM approach and desire for minimum optical loss

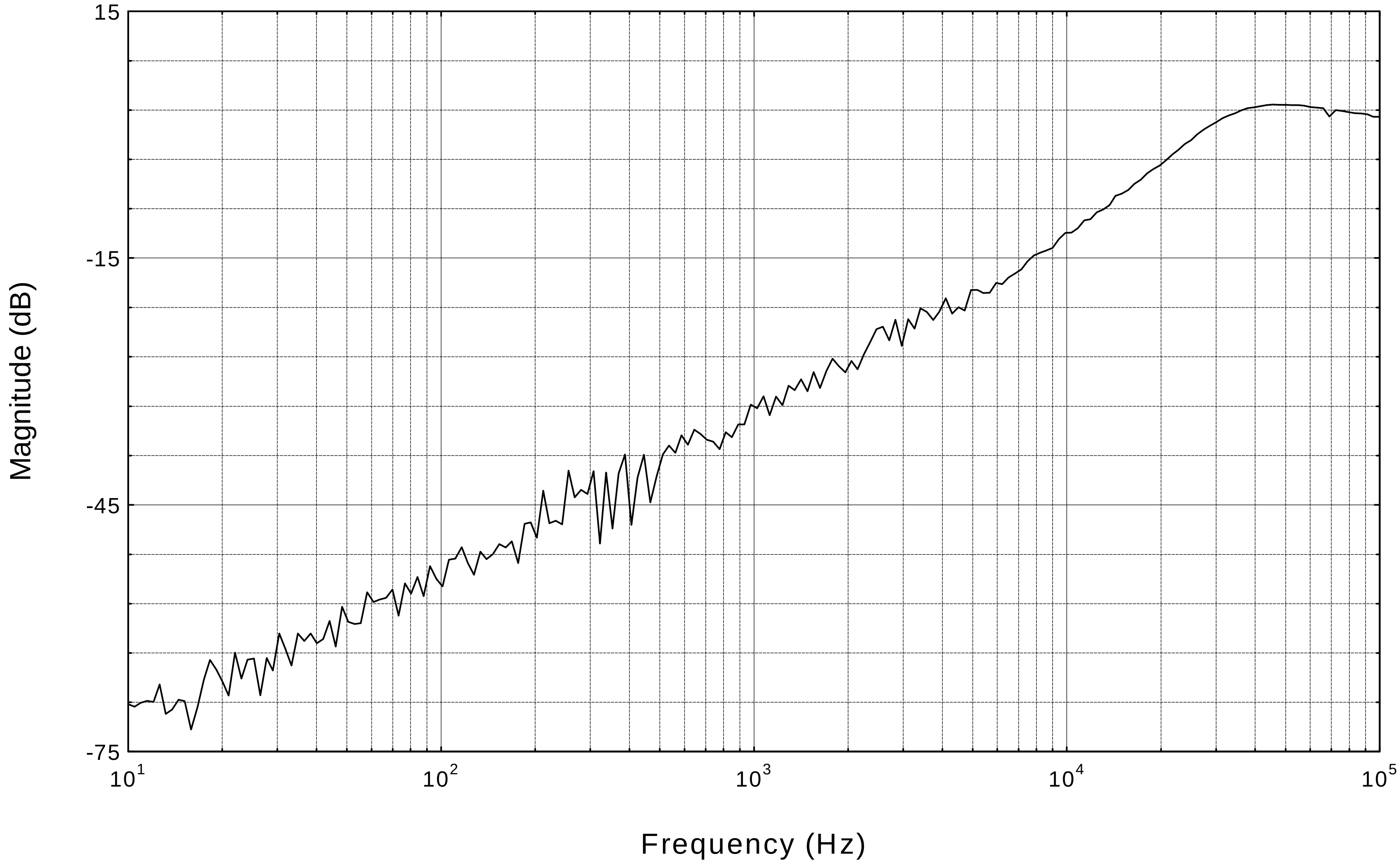
Intensity Servo (ISS) (cont'd)

- Noise
  - A transimpedance of 2.5 kΩ is used for the photodiode which is a modified Thorlabs PDA55
  - ~4 mW of incident light yields a calculated shot noise limited sensitivity of ~1.8×10^{-8}

