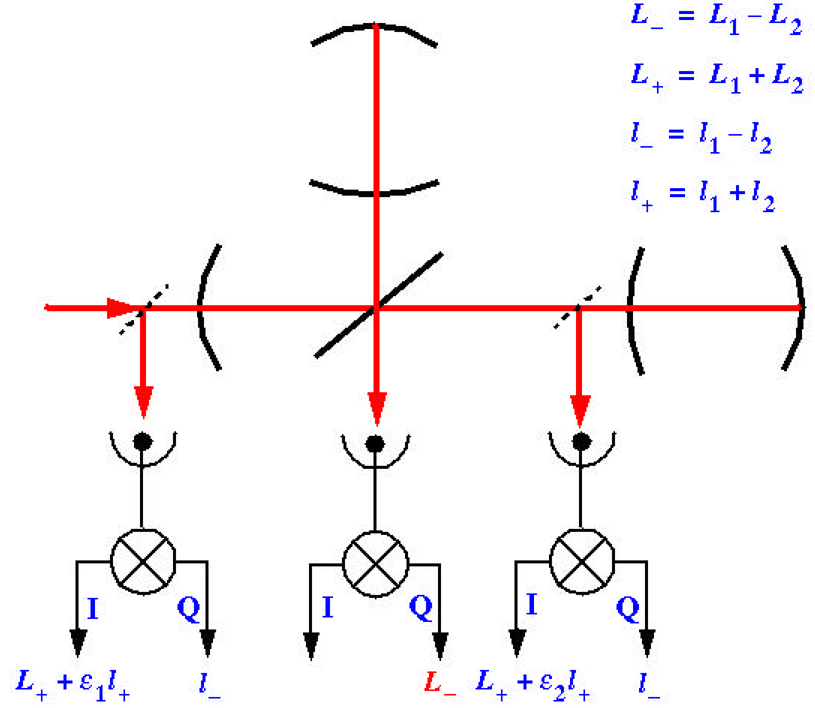
Physics of LIGO
Lecture 3

Last week:

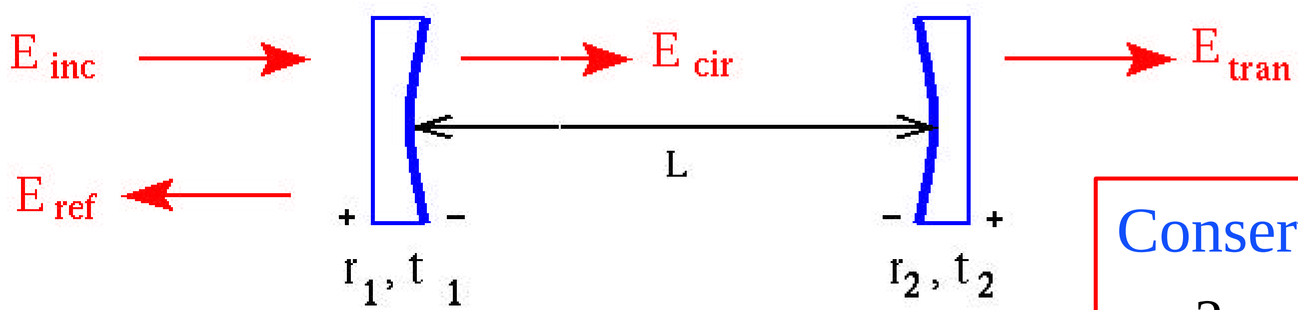
- LIGO project
- GW physics, astrophysical sources
- Principles of GW IFO's
- Engineering and Science runs
- Noise in GW IFOs
- Focus on thermal noise

This week:

- Cavity Optics
- LIGO Control systems
- Advanced LIGO
- Data analysis



Fabry-Perot Optical Resonator Cavities



Conservation of energy:

$$r_i^2 + t_i^2 + L_i = 1$$

$$R_i + T_i + L_i = 1$$

$$E_{cir} = t_1 E_{inc} + r_1 r_2 e^{-2ikL} E_{cir} = \frac{t_1}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

$$E_{ref} = r_1 E_{inc} - t_1 r_2 e^{-2ikL} E_{cir} = \frac{r_1 - r_2 (1-L) e^{-2ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

$$E_{tran} = t_2 \ e^{-ikL} E_{cir} = \frac{t_1 t_2 e^{-ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

When *2kL = n(2p), (ie, L=n l/2),*

E_{cir} , E_{tran} maximized $\Rightarrow$ resonance!

Cavity coupling

$$E_{ref} = \frac{r_1 - r_2(1-L)e^{-2ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

- if $r_1 = r_2(1-L)$, $E_{ref} = 0$ on resonance; optimal coupling
- if $r_1 > r_2(1-L)$, $E_{ref} > 0$ on resonance; under-coupling
- if $r_1 < r_2(1-L)$, $E_{ref} < 0$ on resonance; over-coupling

Free Spectral Range: $f_{FSR} = c/2L$

(eg, for 4 km arms, f_{FSR}=37.5 kHz)

LIGO: carrier is resonant in arms, sidebands not; f_{SB} far from f_{FSR}

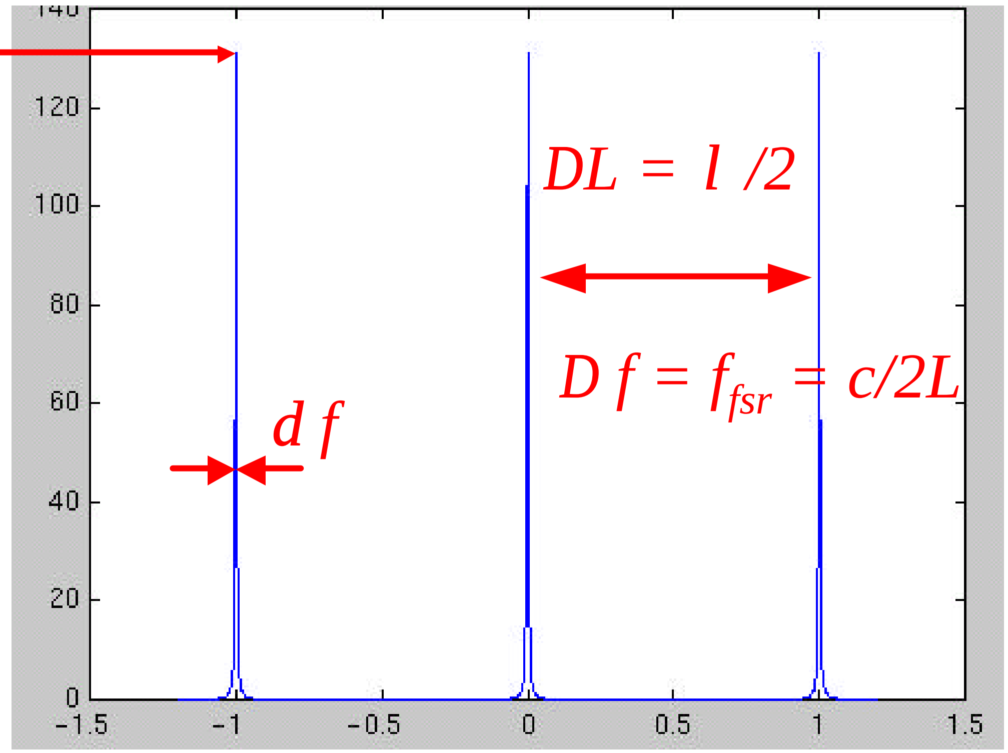
More cavity parameters

- Finesse: peak separation / full width of peak
- Finesse = $F = \frac{p\sqrt{r_1 r_2}}{1 - r_1 r_2}$ = 208 for LIGO 4km arms
- Light storage time = $t_{stor} = \frac{L}{c}\frac{\sqrt{r_1 r_2}}{(1 - r_1 r_2)}$ = 870 µsec for LIGO arms
- Cavity pole = f_{pole} = $1/(4pt_{stor})$ = 91 Hz for LIGO arms
- Cavity gain = $G_{cav} = \left(\frac{t_1}{1 - r_1 r_2}\right)^2$ = 130 for LIGO arms
- Visibility: V = 1 – P_{min}/P_{max} , Power in/out of lock
- LIGO 4km arms: $t_1^2 = 0.03$, $r_2^2 \approx 0.99997$

FP circulating field

Power Gain

$$\left|\frac{E_{circ}}{E_{in}}\right|^2$$



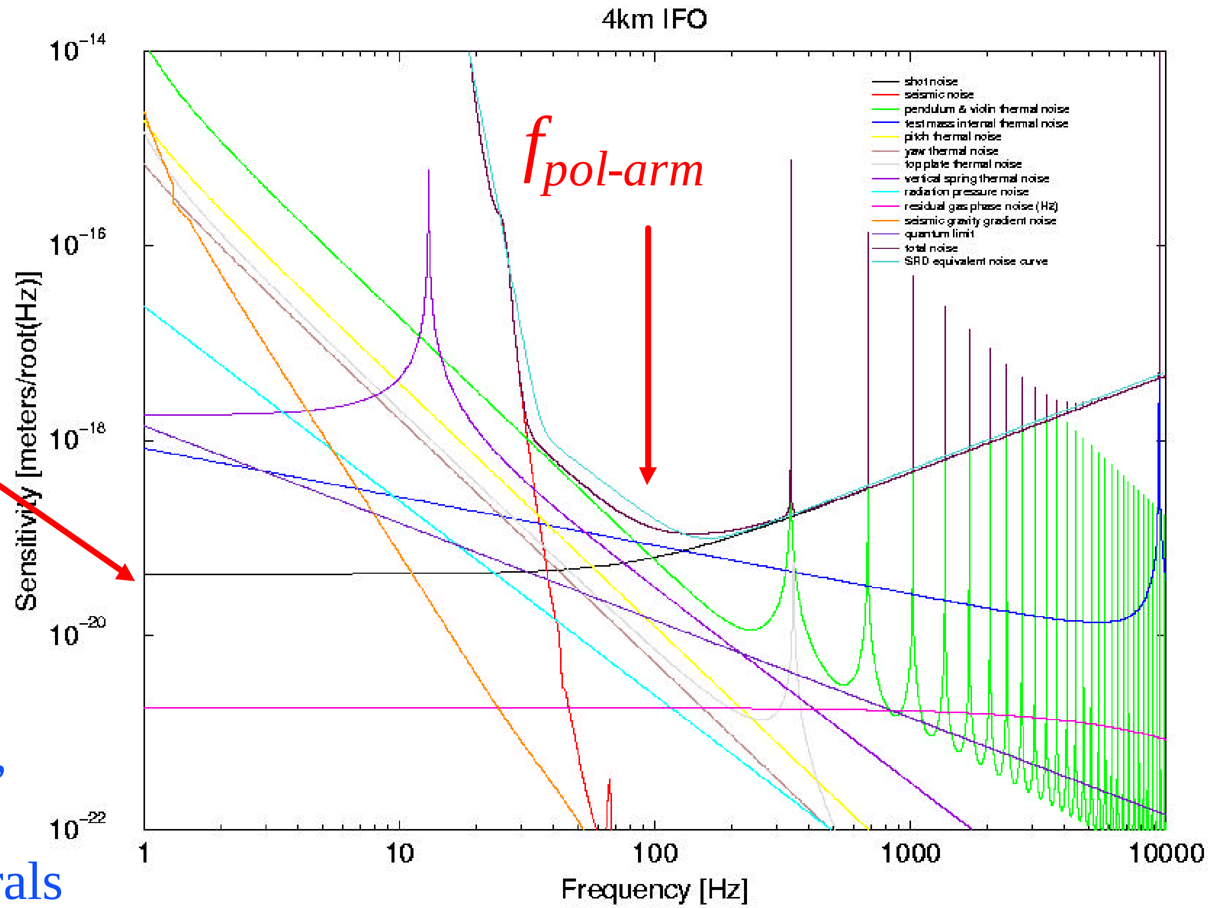
Finesse = d f /f_{fsr}

Dn = D(2kL)/2p = Df/f_{fsr} = DL/(l /2)

Arm cavity parameters and LIGO sensitivity

As r_{ITM} is increased,
G_{arm} is increased,
$f_{pol\text{-}arm}$ is decreased.

$$h_{dc} \sim 1/\sqrt{G_{arm} P_{laser}}$$



Given other noise sources (seismic, thermal), choose r_{ITM} to optimize Sensitivity to binary inspirals

Contrast

- Contrast is a measure of how perfectly light interferes at beamsplitter

$$C = \frac{P_B - P_D}{P_B + P_D}$$

- P_D is minimum carrier power at dark port with both arms in lock
- P_B is maximum carrier power at bright port with both arms out of lock
- Contrast defect 1-C is non-zero due to mode mismatch between arms; imperfect mirrors; etc
- This produces excess noise at GW output, reducing S/N

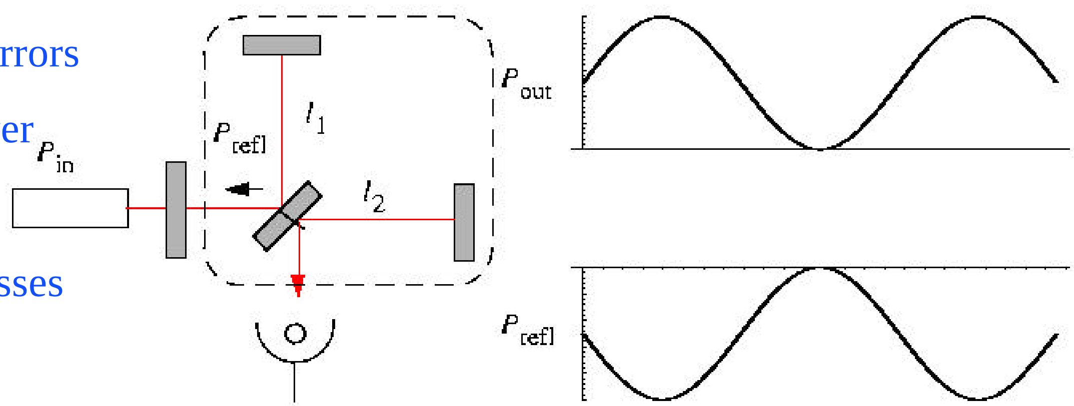
Power recycling

Optimal sensitivity requires high laser power

- predicted sources require shot noise of ~300 W on BS
- suitable lasers produce ~10 W, only ~6W at IFO input

Power Recycling: Make resonant cavity of IFO and *recycling* mirror

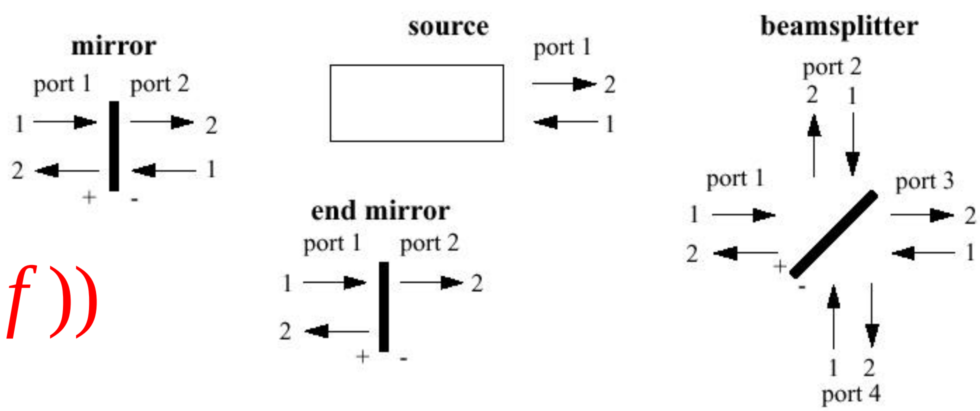
- use IFO at `dark fringe'; then input power reflected back
- known as Recycling of light (Drever, Schilling)
- Gain of ~50 possible, with losses in real mirrors
- allows present lasers to deliver needed power
- increases stored energy
- just extract small amount (or so) if GW passes



Field equations, dynamics

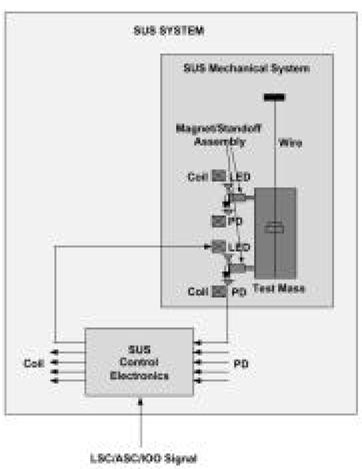
- Any arbitrary configuration of mirrors, beam splitters, sources, defines a set of static fields, and a set of linear relations between them (which depend on phase advances, reflectivities and transmissivities, etc)
- It is thus easy to solve for all the static fields in any configuration
- Dynamics: shake a mirror (or wiggle a source field) at frequency f, and all the fields respond with a wiggle at that frequency.
- Can then calculate the (complex) transfer function between any mirror and any field
- M. Regehr, ***Twiddle***

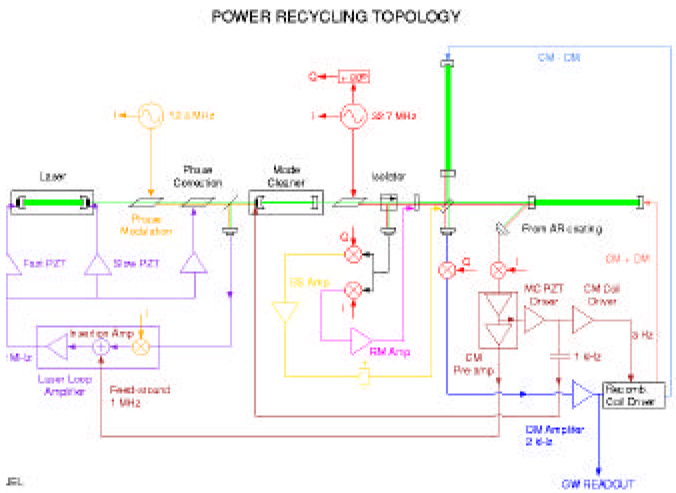
$$T(\tilde{x}_{mirr}(f) \to \tilde{E}_{port}(f))$$

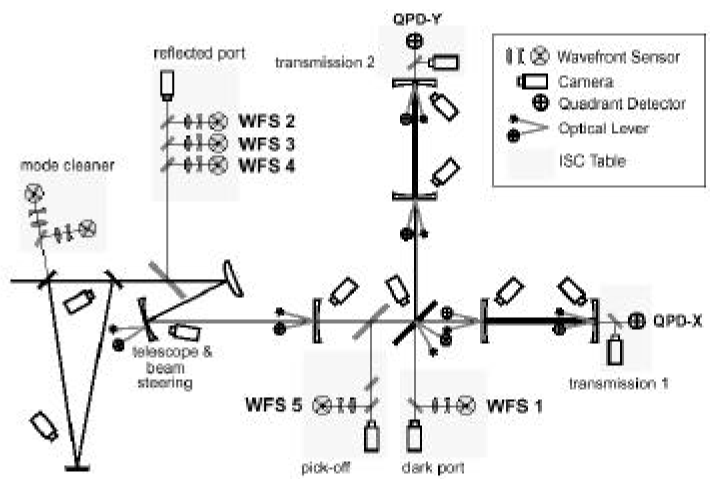


LIGO Control systems

- Start with a “simple” system: control of a mirror (AKA “optic” or “test mass”) suspended on a pendulum
- Control of a Fabry-Perot optical cavity (P-D-H reflection locking)
- Control of a Michelson IFO (Schnupp tranmission locking)
- Controlling all the length degrees of freedom in a LIGO IFO
- Controlling all the alignment degrees of freedom in a LIGO IFO



