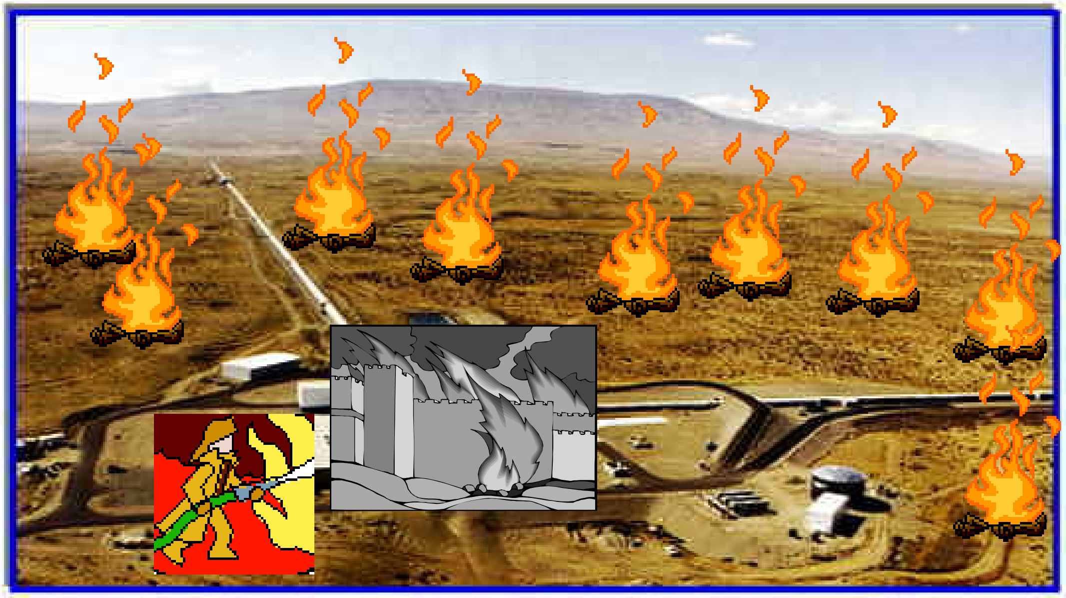
# Physics of LIGO
# Lecture 4

- LIGO II
- LIGO I sub-systems



Transparencies will be posted at:
http://www.ligo.caltech.edu/~ajw
And in the DCC!

# LIGO I schedule

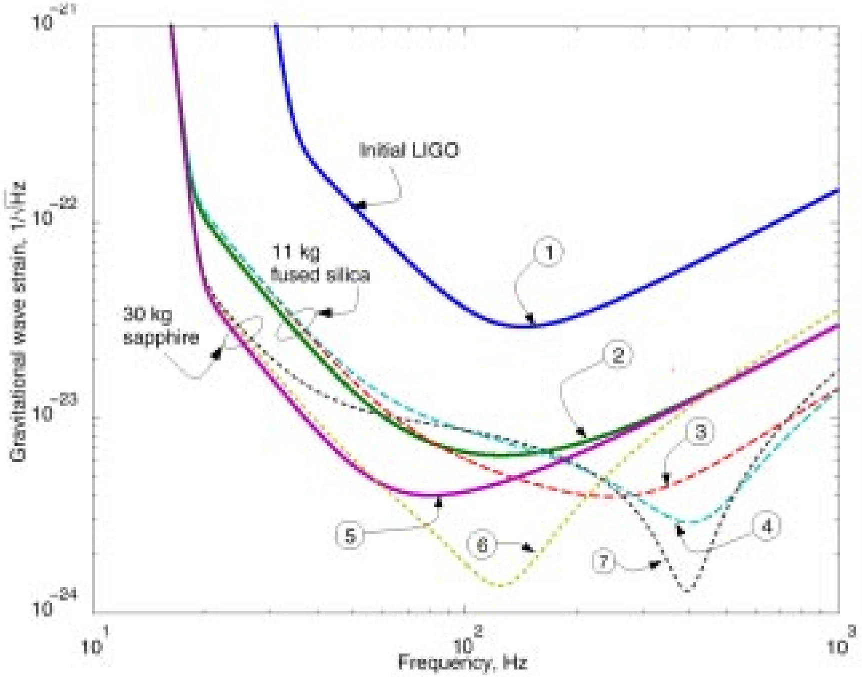
| | |
|---|---|
| 1995 | NSF Funding secured ($360M) |
| 1996 | Construction Underway (mostly civil) |
| 1997 | Facility Construction (vacuum system) |
| 1998 | Interferometer Construction (complete facilities) |
| 1999 | Construction Complete (interferometers in vacuum) |
| 2000 | Detector Installation (commissioning subsystems) |
| 2001 | Commission Interferometers (first coincidences) |
| 2002 | Sensitivity studies (initiate LIGO I Science Run) |
| 2003+ | LIGO I data run (one year integrated data at $h \sim 10^{-21}$) |
| | |
| 2005 | Begin LIGO II installation |