Intensity Servo



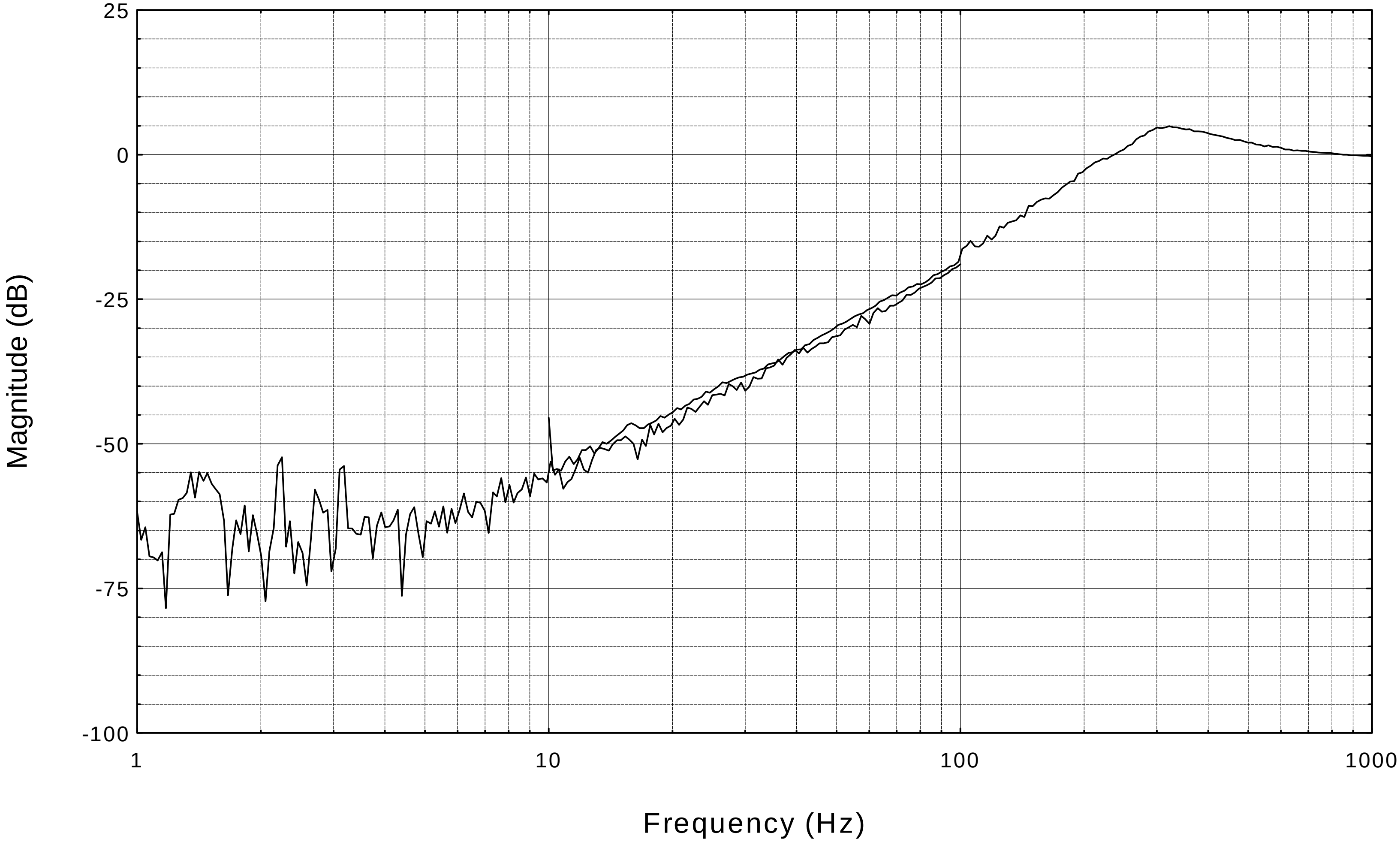
ISS Inverse CLTF



Pre-modecleaner (PMC)

- Frequency Response
  - DC gain of 85 dB
  - Poles at 2 Hz and 10 Hz
  - Zero at 425 Hz
  - 9 kHz notch
  - Response limited by resonances in cavity body and piezo element

PMC CLTF



External Diagnostic Modes

- Beam Finding Mode (BF)
  - Can be implemented either by use of EPICS subroutine or external function generator driving the ISS external modulation inputs
  - 1 Hz square wave at up to 50 % modulation depth
  - No impact on other PSL servos in present configuration

External Diagnostic Modes (cont'd)

- Cavity Ringdown Mode (CR)
  - Uses same input as Beam Finding Mode
  - Modulation frequency only limited by ISS response (~50 kHz UGF)

External Diagnostic Modes (cont'd)

- System Diagnostics Mode (SD)
  - Intensity modulation can be achieved through the ISS test input as in BF and CR mode
  - Two methods of PSL frequency modulation
    - Test input on FSS card
    - Test input on VCO (Same as wideband frequency feedaround input)
  - Modulation parameters for both SD modes can be met by existing PSL design

External Diagnostic Modes (cont'd)

- Power Reduction Mode (CPR)
  - Pending exact calibration of the intensity servo setpoint, this feature is accomplished using the EPICS interface to the ISS reading directly in watts of optical power

Data Acquisition

- The following items are included for interface to the LIGO DAQ system
  - FSS, ISS and PMC servo error point and actuator drive signals
  - Reference cavity and PMC incident and transmitted light levels
  - Light levels before and after the modecleaner

Data Acquisition (cont'd)

- Whitening Filters
  - Most signals are inherently simple due to flat noise spectra requiring only gain adjustment
  - Provisions included for daughter cards to allow addition of additional filters