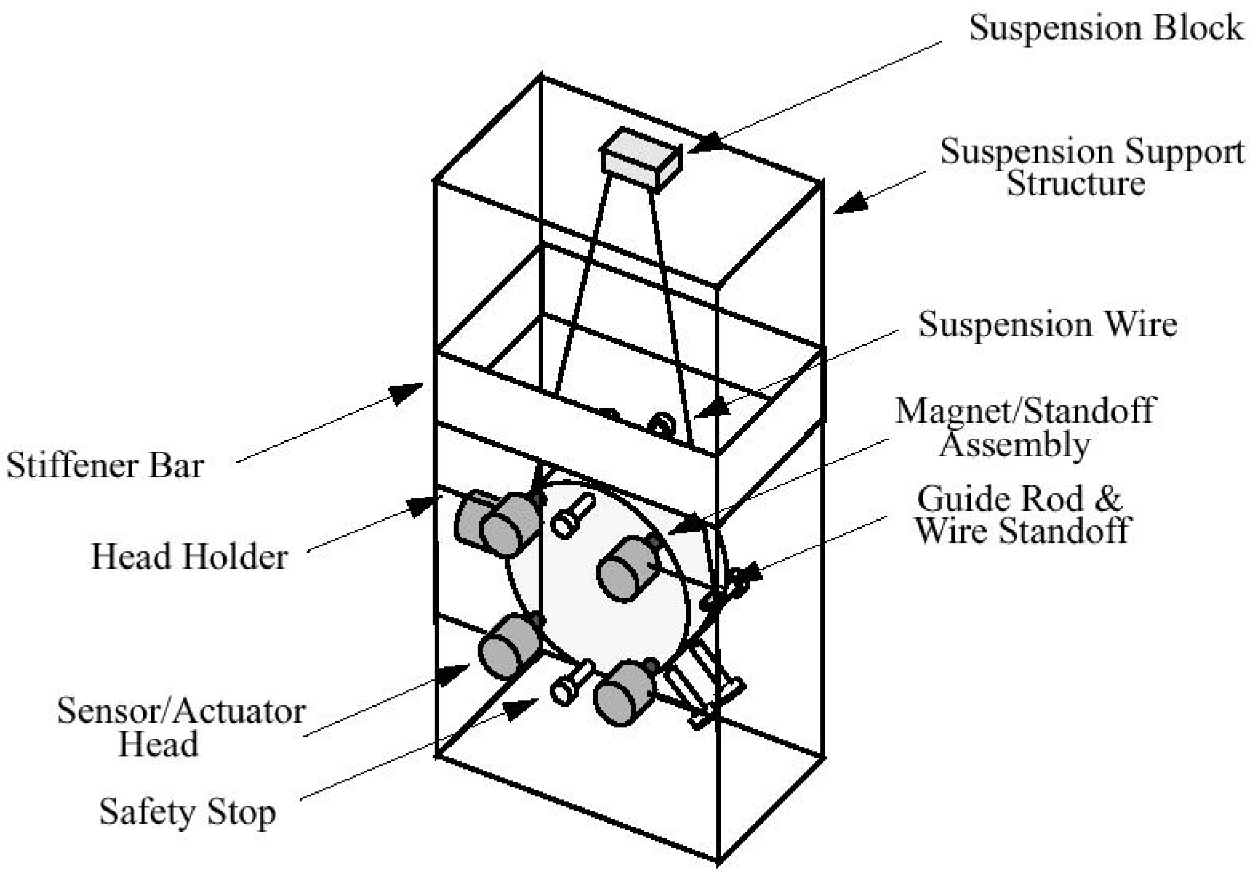




Mirror control

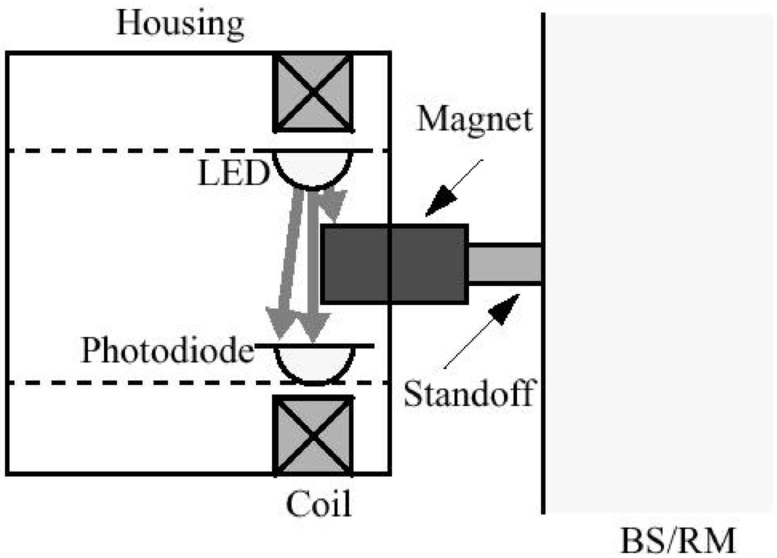
- Seismic isolation system, and pendulum, keep the mirror motion to a minimum.
- Now the mirrors are not being kicked around by the environment (at high frequencies);
- But, being free, they may not be where you need them to be to keep the laser resonant in the cavities!
- Need active control system to keep mirrors at set points (at/near DC), to keep F-P cavities resonant,
- Without injecting noise at high frequencies
- $\Rightarrow$ Carefully designed feedback servo loops

LIGO I Suspensions



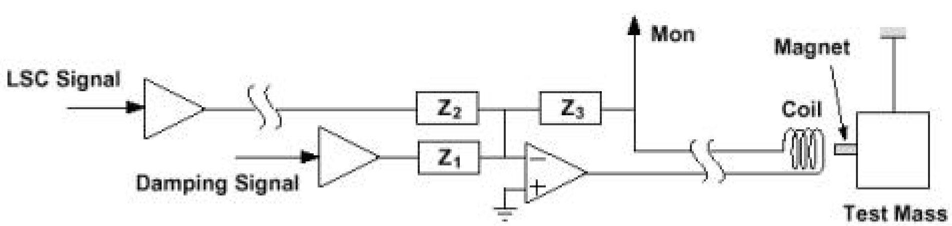
OSEMs

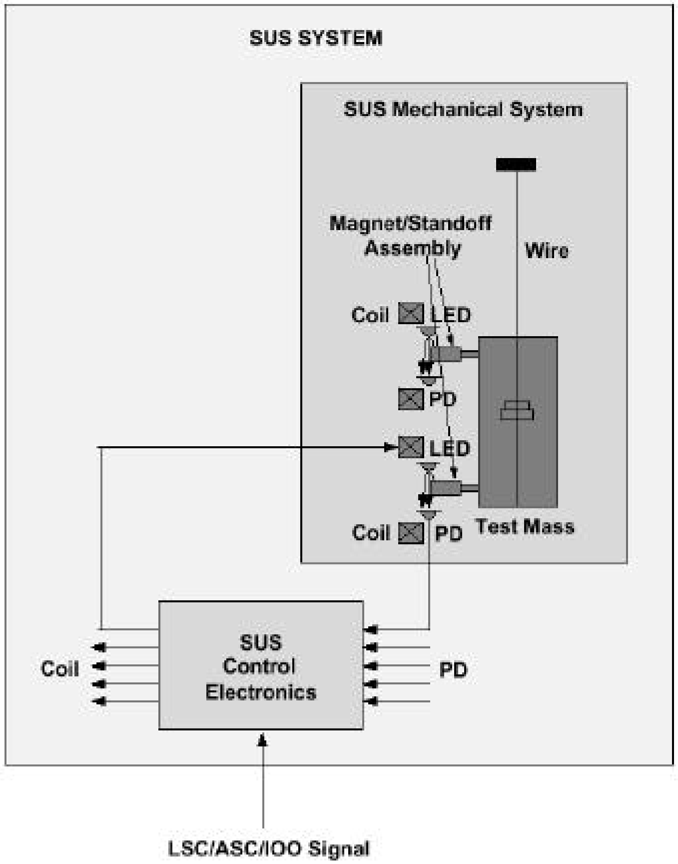
- Five magnets glued to fused Si optic
  - (this ruins the thermal noise properties of the optic – a big problem!)
- LED/PD pair senses position
- Coil pushes/pulls on magnet, against pendulum



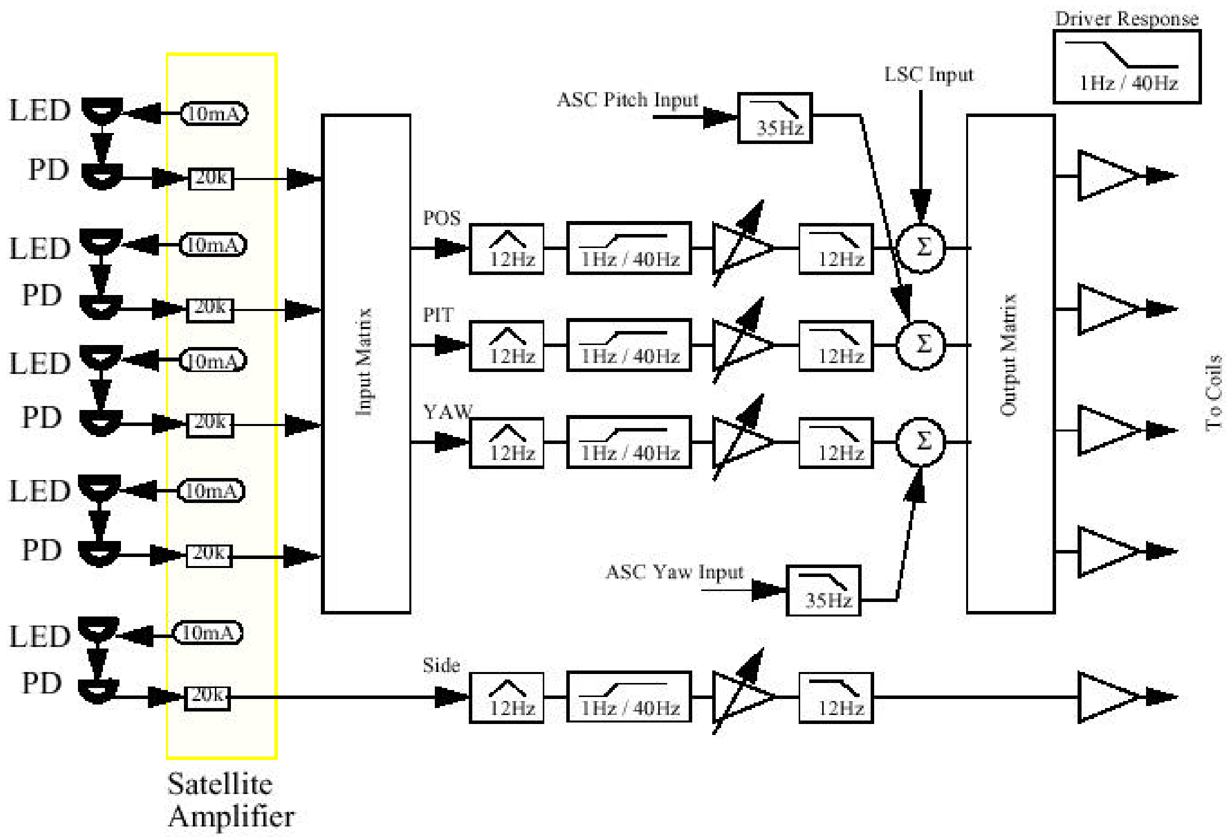
Suspension control system

- Each suspension controller handles one suspension (5 OSEMs)
- Local velocity damping
- Input from LSC and ASC to fix absolute position, pitch, yaw of mirror to keep cavity in resonance





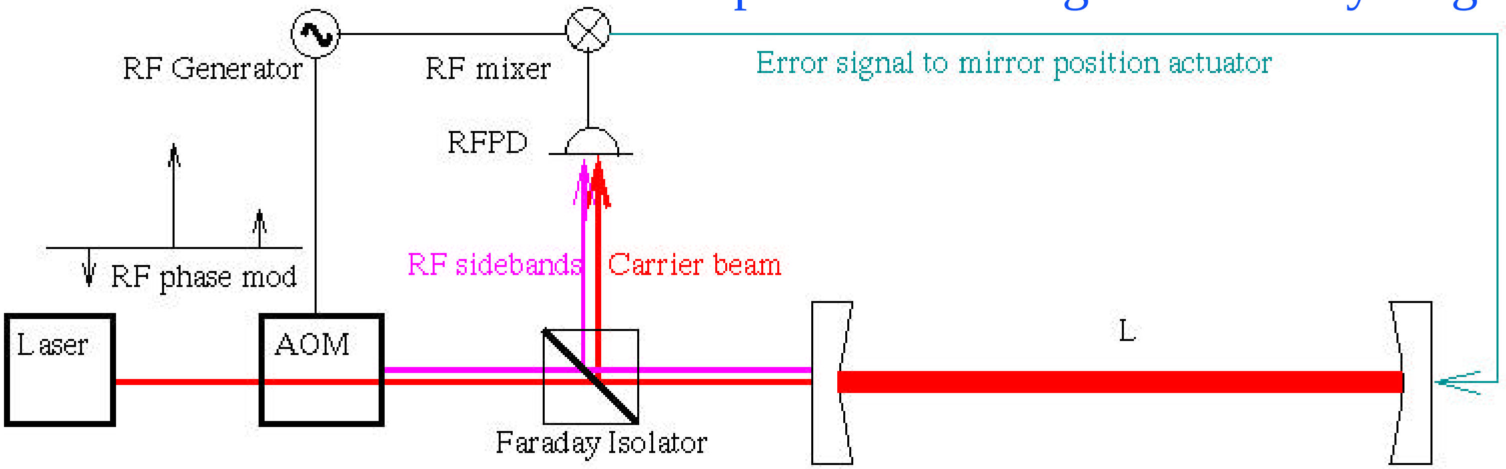
Suspension controller (local analog version)



Cavity control

Pound-Drever (reflection) locking used to control lengths of all the optical cavities in LIGO

- Phase modulate incoming laser light, producing RF sidebands
- Carrier is resonant in cavity, sidebands are not
- Beats between carrier and sidebands provide error signal for cavity length



Phase modulation of input beam

Phase modulation adds sidebands to the beam:

$$E_{inc} = E_{laser} e^{i(wt + \Gamma \cos \Omega t)} \approx E_{laser} e^{iwt} \left(J_0(\Gamma) + J_{+1}(\Gamma) e^{i\Omega t} + J_{-1}(\Gamma) e^{-i\Omega t} \right)$$

Ω = RF modulation frequency ($\Omega/2\pi \sim 30$ MHz)

Γ = modulation depth

J_i = Bessel functions; $J_{\pm 1} \approx \pm \Gamma/2$ for $\Gamma<1$

$$E_{ref} = \left(E_0^{ref} + E_{+1}^{ref} e^{i\Omega t} + E_{-1}^{ref} e^{-i\Omega t} \right) e^{iwt}$$

Arrange the length of the cavity, and the value of Ω, so that

•carrier is resonant in FP cavity, sidebands are not,

•so they have different reflection coefficients

•phase of carrier is sensitive to length changes in cavity, sidebands are not

Demodulation

$$S_{ref} = \left(\left|E_0\right|^2 + \left|E_+\right|^2 + \left|E_-\right|^2 \right) + 2\,\mathrm{Re}\left(\left(E_0^* E_+ + E_0 E_-^* \right) e^{i\Omega t} \right) + 2\,\mathrm{Re}\left(E_+^* E_- e^{i2\Omega t} \right)$$

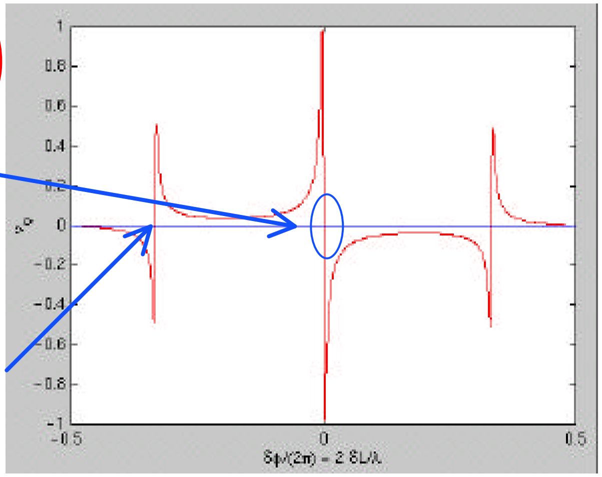
Use an electronic "mixer" to multiply this by

$\cos\Omega t$ or $\sin\Omega t$, average over many RF cycles, to get:

- In-phase demodulated signal $\quad n_I = 2\,\mathrm{Re}\left(E_0^* E_+ + E_0 E_-^* \right)$
- Quad-phase demodulated signal $\quad n_Q = 2\,\mathrm{Im}\left(E_0^* E_+ + E_0 E_-^* \right)$

Which are sensitive to length of cavity (very near resonance)

And can be used as an *error signal* to control cavity length

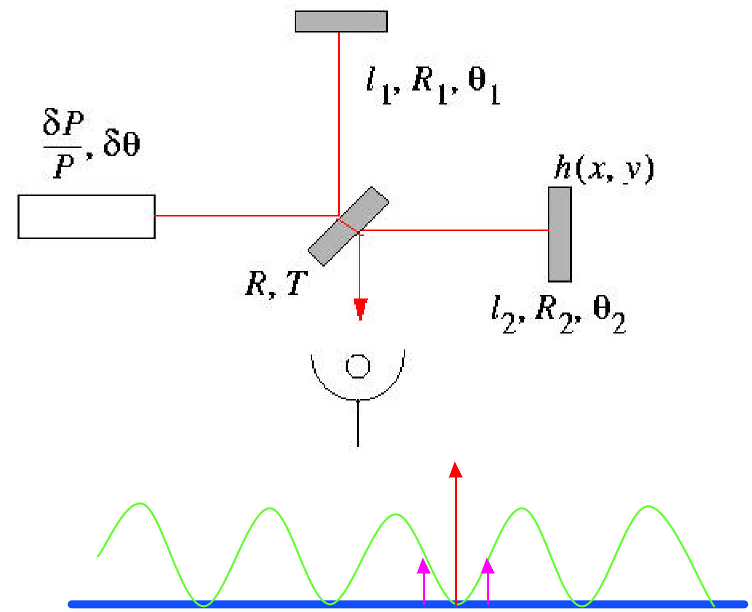


Sideband resonant - error signal has wrong sign

Schnupp Asymmetry

GW signal (L_-) is measured using light *transmitted* to dark port. Signal power is quadratic in L_- ; not as sensitive as linear dependence.

To keep the dark port dark for the main (carrier) laser light, use Schnupp (tranmission) locking as opposed to reflection locking, for l_- signal.



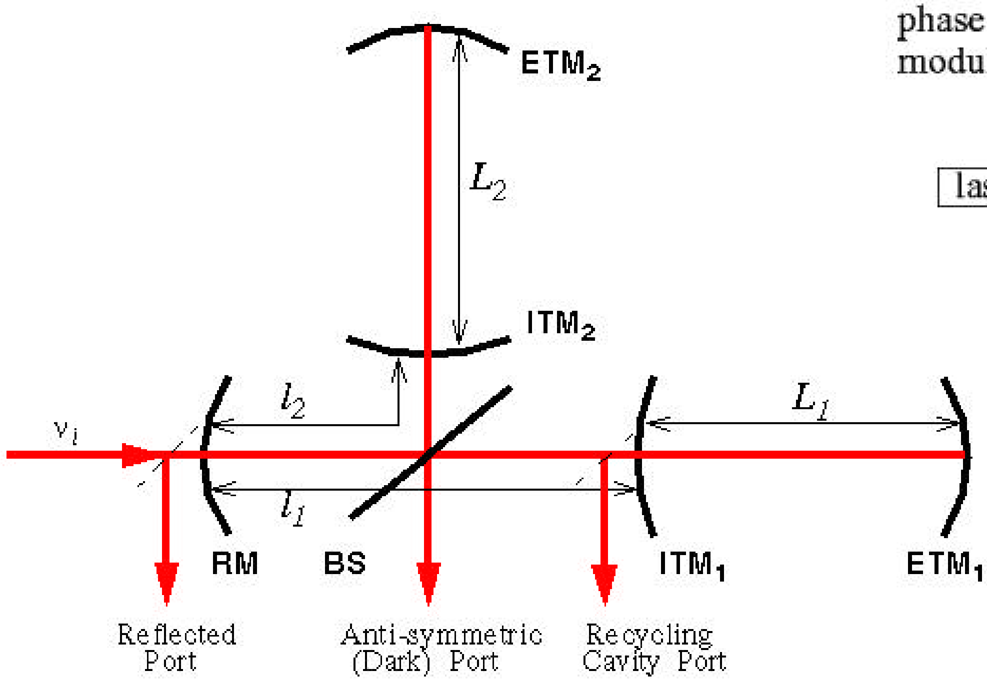
• In absence of GW, dark port is *dark*;
carrier power ~ $\sin^2(\Delta\phi)$,
quadratic in $\Delta\phi = 2k\, l_-$ for small signal

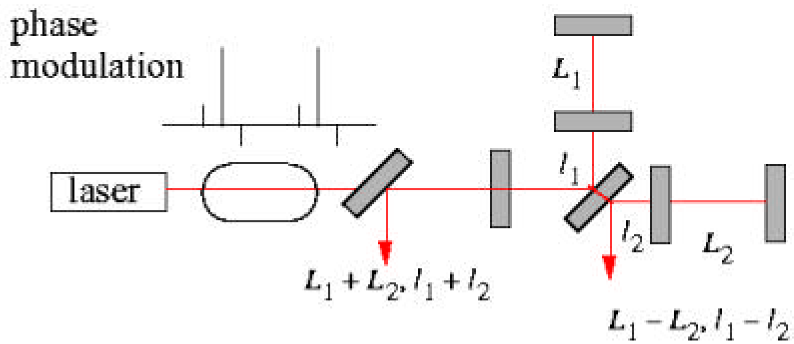
• Add Schnupp (Michelson) asymmetry: $l_1 \neq l_2$ ($l_- \neq 0$); port still dark for carrier ($l_1 = l_2 \mod \lambda_c$), but sidebands leak out to dark port PD to act as local oscillator for RF-detection of GW signal.

$$n_Q = 2\,\mathrm{Im}\left(E_0^* E_+ + E_0 E_-^*\right)$$

• Error signal is then *linearly* proportional to amount of carrier light (GW signal)