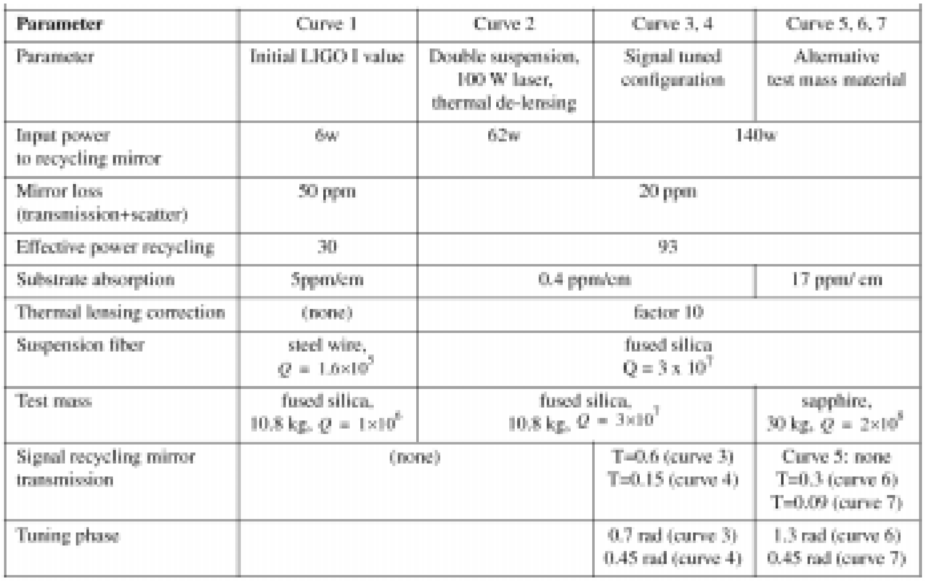
# LIGO II
## *incremental improvements*

- Reduce shot noise: higher power CW-laser: 12 watts ⇒120 watts
- Reduce shot noise: Advanced optical configuration: signal recycling mirror (7th suspended optic) to tune shot-noise response in frequency
- To handle thermal distortions due to beam heating: advanced mirror materials, coatings, thermal de-lensing compensation (heating mirror at edges)
- Reduce seismic noise: Advanced (active) seismic isolation. Seismic wall moved from 40 Hz ⇒ < 10 Hz.
- Reduce seismic and suspension noise: Multiple pendulum suspensions to filter environmental noise in stages.
- Reduce suspension noise: Fused silica fibers, silica welds.
- Reduce test mass thermal noise: Last pendulum stage (test mass) is controlled via electrostatic forces, coupled capacitively (no magnets).
- Reduce test mass thermal noise: High-Q material (sapphire).