The control problem in LIGO

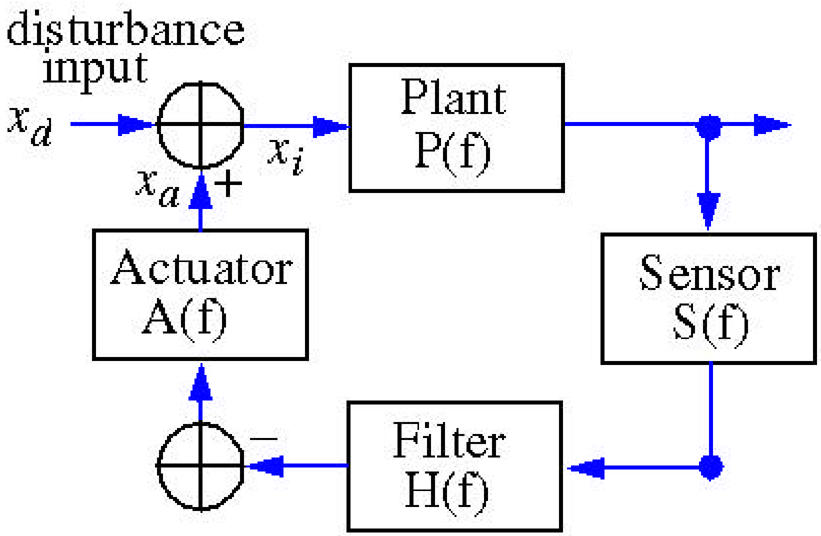




- **Four interferometer lengths ⇒ four sensors/actuators**
- **Ten mirror angles ⇒ ten sensors/actuators**

LIGO

Elements of a control system



$$x_a = -PSHAx_i$$

$$x_i = x_d + x_a$$

$$x_i = \frac{x_d}{1 + G(f)}$$

where

$$G(f) = PSHA$$

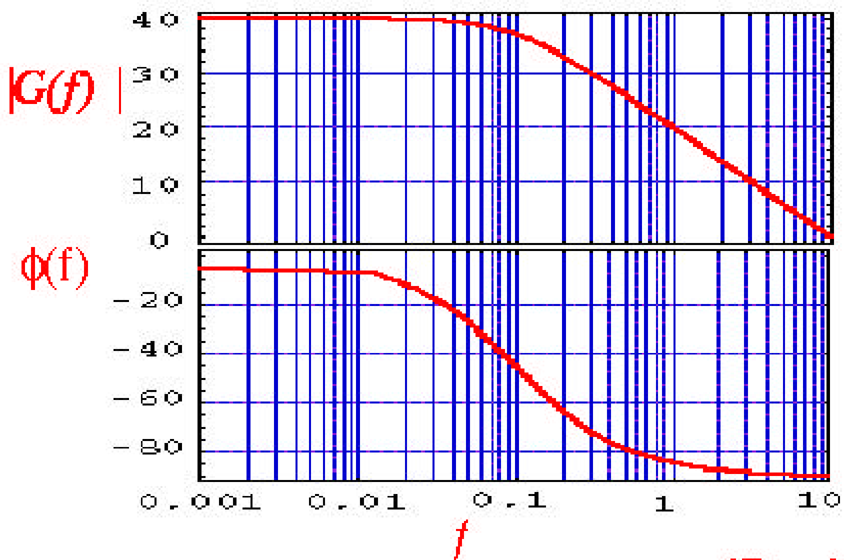
- Time delays are inevitable; Plant, and control system, response is best characterized in *frequency domain* (as in communication engineering)

- When $G(f) >> 1$ then $x_i << x_d$,

  Plant input is much smaller than original disturbance

Controls terminology

- Transfer function (frequency response) magnitude [$|G(f)|$] and phase [$\phi(f)$] of output when input is a sinusoid of unit magnitude at frequency f
- Bode Diagram:
- Pole: magnitude falls off with f ($f > f_o$), phase lags
- Zero: magnitude increases with f ($f < f_o$), phase leads



$dB = 20 \log_{10} G(f)$

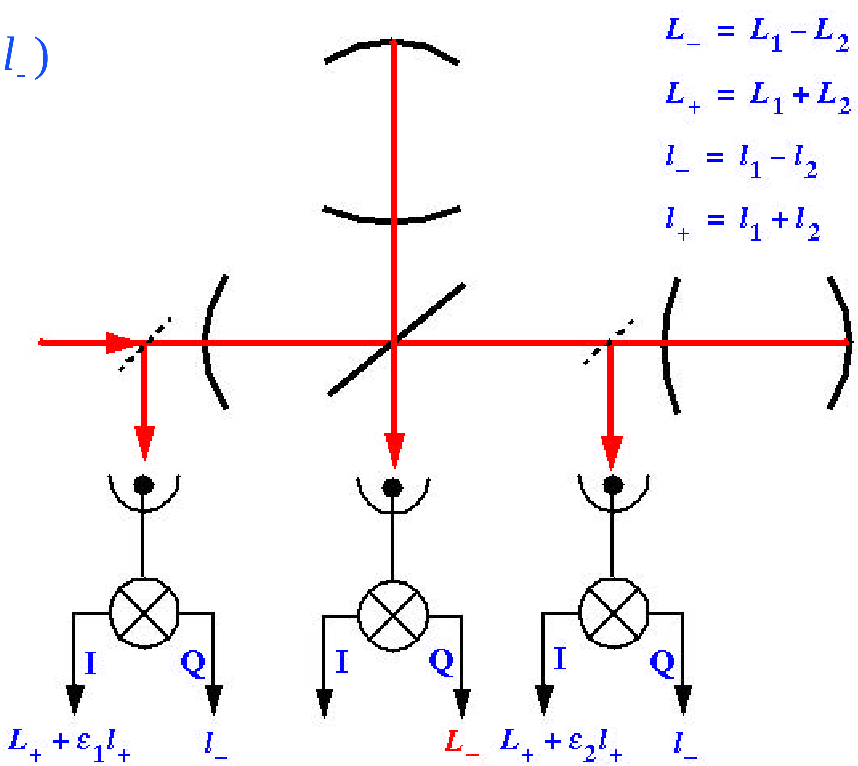
Want high gain at frequencies where control is effective (sensor fidelity, actuator response), and phase < 90°;

Then fast rolloff of gain to avoid injecting noise

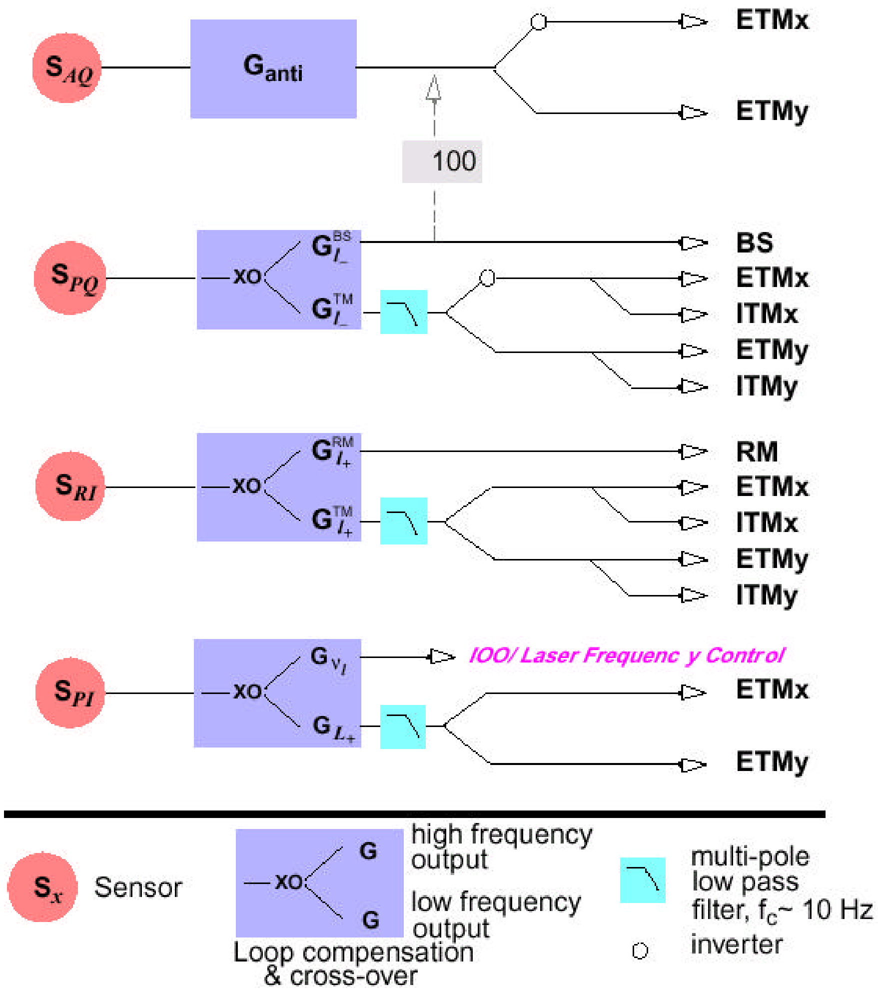
Length Sensing and Control (LSC)

Length control:

- 4 length degrees of freedom (L_+, L_-, l_+, l_-)
- L_- = gravity wave signal
- l_- = Michelson dark fringe (*contrast*)
- Diff mode (L_-, l_-) controlled by quad-phase demod signal
- Common mode (L_+, l_+) controlled by in-phase demod signal
- Need *gain hierarchy* to control l_+
- Hold lengths to 10^{-9} m in presence of 10^{-5} m (seismic) noise



Servo gains and bandwidth

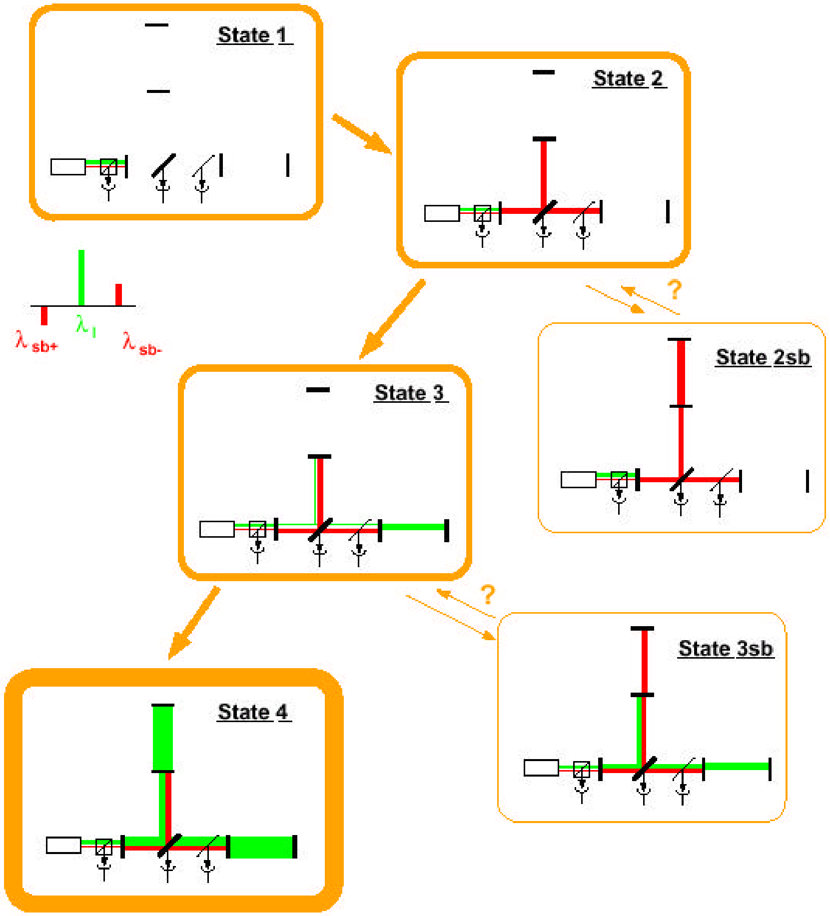


Lock Acquisition

- Servo control loops work (acquire lock) only in the linear regime, when mirrors are very close to resonance.
- When we start, or after any big bump, mirrors are far from resonance, swinging freely.
- If mirrors are moving slow enough, as they pass through resonance, the servo can grab and hold the mirror in place (while keeping it free for f > 100 Hz!).
- Each of the 4 length control loops depends on the position of all the mirrors. Must carefully choose the order in which lock is acquired on the length degrees of freedom, especially given the gain hierarchy.
- Lock acquisition must be fast and robust, to keep IFO fully locked as much as possible (lock duty cycle).
- This is one of the biggest challenges in making LIGO work!

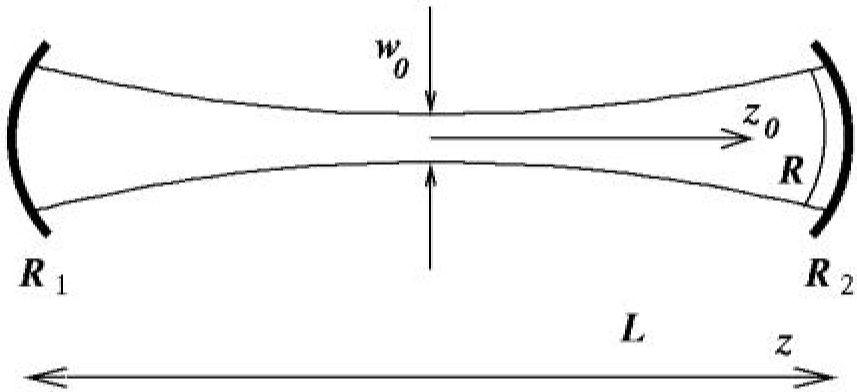
Lock Acquisition sequence

- A sequence of steps, each with changes to control loop gains and signs
- Automated lock acq procedures guide the transitions
- MTTL: $t_{lock} \sim \dfrac{l/2}{v_{thr} P(v < v_{thr})}$



Transverse profile of beam in FP cavity: Hermite-Gaussian modes

The transverse profile of a beam resonant in a FP cavity is completely determined by L, R_1, R_2, l



Beam waist: $w_0 = \lambda/\pi \ f(L,R_1,R_2)$

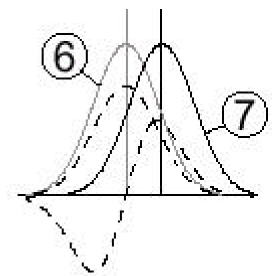
Rayleigh length: $z_0 = \pi w_0^2/\lambda$

- beam waist at position z : $w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2}$
- beam ROC at position z : $R(z) = z + \frac{z_0^2}{z}$
- beam *Guoy phase* at position z : $h(z) = \tan^{-1}\left(\frac{z}{z_0}\right)$

Hermite Gaussian Modes

$$E(x,y,z)=\sum a_{mn}U_{mn}(x,y,z), \quad U_{mn}(x,y,z)=U_m(x,z)U_n(y,z)e^{-ikz}$$

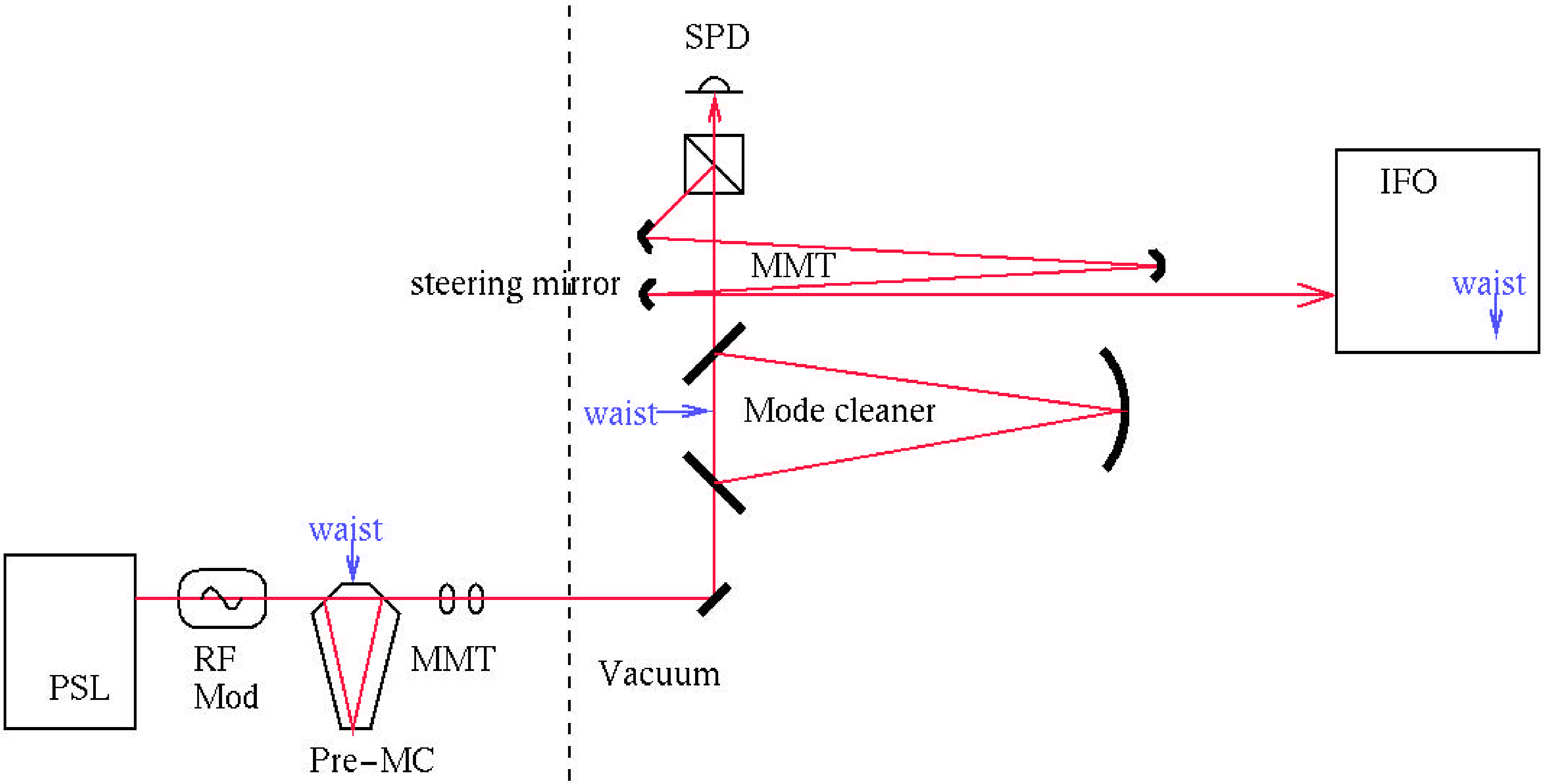
- U_{mn} are *Hermite-Gaussian* or TEM_{mn} transverse modes



$$U_m(x,z)=\sqrt{\frac{\sqrt{2/p}}{2^m m!\,w(z)}}\;H_m\left[\frac{\sqrt{2}x}{w(z)}\right]e^{-x^2\left[\frac{1}{w(z)^2}+\frac{ik}{2R(z)}\right]}e^{i(m+\frac{1}{2})h(z)}$$

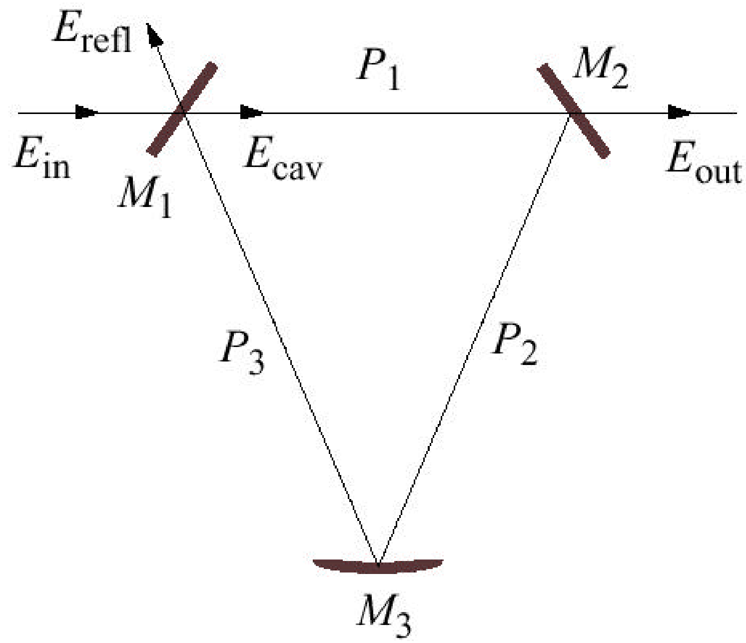
- In a perfect IFO (perfect mirror ROCs, perfect alignment, all cavities *mode matched*), only TEM_{00} mode exists.
- In LIGO cavities, all higher order modes (TEM_{01}, TEM_{10}, etc) represent *beam loss* and *excess noise*;
- Must control mirror imperfections, pitch and yaw, input beam position and direction, mode matching between cavities, *etc*, to minimize this.

Input Optics (IOO)



Mode Cleaner

- Filter out HOMs
- Filter frequency noise from laser
- Triangular MC ensures that reflected light doesn't head back to laser, accessible for reflection locking
- M_3 is very curved, to ensure tight beam (small g-factor)
- Waist is halfway between M_1 and M_2

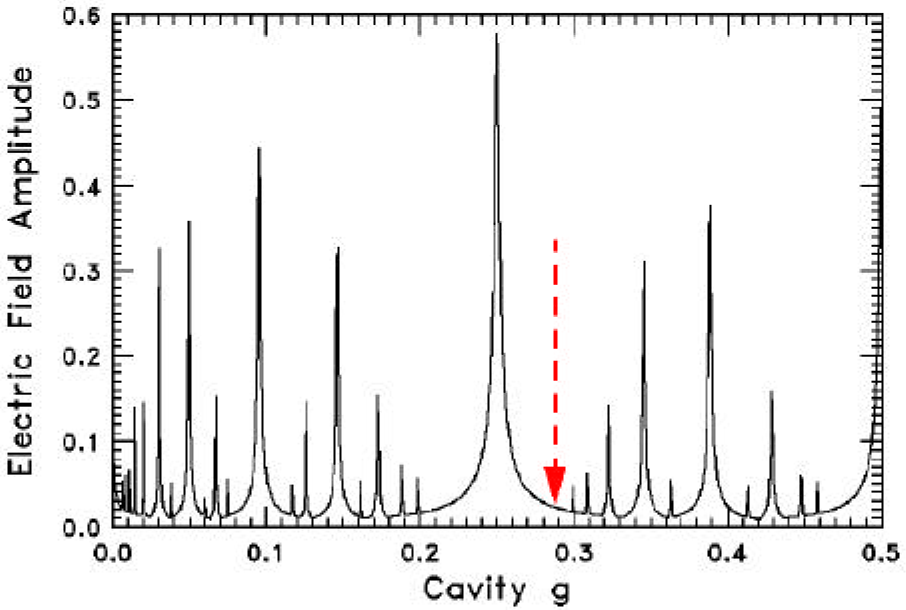


Cavity g-factor

- LIGO Mode Cleaner has two flat and one curved mirror.
- The radius of curvature (ROC) of curved mirror determines g-factor.

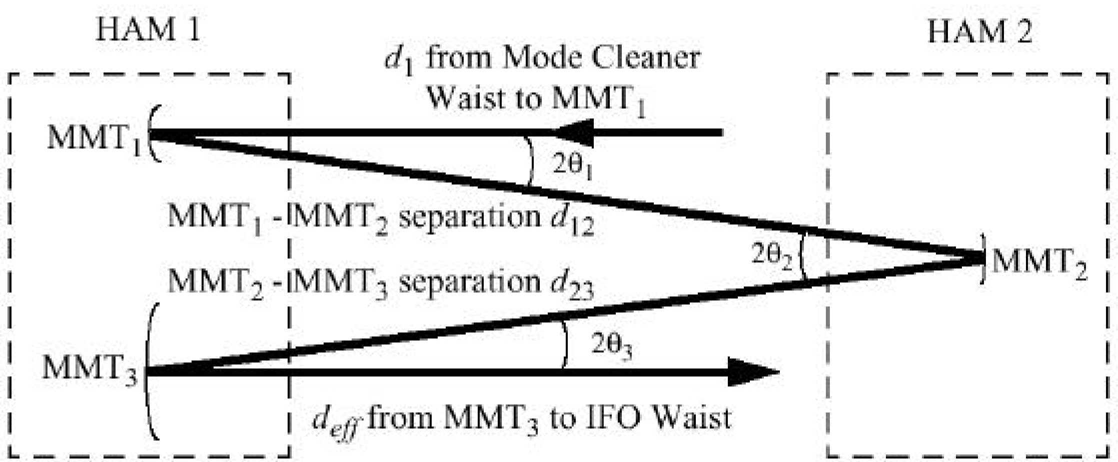
$$g = \left(1 - \frac{L}{R}\right)$$

- $g<1$ gives a stable cavity (beam does not diverge as in $R<0, g>1$).
- As g-factor decreases below 1, Guoy phase difference of HOMs gets larger; only one mode resonates in cavity
- g-factor of FP cavity with two curved mirrors is $g = g_1 g_2$, with $g_i = (1 - L/R_i)$



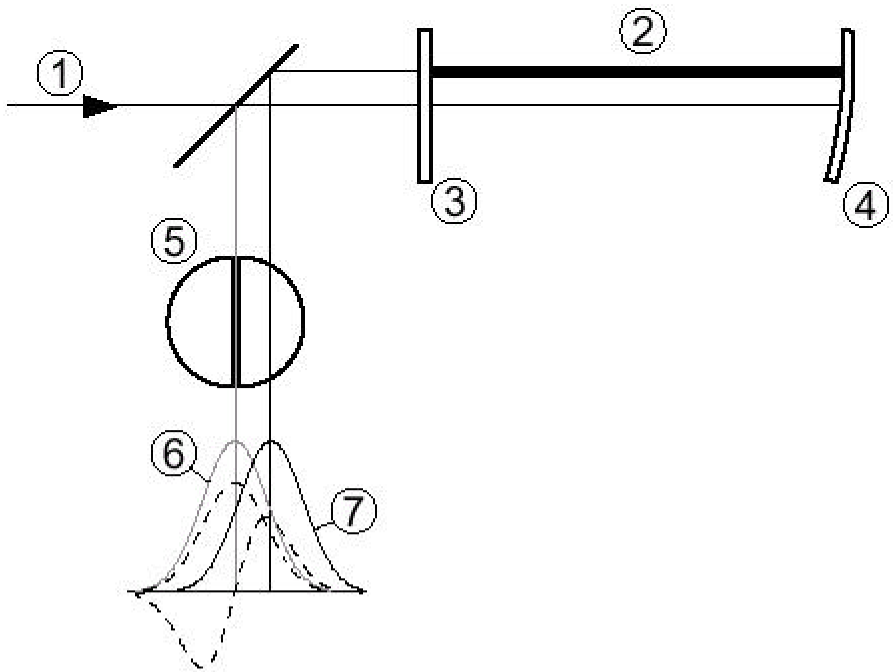
Mode Matching telescope

- Mode Cleaner defines the gaussian beam, with waist in the MC
- The IFO gaussian beam has a waist in the arm cavity
- Need optical telescope to match these beams
- LIGO uses suspended mirrors, rather than transmissive lenses, to minimize noise
- Last MMT mirror steers the beam into IFO



Alignment signals from a misaligned F-P IFO

1) incoming laser beam
2) resonant cavity mode
3) Partially transmitting ITM
4) Tilted ETM
5) Segmented PD (Wavefront Sensor)
6) Reflected SB
7) Reflected carrier light (solid) with modal decomposition (dashed)



Sense and servo out the higher order modes (TEM_{01}, TEM_{10})

Need to control mirror angles to ~ 10^{-8} rad!

Prototype IFOs

- Several table-top (non-suspended) IFOs for development of RSE/DR – Caltech (Jim Mason), UFla, ANU, TAMA 3
- **40 meter (Caltech)** :
  full engineering prototype for optical and control plant for AdvLIGO
- **Thermal Noise Interferometer (TNI, Caltech)** :
  measure thermal noise in AdvLIGO test masses (sapphire)
- **LIGO Advanced Systems Testbed IFO (LASTI, MIT)** :
  full-scale prototyping of AdvLIGO seismic isolation & suspensions
- **Engineering Test Facility (ETF, Stanford) :**
  Initial seismic isolation prototype; advanced IFO configs (Sagnac)
- **10 meter IFO at Glasgow** : prototype optics and control of RSE
- **TAMA 30 meter (Tokyo) :** Advanced technologies
  (SAS, RSE, control schemes, sapphire, cryogenic mirrors)
- **AIGO 80m IFO at Gingin** :
  high powered laser, thermal effects, control stability

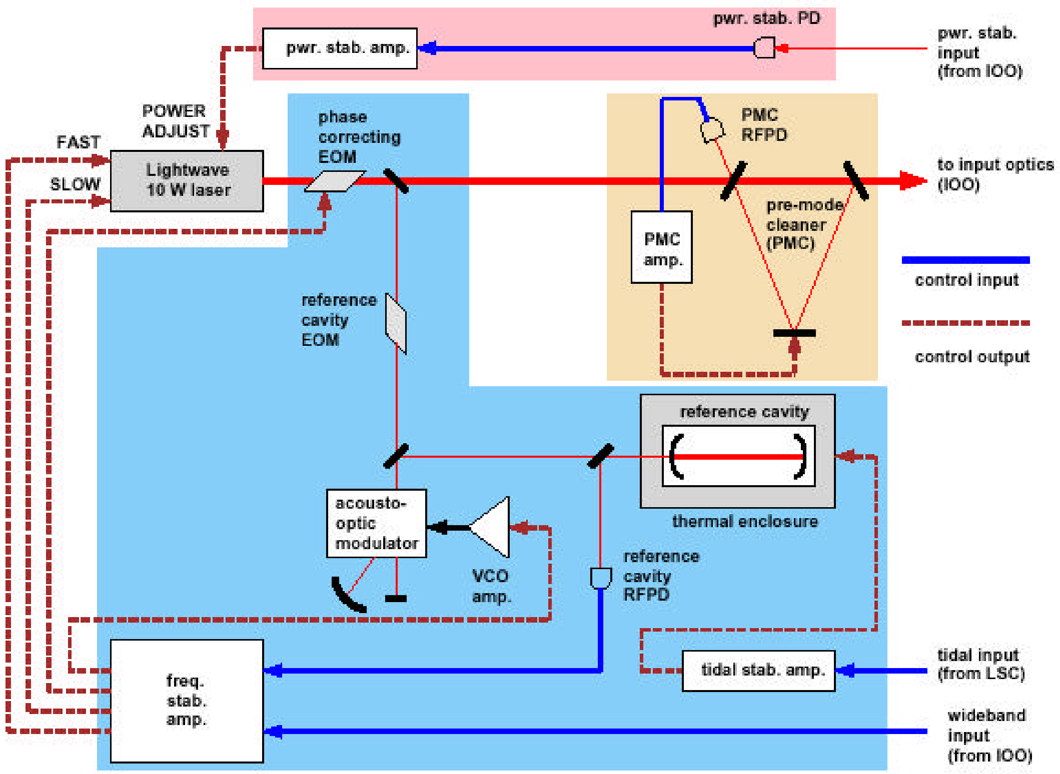
LIGO Subsystems

- PSL – Pre-Stabilized Laser
- IOO – Input Optics
- SUS – Suspension (mechanical and electronic)
- ISC – Interferometer sensing and control
- LSC – Length sensing and control
- ASC – Alignment sensing and control
- Oplev – Optical levers
- WFS – Wavefront sensors
- GDS – Global Diagnostic System
- PEM – Physical environment monitoring
- VAC – Vacuum system control
- DAQS – Data acquisition System
- CDS – Control and Data Systems
- LDAS – LIGO Data Analysis System

My apology if I omitted your favorite subsystem or give it short shrift!

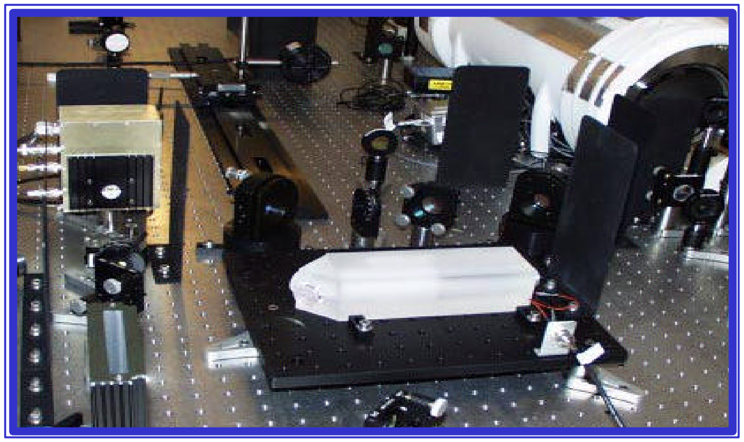
Pre-Stablized Laser (PSL)

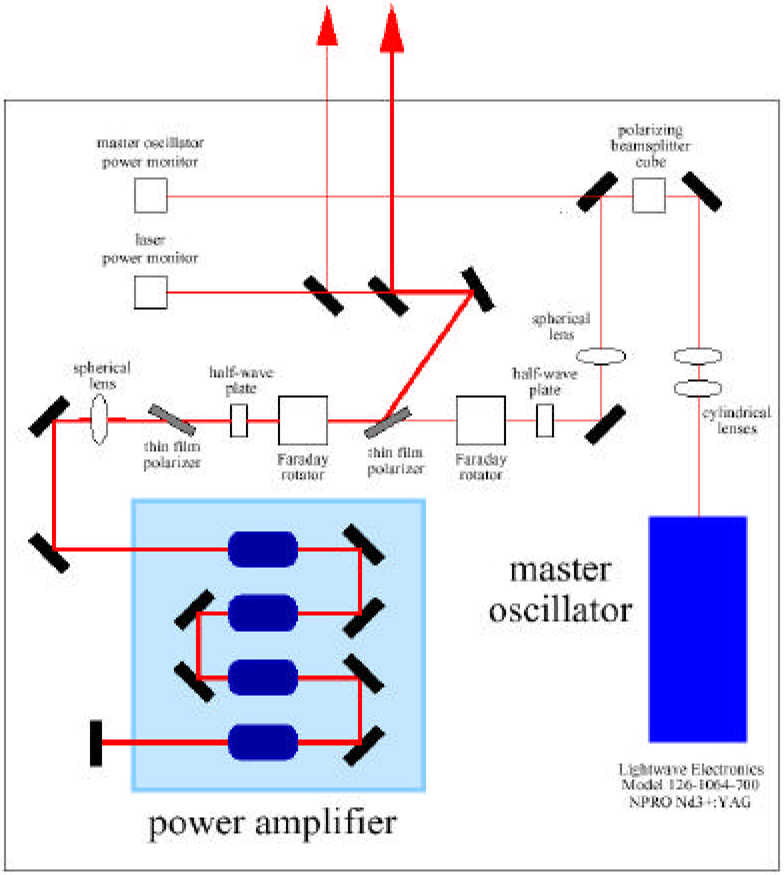
- Start with high-power (10watt) CW Nd:YAG IR (1.064 um) MOPA laser
- Frequency stabilization
  - (fast and slow)
- Power stabilization
- Transverse “mode cleaning”
- Phase correction



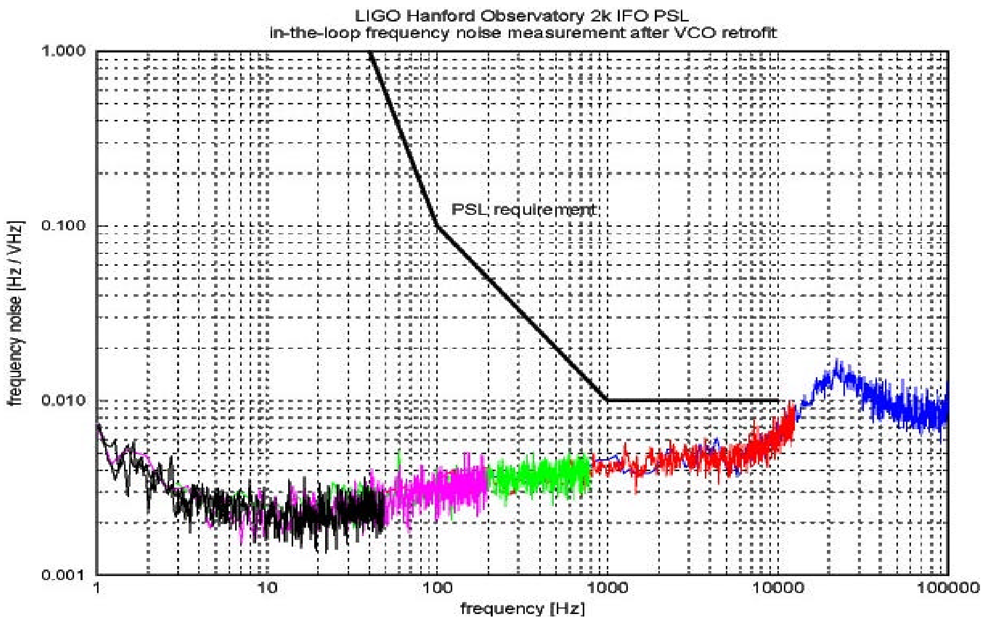
Pre-stabilized laser (PSL)

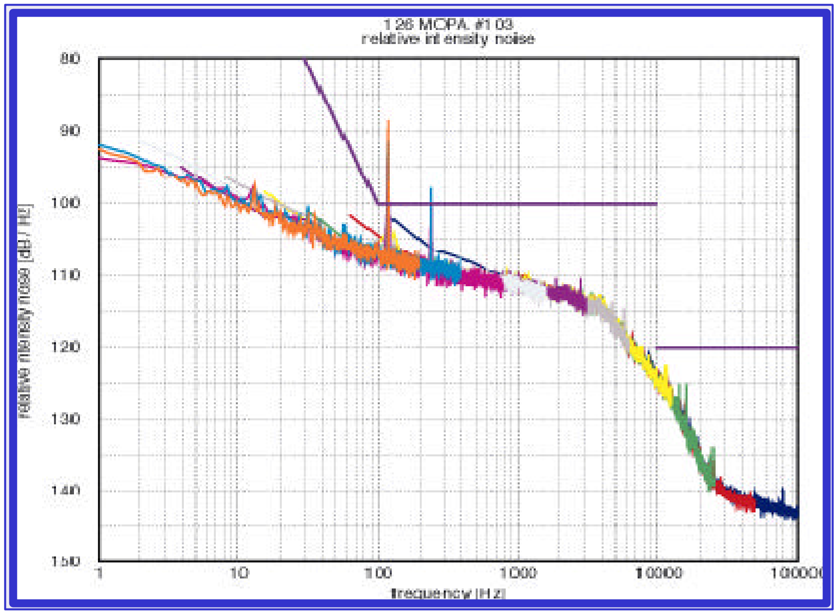
- Nd:YAG MOPA (Master Oscillator Power Amplifier)
- 1.064 μm
- Output power > 8W in TEM00 mode