# LIGO II

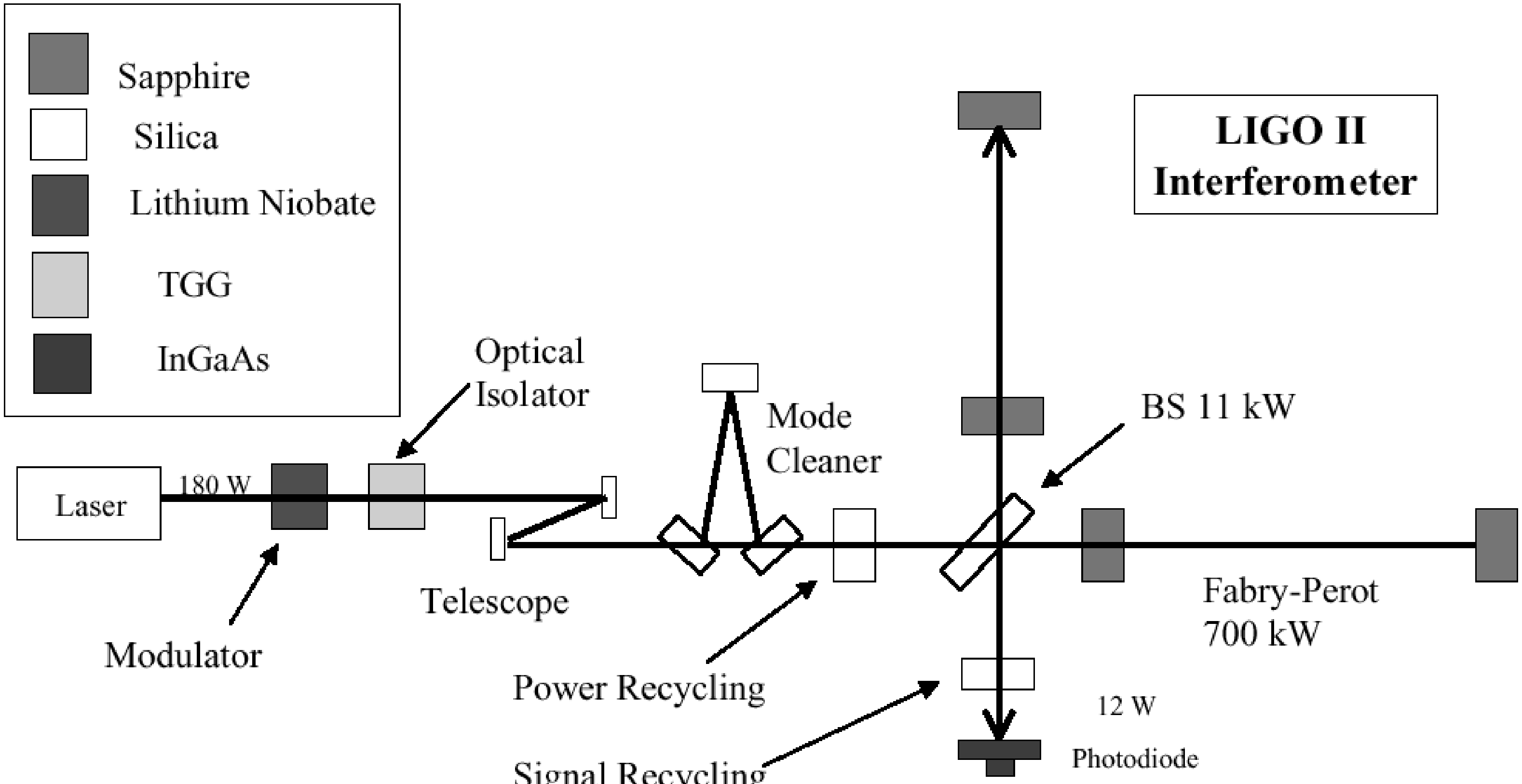
## *predicted noise curves*





| **Parameter** | Curve 1 | Curve 2 | Curve 3, 4 | Curve 5, 6, 7 |
|---|---|---|---|---|
| Parameter | Initial LIGO I value | Double suspension,<br>100 W laser,<br>thermal de-lensing | Signal tuned configuration | Alternative test mass material |
| Input power to recycling mirror | 6w | 62w | 140w | |
| Mirror loss (transmission+scatter) | 50 ppm | 20 ppm | | |
| Effective power recycling | 30 | 93 | | |
| Substrate absorption | 5ppm/cm | 0.4 ppm/cm | | 17 ppm/ cm |
| Thermal lensing correction | (none) | factor 10 | | |
| Suspension fiber | steel wire,<br>$Q = 1.6\times10^{3}$ | fused silica<br>$Q = 3 \times 10^{7}$ | | |
| Test mass | fused silica,<br>10.8 kg, $Q = 1\times10^{6}$ | fused silica,<br>10.8 kg, $Q = 3\times10^{7}$ | | sapphire,<br>30 kg, $Q = 2\times10^{8}$ |
| Signal recycling mirror transmission | (none) | | T=0.6 (curve 3)<br>T=0.15 (curve 4) | Curve 5: none<br>T=0.3 (curve 6)<br>T=0.09 (curve 7) |
| Tuning phase | | | 0.7 rad (curve 3)<br>0.45 rad (curve 4) | 1.3 rad (curve 6)<br>0.45 rad (curve 7) |

# LIGO II Optics



Sapphire
Silica
Lithium Niobate
TGG
InGaAs

**LIGO II Interferometer**

Laser
180 W
Modulator
Optical Isolator
Telescope
Mode Cleaner
Power Recycling
Signal Recycling
BS 11 kW
Fabry-Perot 700 kW
12 W
Photodiode