Laser noise pre-stablization

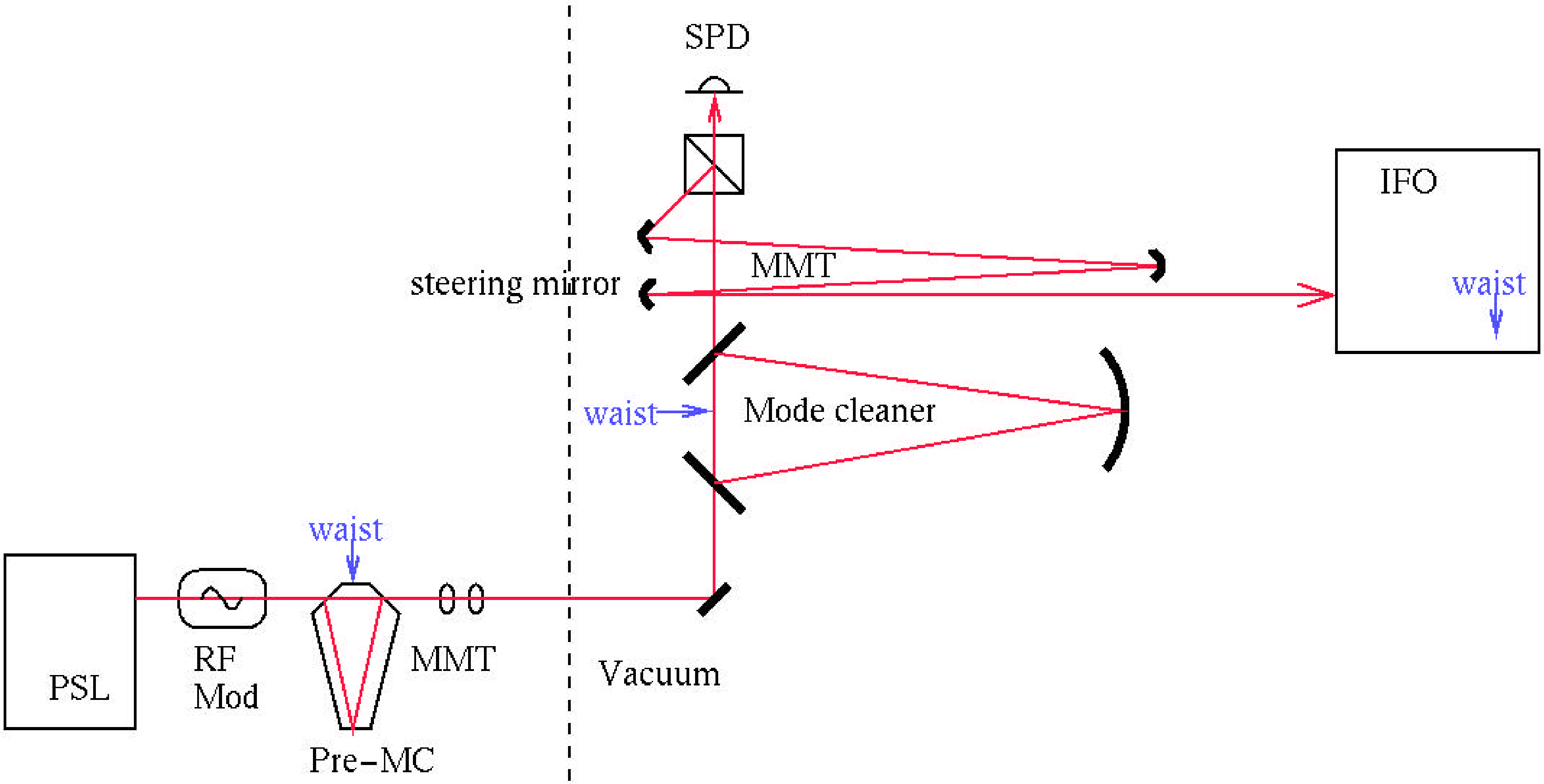




- **frequency noise:**
- $\delta\nu(f) < 10^{-2}$Hz/Hz$^{1/2}$ 40Hz<f<10KHz

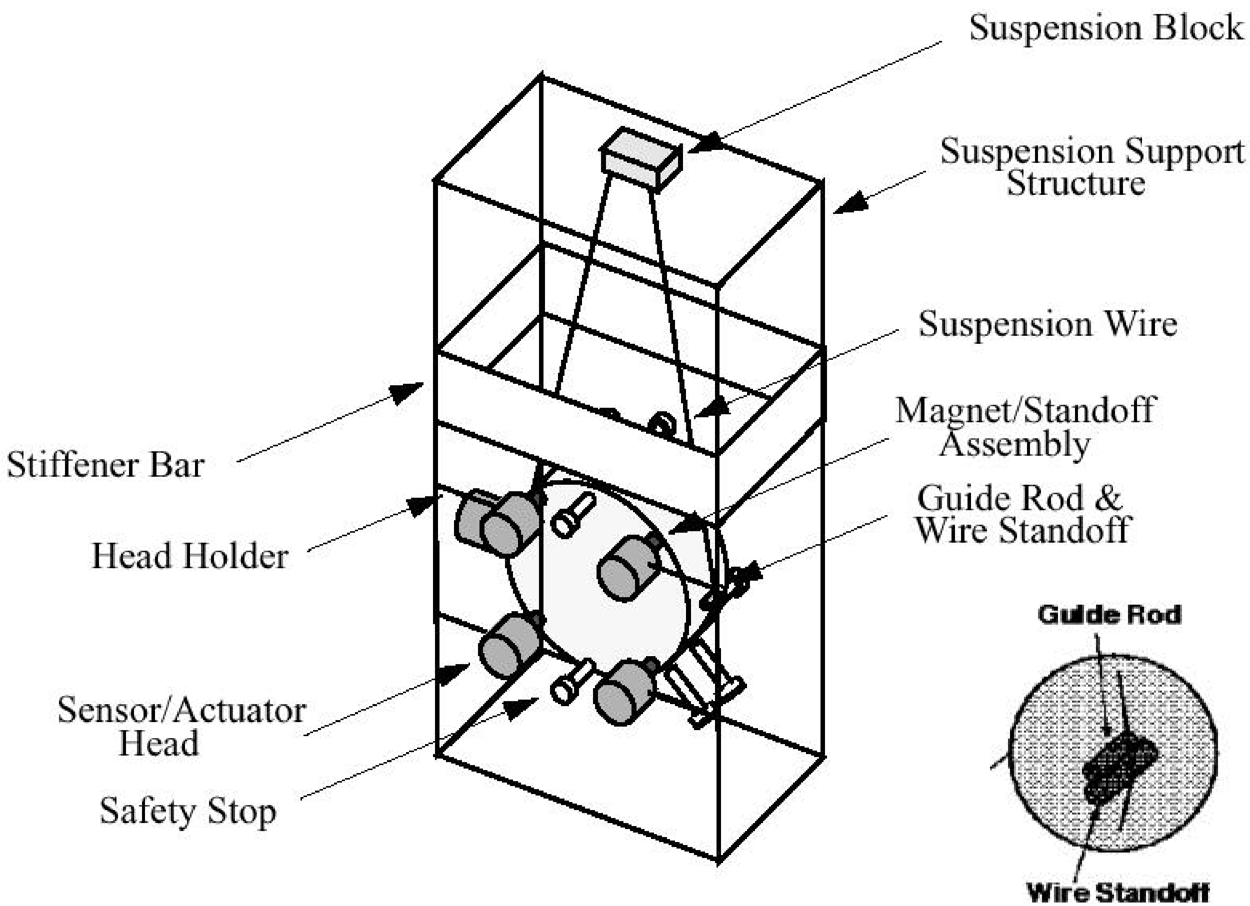
- **intensity noise**:
- $\delta I(f)/I < 10^{-6}$/Hz$^{1/2}$, 40 Hz<f<10 KHz

Input Optics (IOO)



LIGO I Suspensions

- Rigid suspension frame with resonances well above 100 Hz (where pendulum filtering and seismic excitation are small)
- EQ safety stops
- Steel piano wire
- Carefully designed wire standoffs to minimize dissipation in wire violin modes
- 5 OSEMs for control of length, pitch, yaw, side rocking



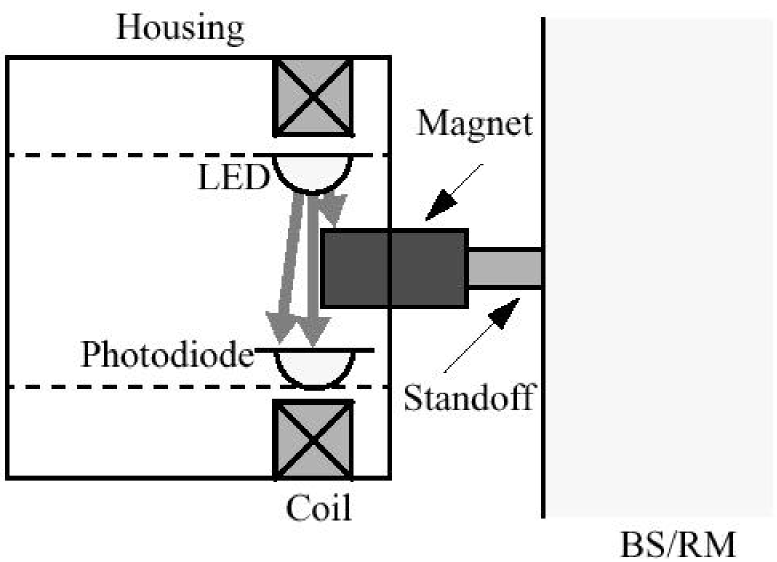
OSEMs

• Five magnets glued to fused Si optic

- •(this ruins the thermal noise properties of the optic – a big problem!)

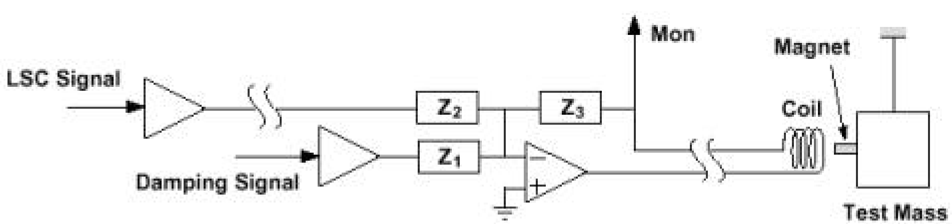
•LED/PD pair senses position

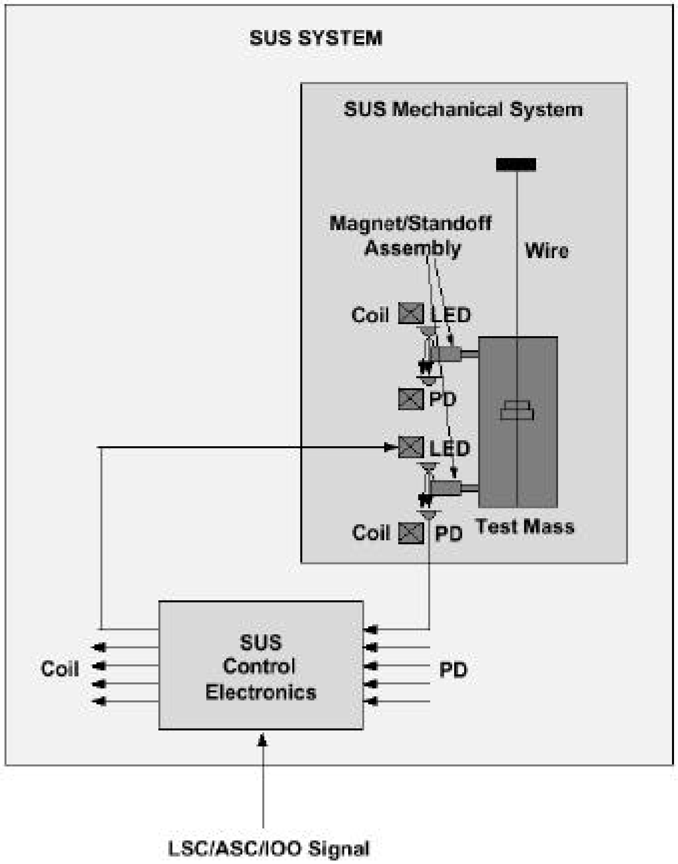
• Coil pushes/pulls on magnet, against pendulum



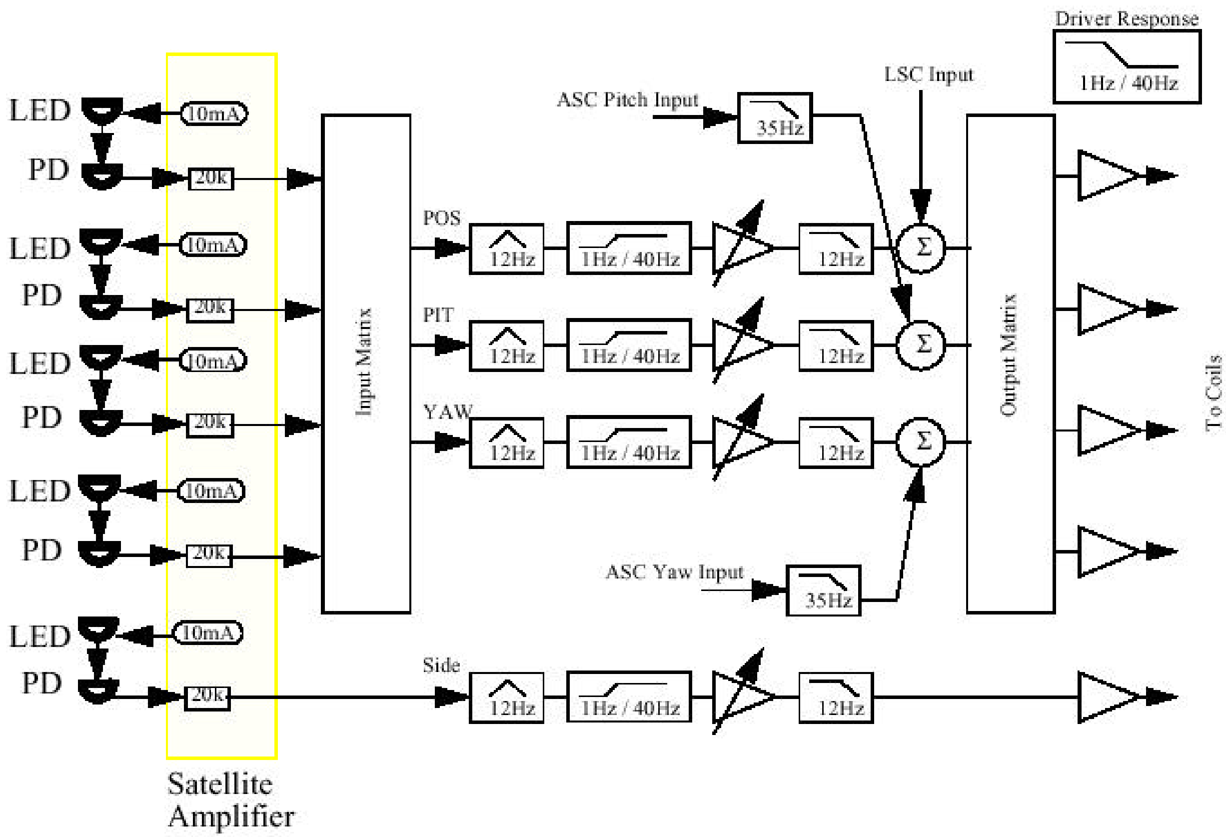
Suspension control system

- Each suspension controller handles one suspension (5 OSEMs)
- Local velocity damping
- Input from LSC and ASC to fix absolute position, pitch, yaw of mirror to keep cavity in resonance





Suspension controller (local analog version)

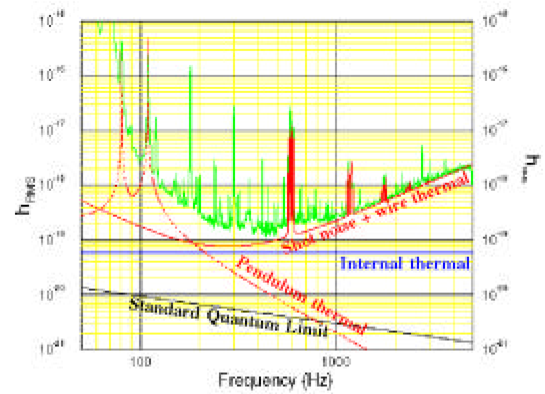


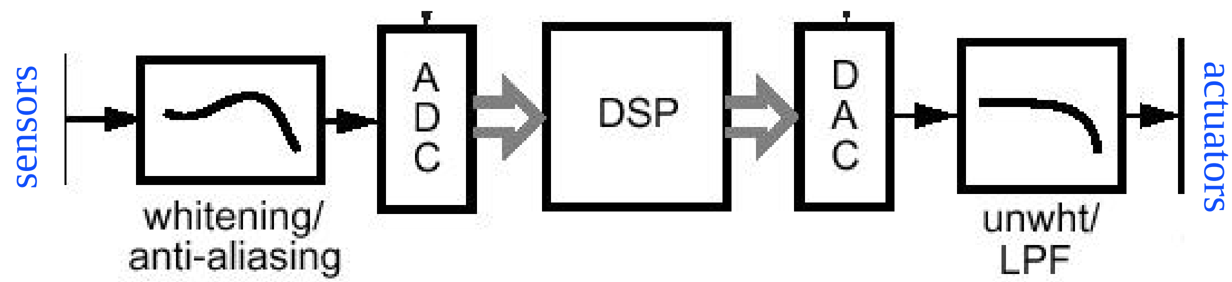
Digital servo electronics chain

- **Whitening:** IFO response, and noise, vary over orders of magnitude from DC to ~ 10kHz
- Analog-to-digital conversion (ADC): 16 kHz, 16-bit accuracy (dynamic range ~ 10^4)
- Noise near DC will swamp signal at 1kHz.

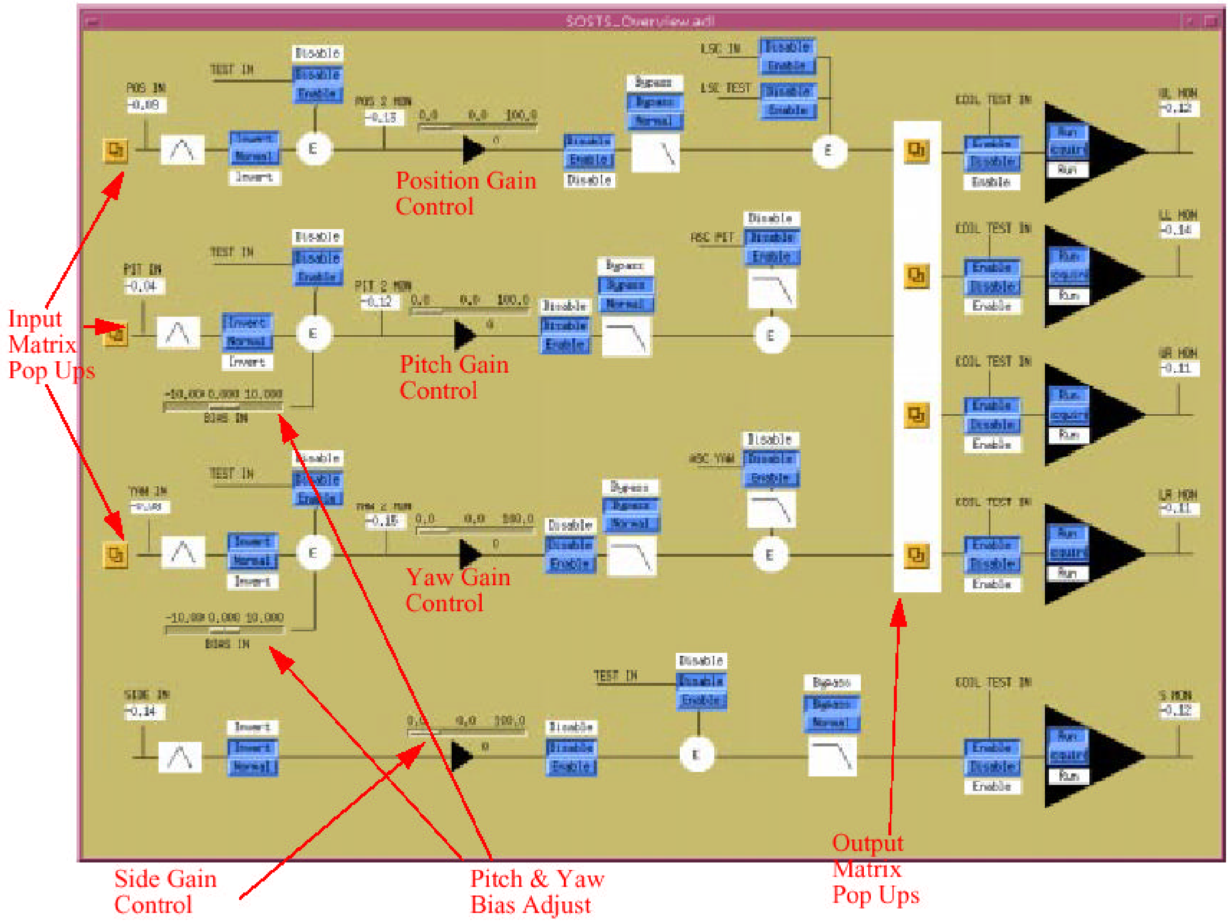
⇒Must whiten: de-emphasize high-noise low-f part of data stream, emphasize higher-f signal

- **Anti-aliasing:** digitization process introduces spurious signals at high frequency
- Fast ADC: 16 kHz ⇒ Nyquist frequency = 8kHz.
- All signals at $f > f_{Nyquist}$ are "aliased" into spurious signals at $f < f_{Nyquist}$
- Must filter input to suppress frequency components > $f_{Nyquist}$
- And also low-pass filtering after digital->analog conversion (DAC) to remove spurious high-f noise.





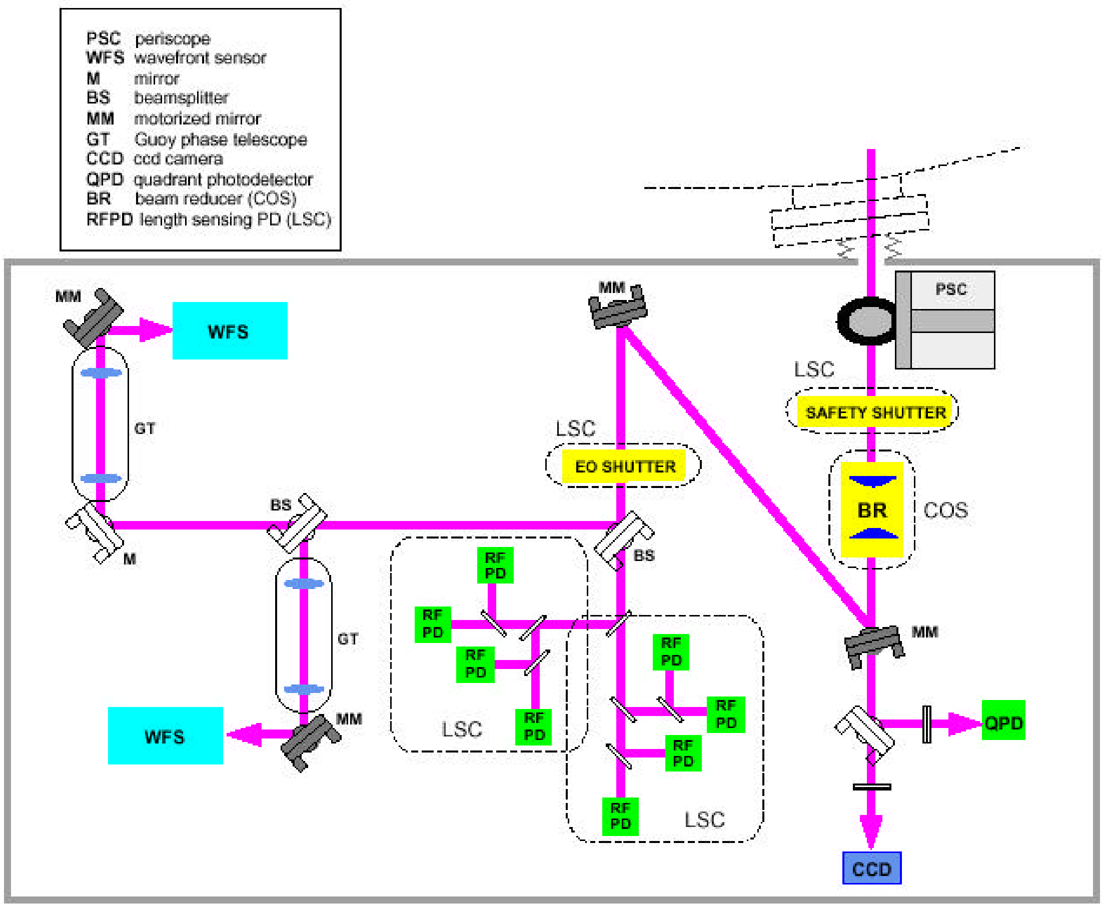
Suspension controller EPICS screen

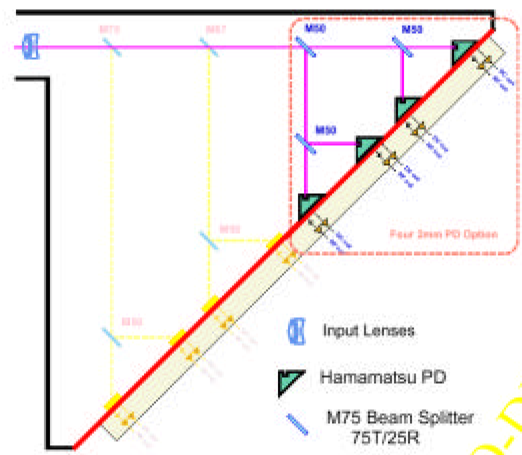


Digital control, DAQS, EPICS

- Each digital system is controlled by a “VME” single-board computer (cpu) running the VxWorks real-time operating system (there are 15-20 cpus for each IFO, running SUS, LSC, ASC, DAQS, VAC, etc)
- Each cpu can exchange data with the others via fast “reflective memory” (VME boards with lots of fast memory, linked to all the others via optical links)
- EPICS (Experimental Physics and Industrial Control System): Each cpu maintains a database of “channels” which can be accessed over the (slow) network, displayed using GUIs for the operator to monitor and change (control).
- EPICS supplies the Channel Access, databases, “state machine” code to be run on VME cpus to maintain and locally control the channels in the database, a Backup And Restore facility, Archive facility, Alarm handling, etc.

IFO sensing and control (ISC) optical table (one of 3!)

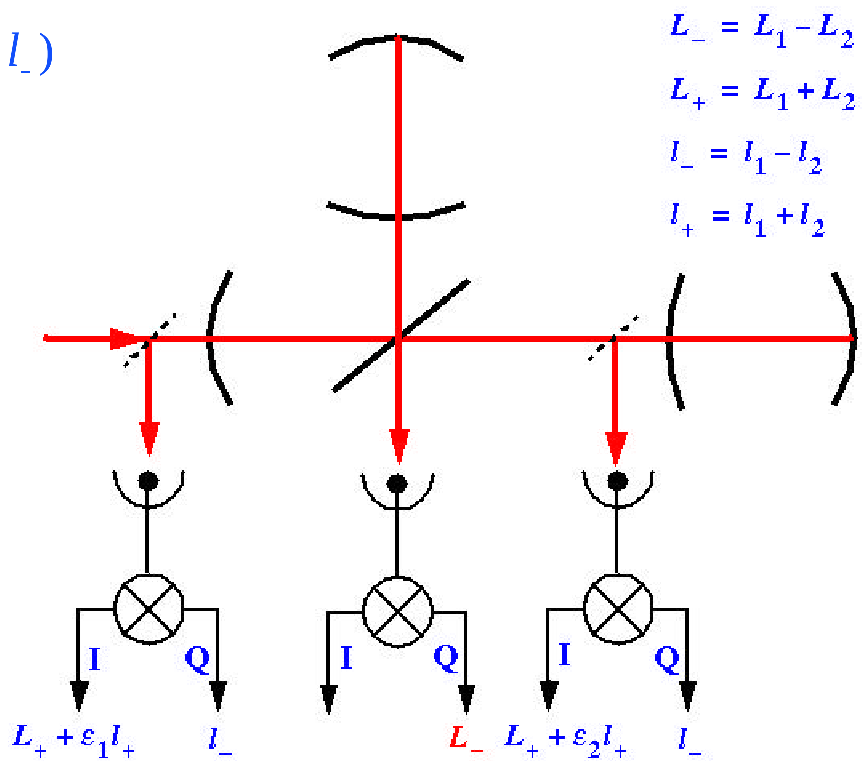




Length Sensing and Control (LSC)

Length control:

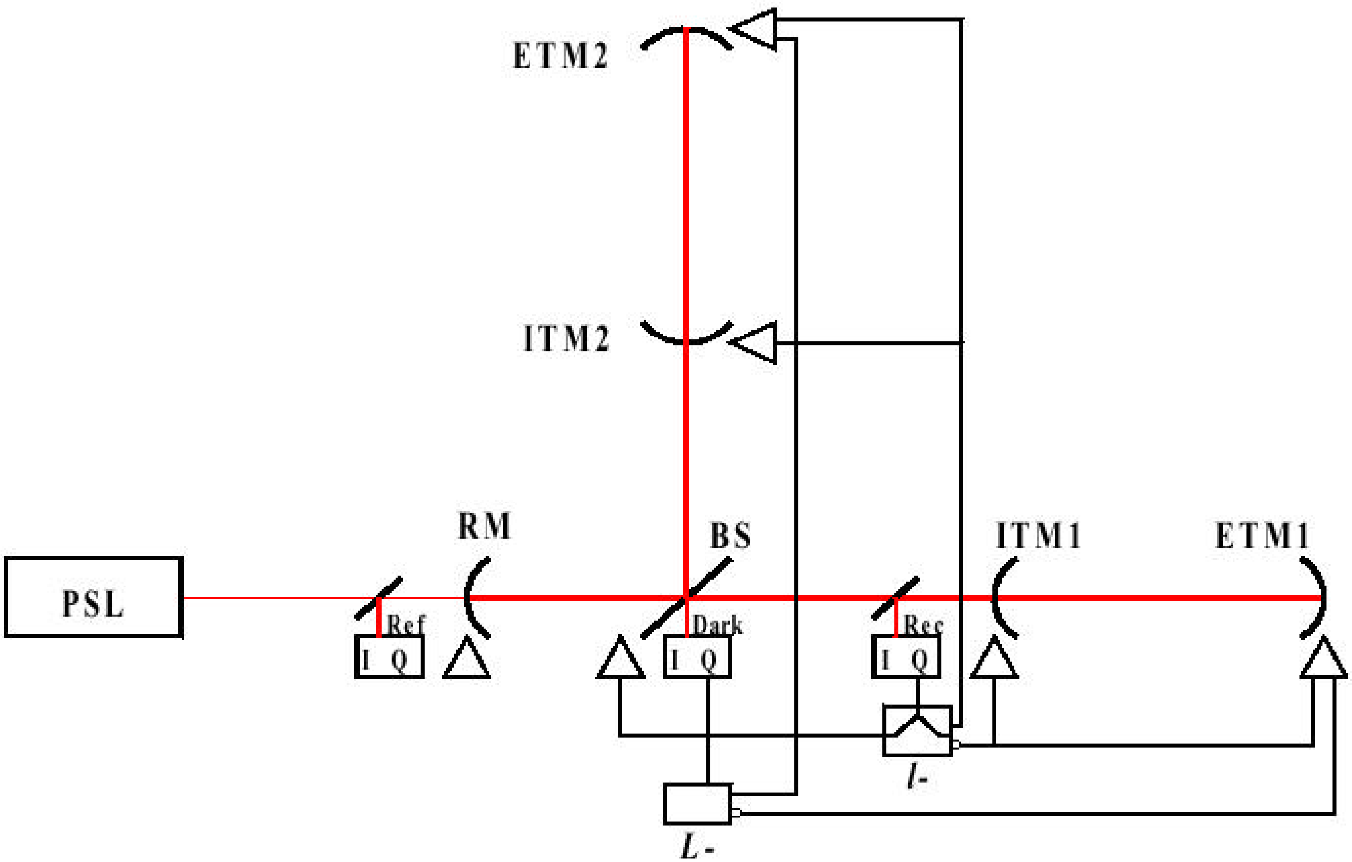
- 4 length degrees of freedom (L_+, L_-, l_+, l_-)
- L_- = gravity wave signal
- l_- = Michelson dark fringe (*contrast*)
- Diff mode (L_-, l_-) controlled by quad-phase demod signal
- Common mode (L_+, l_+) controlled by in-phase demod signal
- Need *gain hierarchy* to control l_+
- Hold lengths to 10^{-13} m in presence of 10^{-5} m (seismic) noise



Length control matrix

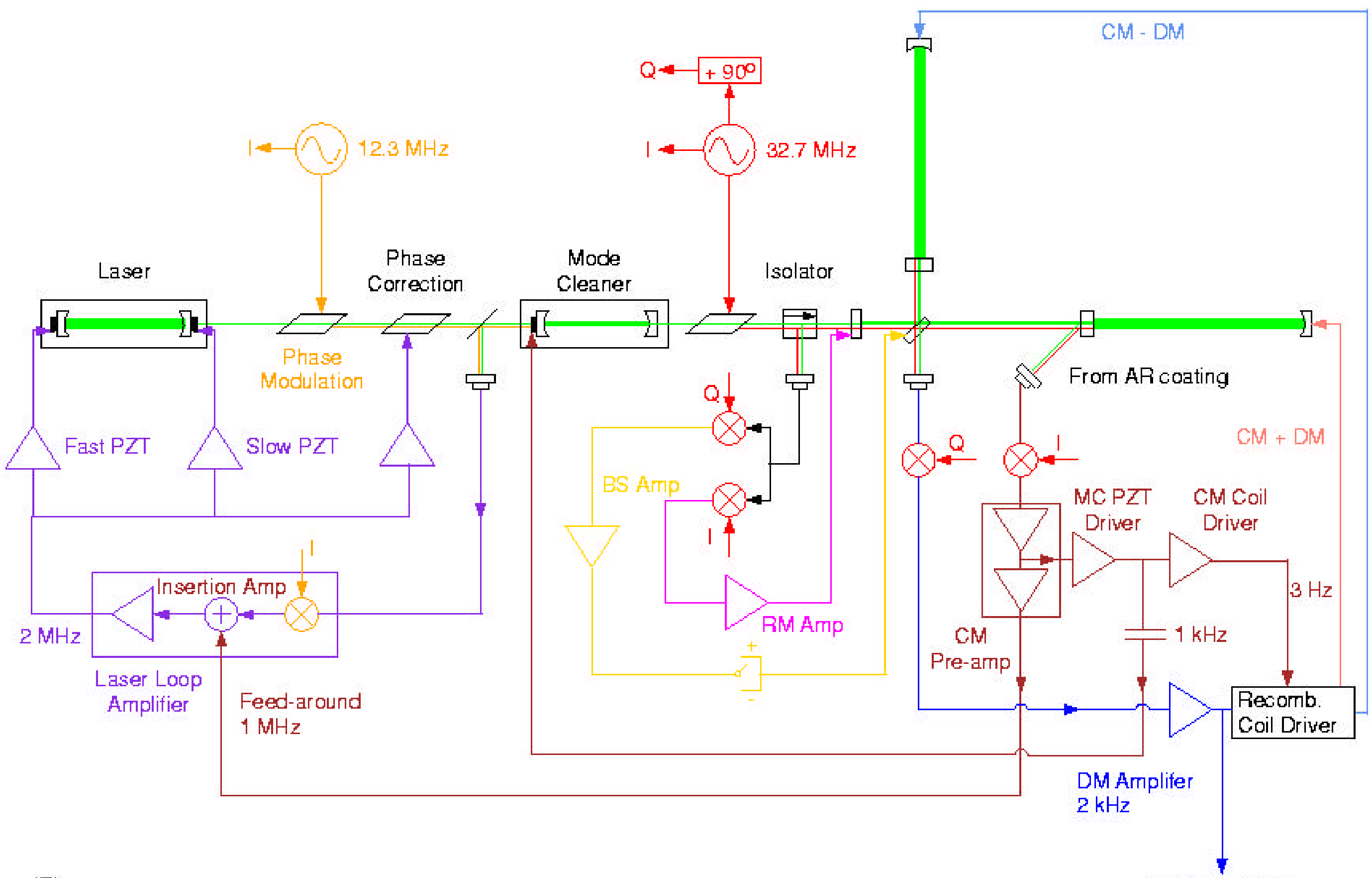
	dS_{AQ}(Volts)	dS_{PQ}(Volts)	dS_{PI}(Volts)	dS_{RI}(Volts)
dL_- (m)	$\frac{-9.6\times10^{11}}{1+s/\omega_c}$	4.72×10^5	0	0
dl_- (m)	$\frac{-7.3\times10^{9}}{1+s/\omega_c}$	6.20×10^7	0	0
dL_+ (m)	0	0	$\frac{-7.82\times10^{10}}{1+s/\omega_{cc}}$	$\frac{2.85\times10^{12}}{1+s/\omega_{cc}}$
dl_+ (m)	0	0	$\frac{-3.14\times10^{8}(1-s/\omega_p)}{1+s/\omega_{cc}}$	$\frac{-2.95\times10^{10}(1+s/\omega_r)}{1+s/\omega_{cc}}$
$d\nu_l$ (Hz)	$\frac{4.54\times10^{-12}}{1+s/\omega_c}$	0	$-\frac{1.11}{1+s/\omega_{cc}}$	$-\frac{82.8}{1+s/\omega_{cc}}$

Length Sensing and Control (LSC)

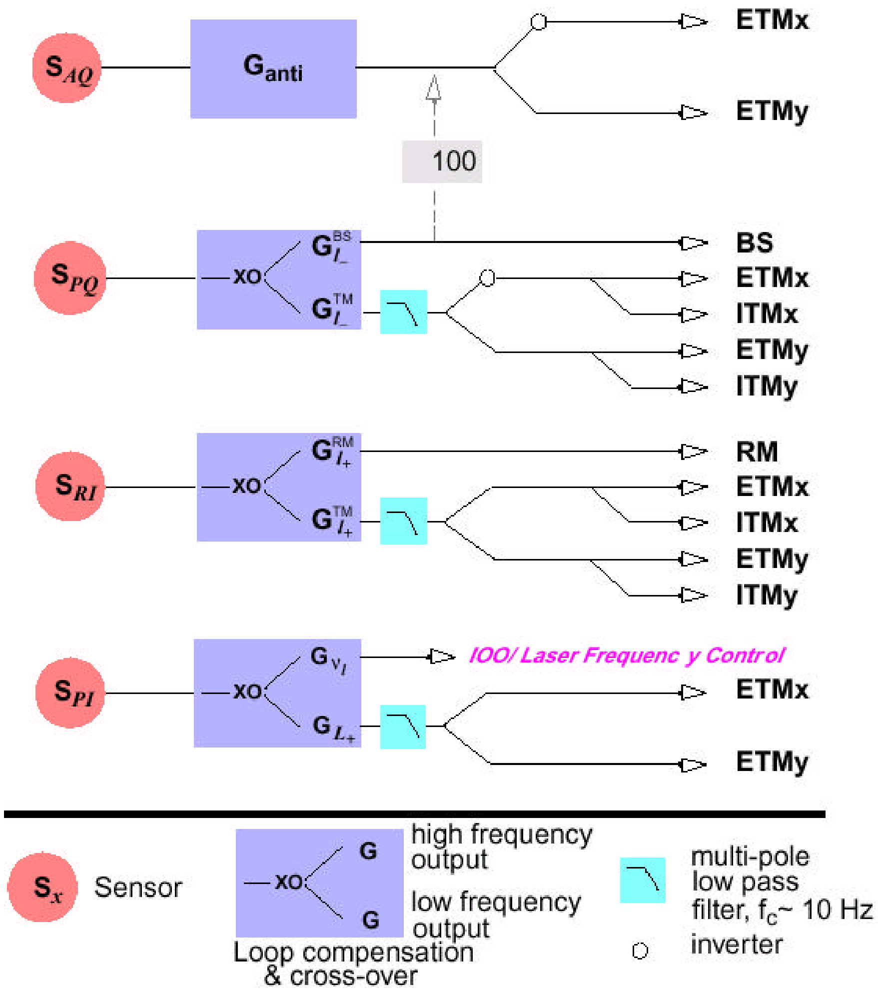


Length Control system topology

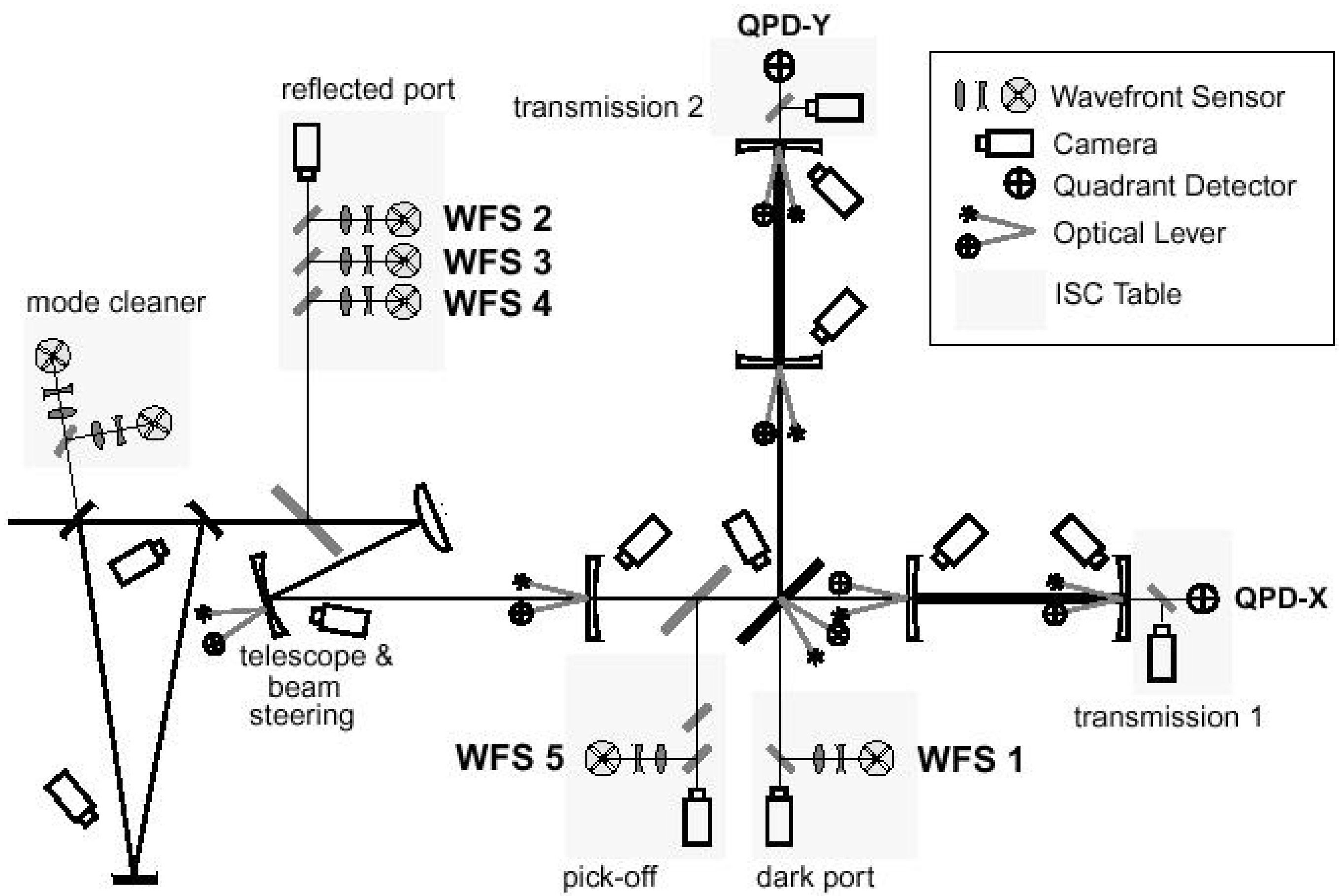
POWER RECYCLING TOPOLOGY



Servo gains and bandwidth



Alignment Sensing and Control (ASC)

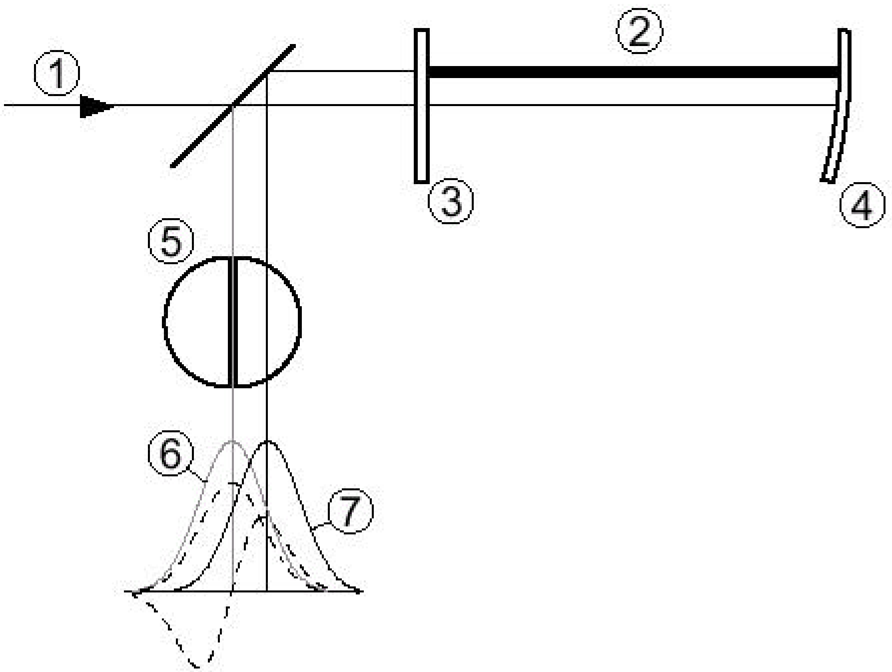


Wavefront sensing (WFS)