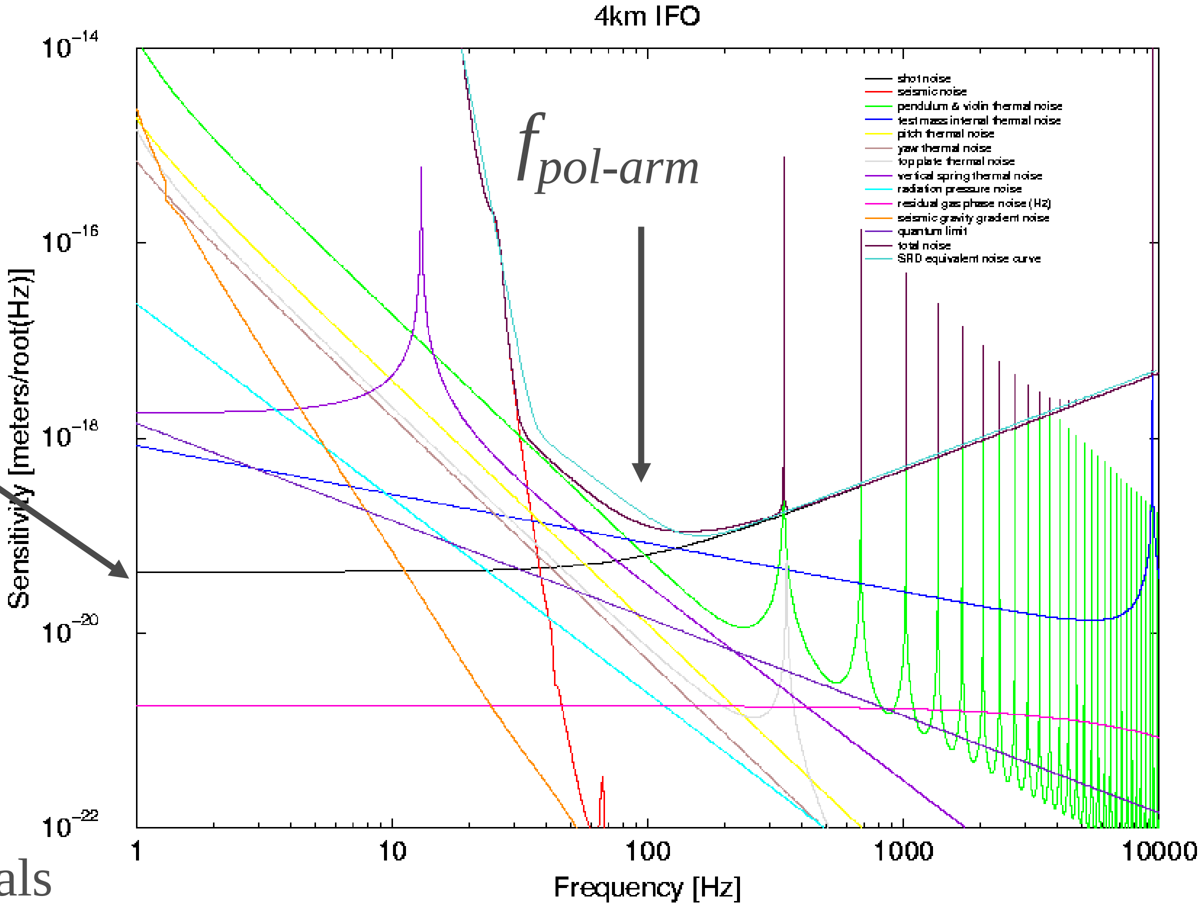
# Signal recycling, RSE

- Problem: the transmissivity of the ITM ($T_{ITM}$) governs *both* the arm cavity gain (power available for sensing $\Delta L$ at $f=0$) *and* the light storage time / cavity pole $f_{arm}$
- Need the ability to optimize these independently
- The shot noise frequency dependence can be optimized (for fixed laser power) by adding one (or more) suspended optics at the dark port (signal recycling or RSE)
- This permits independent control of cavity gain for the carrier and for the *signal sidebands* (audio frequencies of GW signal)
- Combine power recycling (PR) and signal recycling (SR):
  Dual recycling (DR)