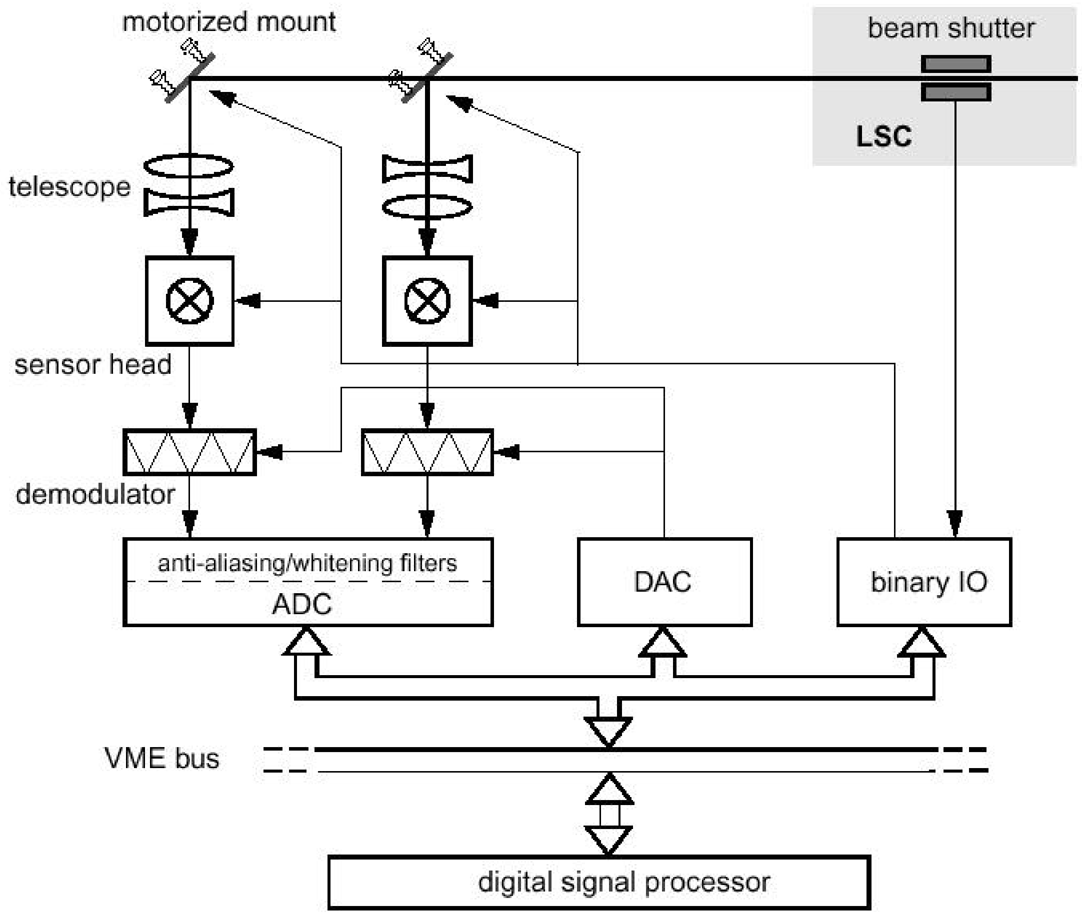
- Sense transverse beam profile in cavity;

  presence of higher-order

  Hermite-Gaussian (TEM_{01}, TEM_{10}) transverse profiles
- Distinguish misalignment of multiple mirrors at only a few output ports, by use of *Guoy phase telescopes*



Wavefront Processing Unit (WPU)



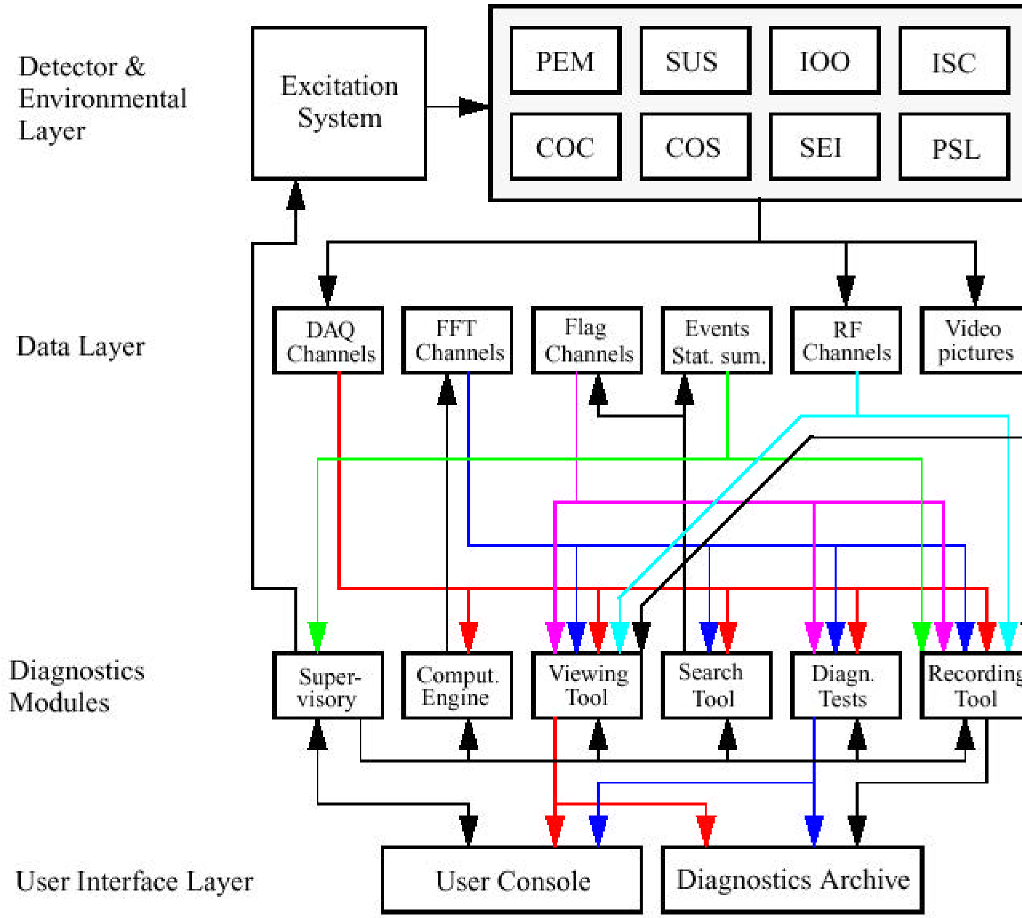
WFS misalignment error signals

M_{ij}	*Angular Degree-of-Freedom*					
Wavefront Sensor	**ΔETM**	**ΔITM**	$\overline{\textbf{ETM}}$	$\overline{\textbf{ITM}}$	**RM**	$\boldsymbol{u_i}$
WFS 1	**-0.044**	**-0.02**	0	0	0	-0.048 u_2
WFS 2a	0	0	-2.0×10^{-3}	**0.026**	**-0.041**	-0.048 u_1
WFS 2b	9.6×10^{-5}	$\mathbf{-5.8 \times 10^{-3}}$	0	4.6×10^{-4}	-7.0×10^{-4}	(-0.14 u_1 - 0.40 u_2 - 0.91 u_3)(0.006)
WFS 3	0	0	-7.0×10^{-4}	-3.2×10^{-4}	$\mathbf{7.3 \times 10^{-3}}$	(0.83 u_1 + 0.13 u_4 - 0.54 u_5)(0.0073)
WFS 4	0	0	$\mathbf{-8.0 \times 10^{-3}}$	$\mathbf{-3.7 \times 10^{-3}}$	6.4×10^{-4}	(0.70 u_1 - 0.46 u_4 + 0.55 u_5)(0.0038)
WFS 5	6.5×10^{-4}	**-0.039**	0	3.2×10^{-3}	-4.4×10^{-3}	(-0.14 u_1 - 0.40 u_2 - 0.91 u_3)(0.04)

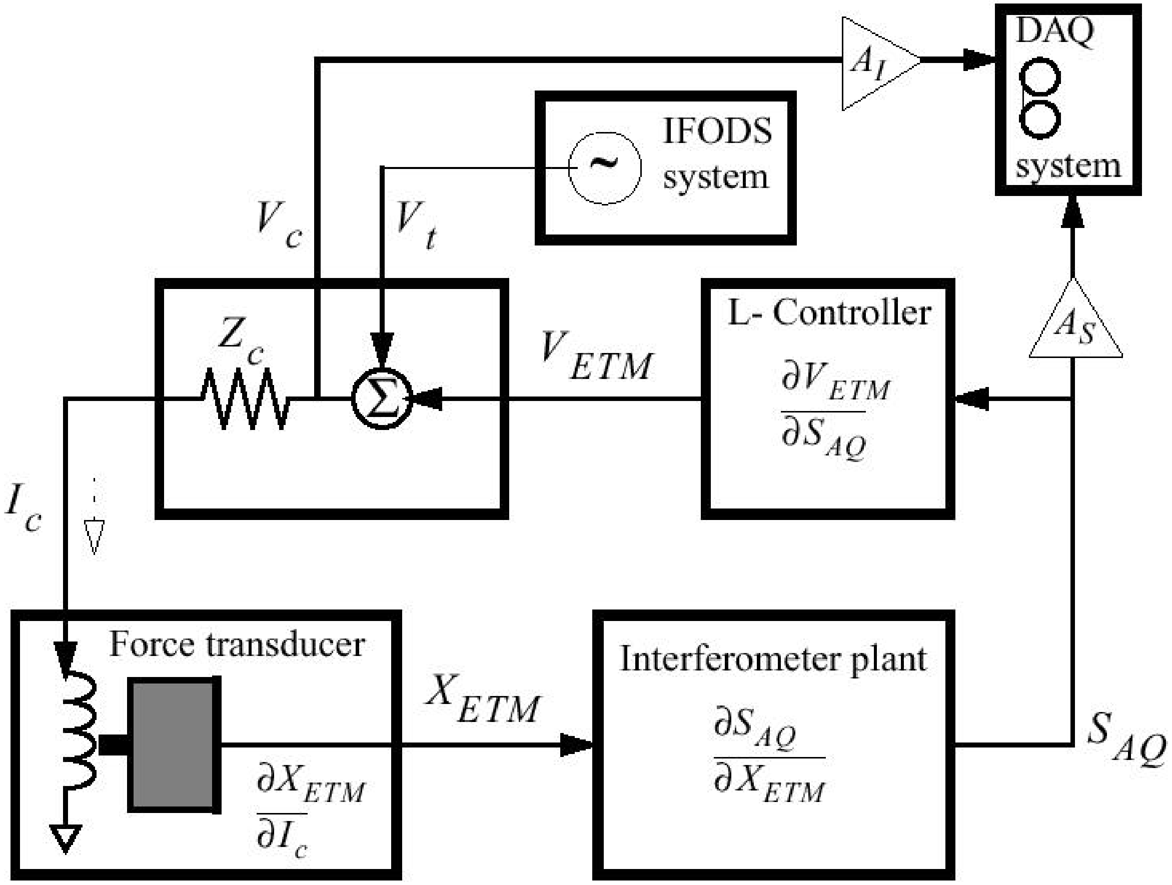
Table 3 Matrix of misalignment error signals, with the sensor locations and design parameters given

Global Diagnostics System (GDS)

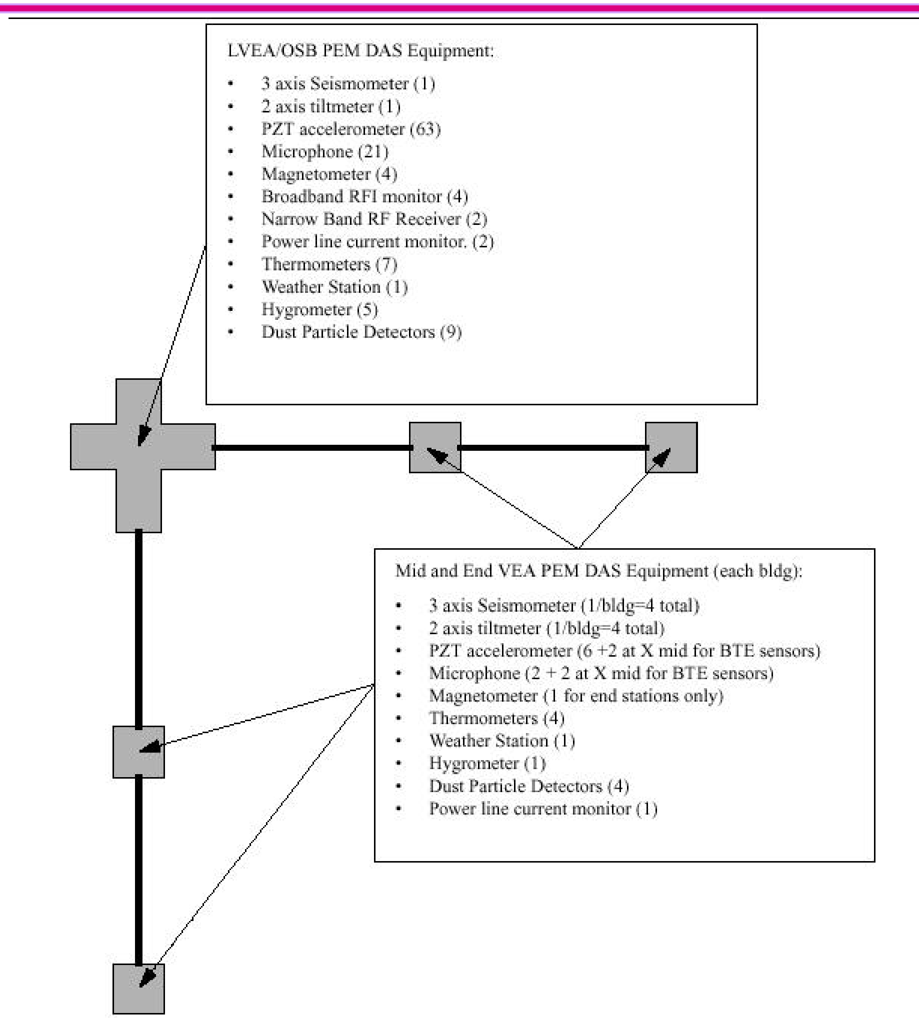
- Swept-sine transfer functions with excitation engine
- Lock acquisition, status and monitoring
- environmental monitoring
- correlating IFO signals
- identifying transients (bumps in the night)
- triggers, alarms
- maintain detector meta-database



Calibration



Physical Environment Monitoring (PEM)



Vacuum control system

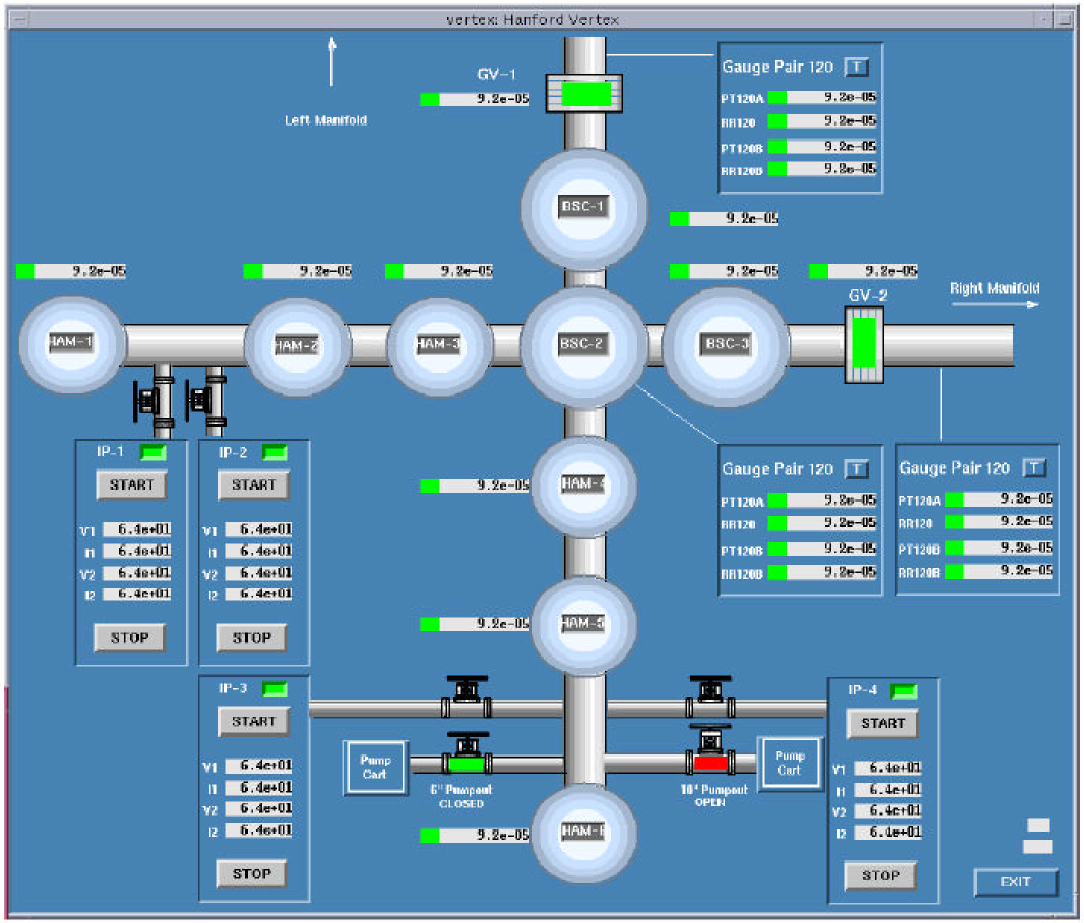
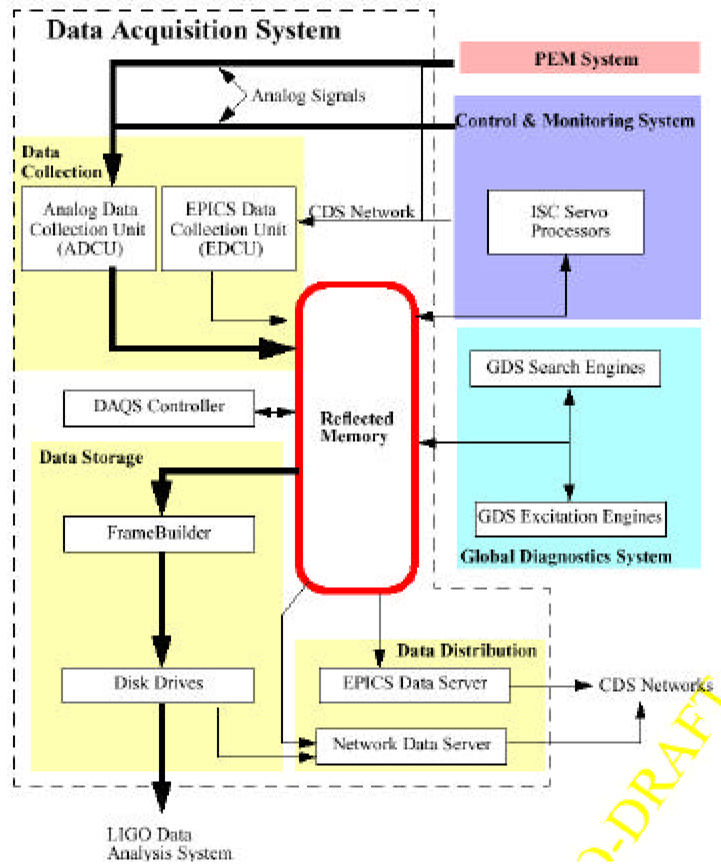


Figure 2: Hanford Vertex Section Display

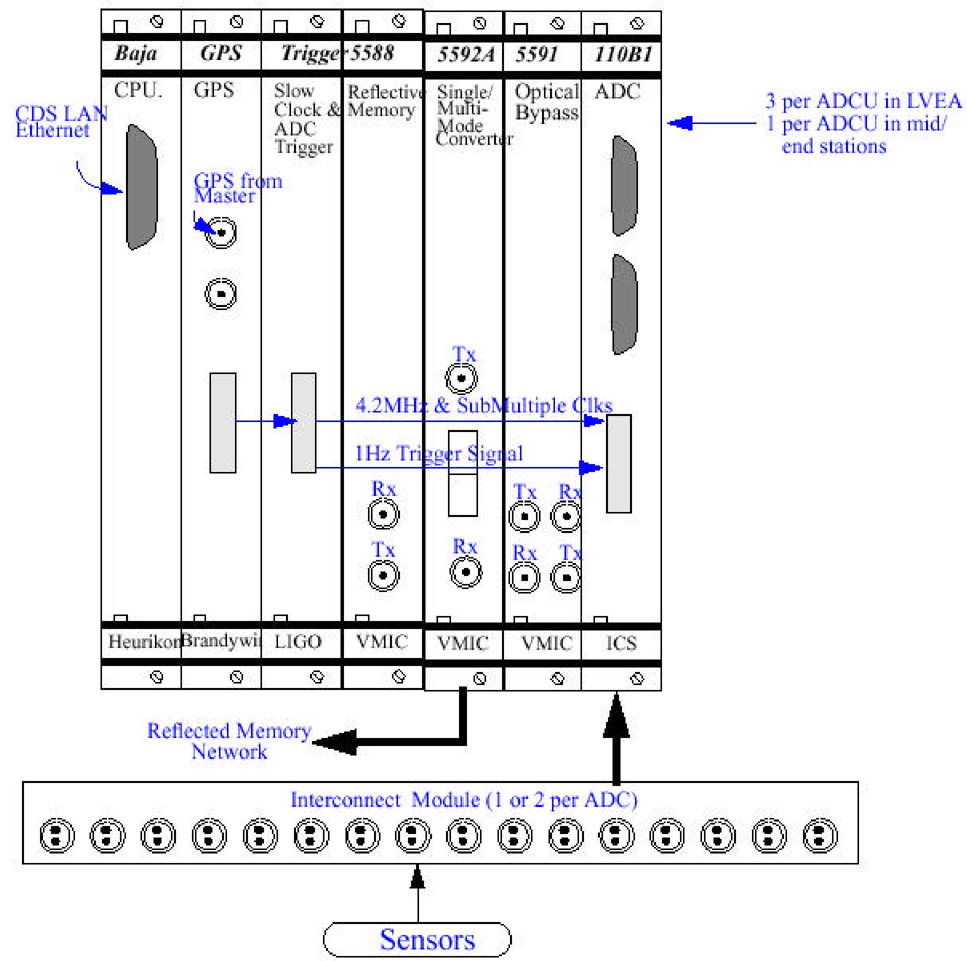
DAQS overview

- Inputs: Analog signals from sensors, to actuators; digital signals from control systems (LSC, ASC, etc)
- Signals needed for LSC, ASC, etc, get digitized in a separate path.
- All information stored in reflective memory, visible to all the cpus in the system that need it.
- I/O to GDS
- Output to frame builder, thence to RAID disk array
- Monitored and controlled via EPICS screens



Analog Data Collection Unit (ADCU)

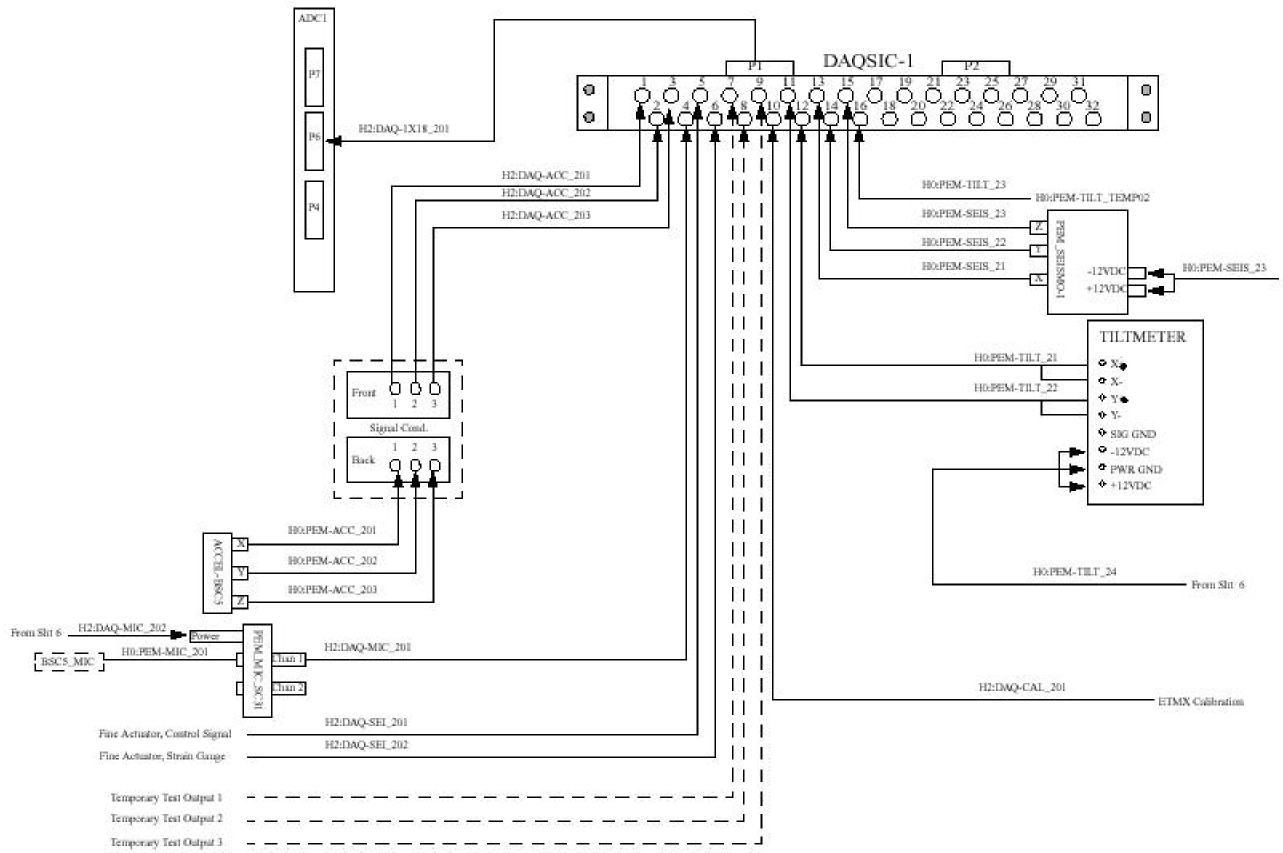
- Fast CPU
- ADC (up to 16 bit, 16 kHz, 32 ch)
- GPS receiver for ADC trigger
- Reflective memory



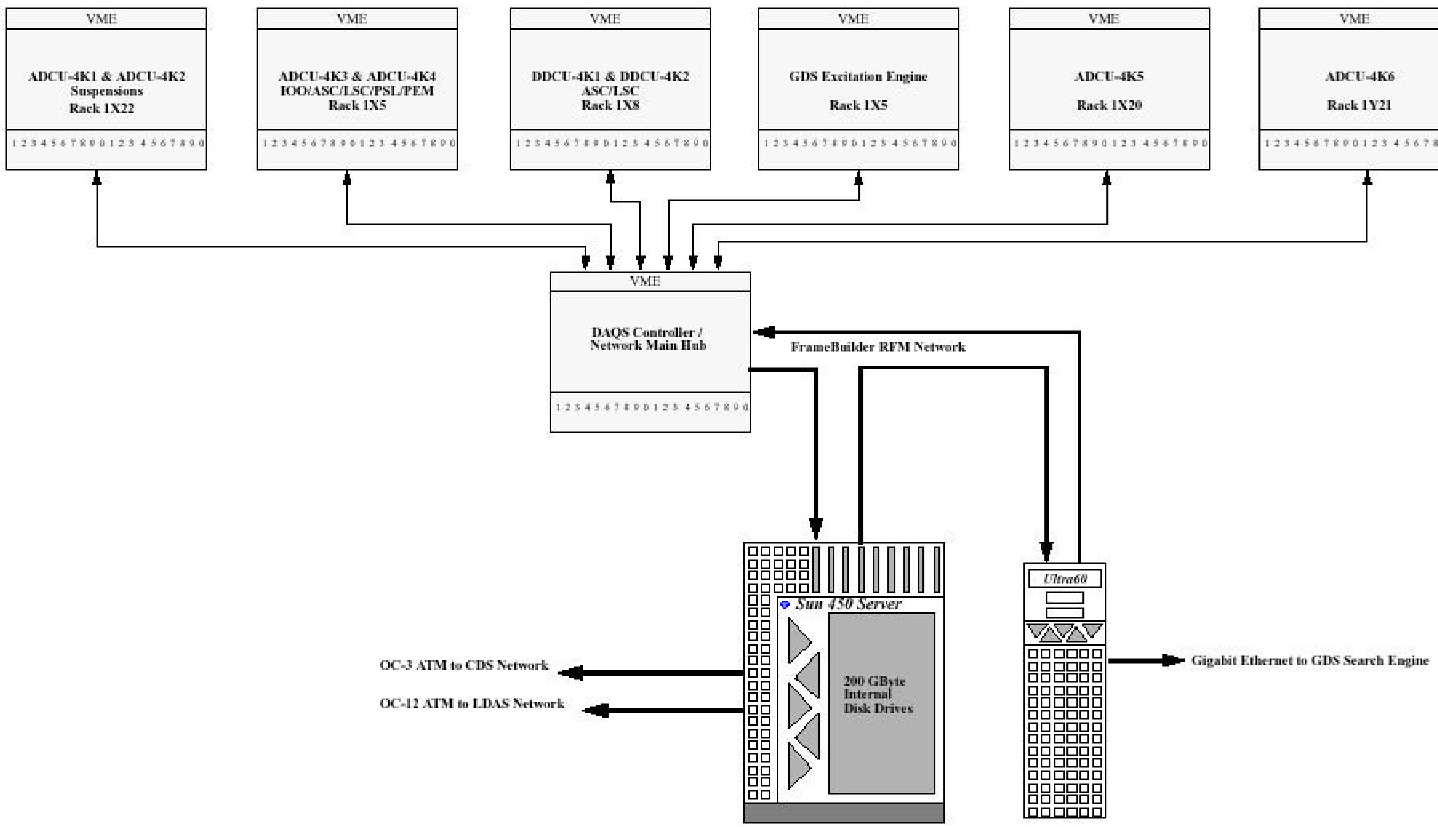
Typical example of what's in an ADCU

ADC-1

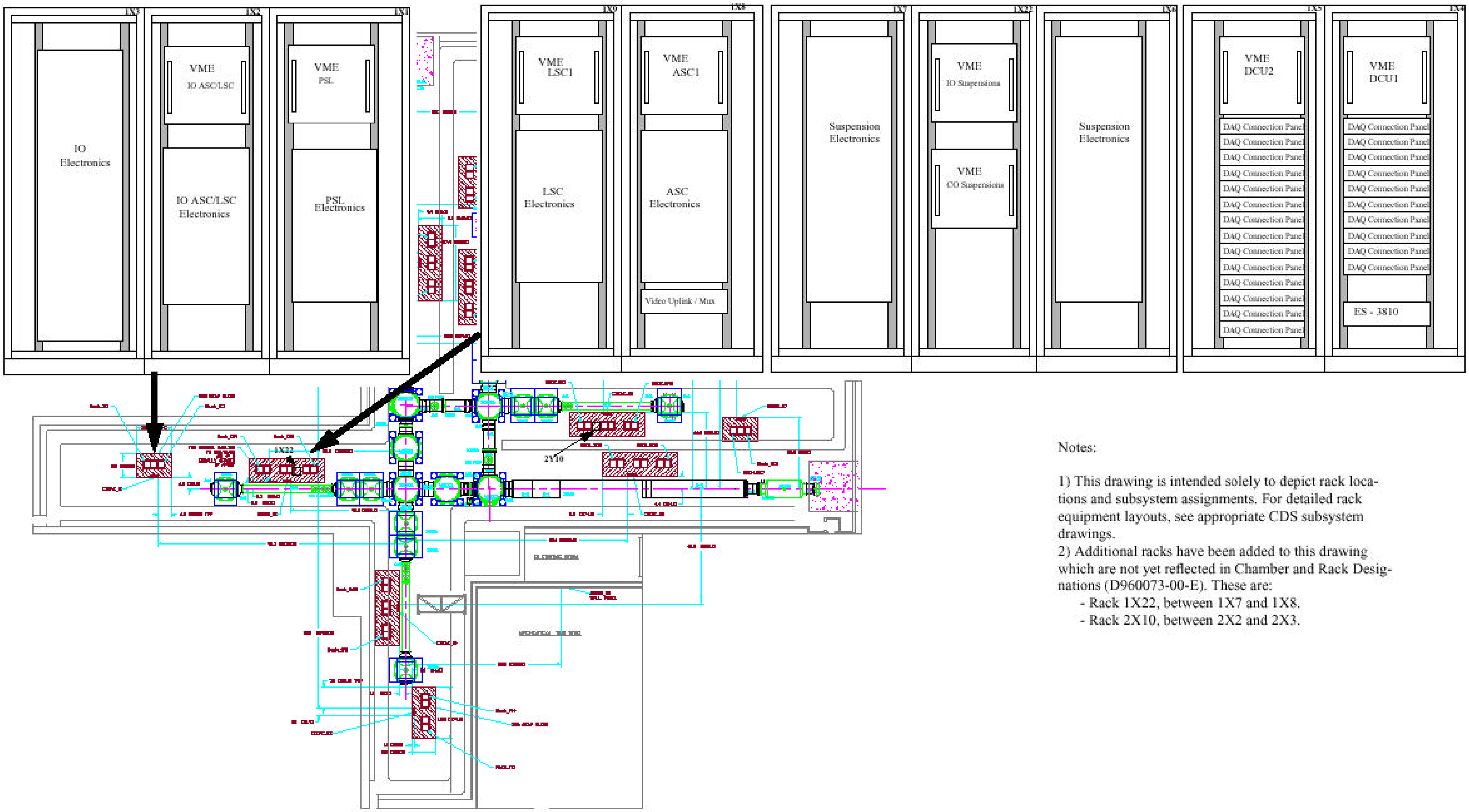
Chan	Name	Rate
00	H0:PEM-BSC5_ACCX	2048
01	H0:PEM-BSC5_ACCY	2048
02	H0:PEM-BSC5_ACCZ	2048
03	H0:PEM-BSC5_MIC	2048
04	H2:SEI-BSC5_FINE1	256
05	H2:SEI-BSC5_FINE2	256
06	H0:GDS-MX_TO1	16384
07	H0:GDS-MX_TO2	2048
08	H0:GDS-MX_TO3	2048
09	H2:LSC-ETMX_CAL	16384
10	H0:PEM-MX_TILTX	256
11	H0:PEM-MX_TILTY	256
12	H0:PEM-MX_SEISX	256
13	H0:PEM-MX_SEISY	256
14	H0:PEM-MX_SEISZ	256
15	H0:PEM-MX_TEMP2	16
16	H2:-SUS-BSC5_SENSOR_SIDE	256
17		
18	H2:SUS-BSC5_COIL_UL	2048
19	H2:SUS-BSC5_COIL_LL	2048
20	H2:-SUS-BSC5_COIL_UR	2048
21	H2:-SUS-BSC5_COIL_LR	2048
22	H2:-SUS-BSC5_COIL_SIDE	2048
23	H2:-SUS-BSC5_COIL_SUM	16384
24	H2:SUS-BSC5_SENSOR_UL	256
25	H2:SUS-BSC5_SENSOR_LL	256
26	H2:-SUS-BSC5_SENSOR_UR	256
27	H2:-SUS-BSC5_SENSOR_LR	256
28		
29		
30	H2:GDS-MX_RAMP3	16384
31	H2:GDS-MX_TRIG4	16384
	TOTAL (BTYES/SEC)	215056



DAQS crates for one IFO



Racks and racks of electronics



Notes:

1) This drawing is intended solely to depict rack locations and subsystem assignments. For detailed rack equipment layouts, see appropriate CDS subsystem drawings.
2) Additional racks have been added to this drawing which are not yet reflected in Chamber and Rack Designations (D960073-00-E). These are:
- Rack 1X22, between 1X7 and 1X8.
- Rack 2X10, between 2X2 and 2X3.

DAQS data channels and rates

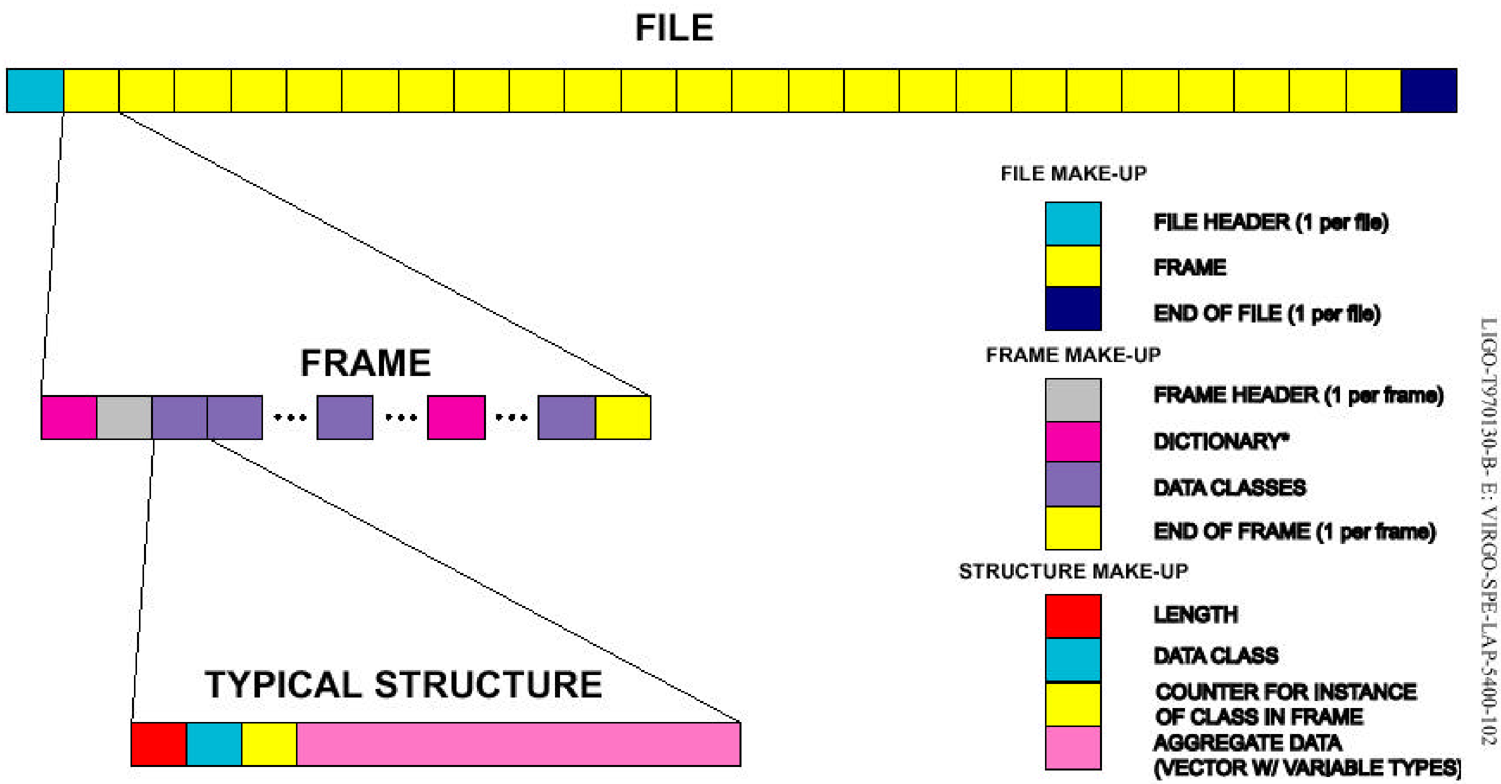
- Each IFO has dozens of fast (16 kHz) and hundreds of slow (< 1 kHz) channels; equivalent of ~ 150 fast channels/IFO.
- (16 kHz) × (2 bytes) × (3 IFOs) × (150 ch/IFO) × (3×10^7 sec/year) × (2 years) × (50% duty cycle) = 500 Tbytes!
- Store full data stream on disk for ~ 1 day.
- Archive 10% of data to tape: 50 Tbytes!
- GW stream alone, decimated to 1 kHz: 200 GB
- Data stored in Frames and in Meta-Database

System	*DAQS Network*		*Data Storage*	
	Channels	*Rate (MByte/sec)*	*Channels*	*Rate (MByte/sec)*
LHO-4K	510	4.22	300	1.88
LHO-2K	548	4.37	332	1.99
LHO-PEM	204	0.89	204	0.89
LHO-VAC	500	0.01	500	0.01
LHO-GDS	133	2.45		
LLO-4K	515	4.22	305	1.89
LLO-PEM	95	0.46	95	0.46
LLO-VAC	300	0.01	300	0.01
LLO-GDS	76	0.89		

Frames

- Frame is a common data format developed and adopted by the LIGO and VIRGO gravitational wave detectors.
- The predominant type of data stored in Frames is time series data of arbitrary duration. It is possible, however, to encapsulate in Frames other types of data, e.g., spectra, lists, vectors or arrays, etc. A Frame contains data for a specified epic in time.
- Frame Class Library (fcl) is a set of *c*++ OO-tools for creating, manipulating, and reading frames.

Frame structure



* Dictionary structure behavior is unique in that:
1. It preceeds header for first frame of file;
2. Dictionary is built up incrementally as addititional structures are incorporated into frame
3. It is valid for entire file (persistent)

Frame structures