# Arm cavity parameters and LIGO sensitivity

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

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



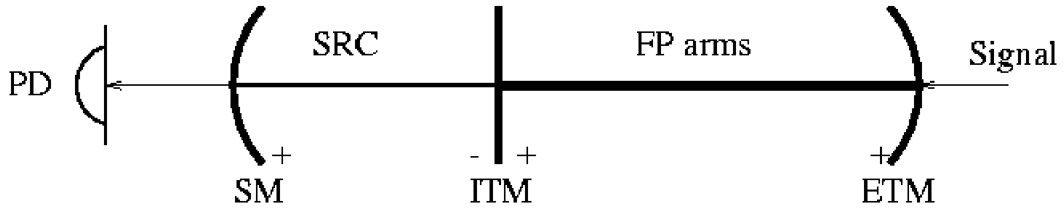
Given other noise sources (seismic, thermal), choose $r_{ITM}$ to optimize Sensitivity to binary inspirals

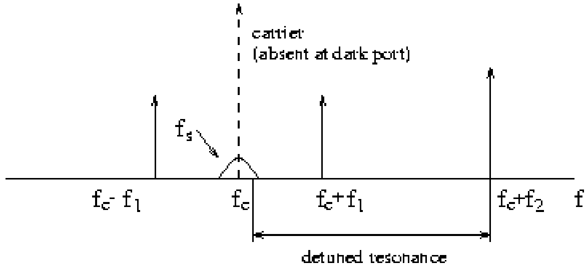
# Coupled cavity response

Simplified analysis:

- fold beam splitter + arms together
- model as a single FP cavity
- adding SM produces a coupled cavity
- ITM+SM forms a *compound mirror*, with reflectivity

$$r_{cm} = r_{ITM} - \frac{t_{ITM}^2 r_{SM} e^{-i\phi}}{1 - r_{ITM} r_{SM} e^{-i\phi}} \quad \text{With} \quad \phi = 2kl_s = 4\pi l_s(f_{carr}+f_{sig})/c$$





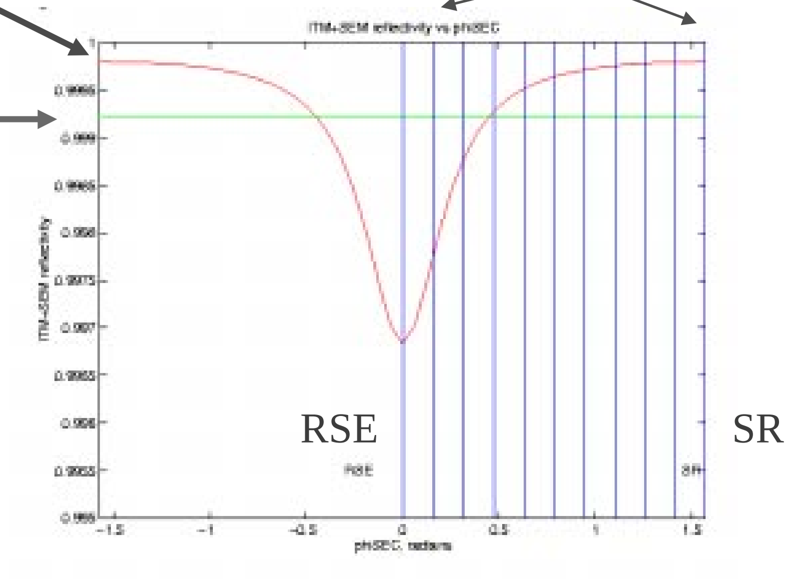
# Tuning the signal response

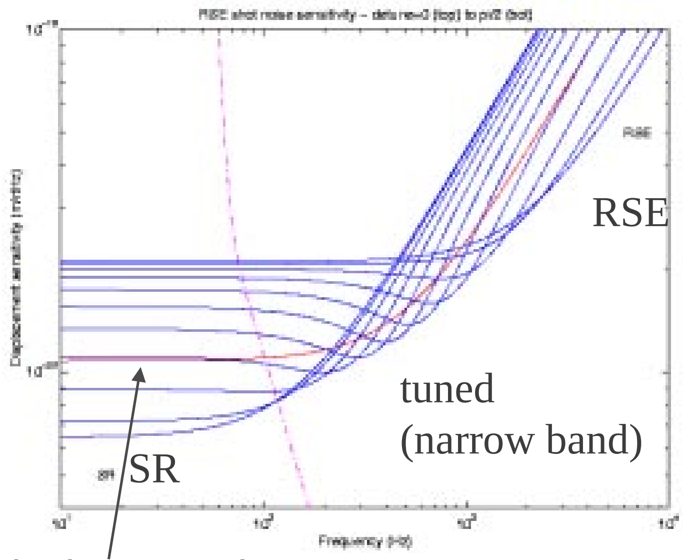
By choosing the phase advance of the signal ($f_{carr}+f_{sig}$) in the signal recycling cavity, can get longer (SR) or shorter (RSE) storage of the signal in the arms:

$$\phi = 2kl_s = 4\pi l_s(f_{carr}+f_{sig})/c$$

$r_{CC}$

$r_{ITM}$

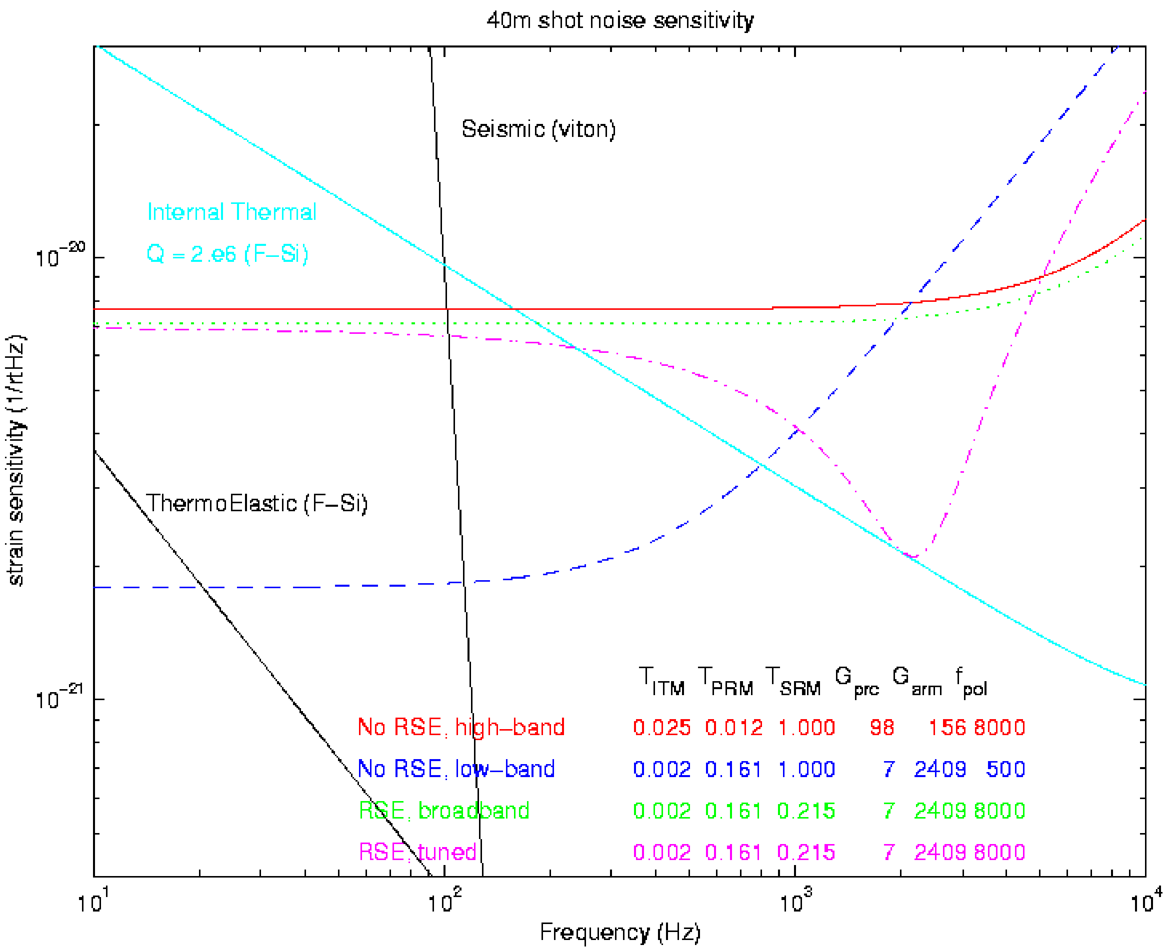




The red curve corresponds to $r = r_{ITM}$, ie, no SR mirror

# Using DR to optimize sensitivity

Now we can independently tune $h_{DC}$ and $f_{polarm}$ to optimize sensitivity (eg, hug the thermal noise curve)

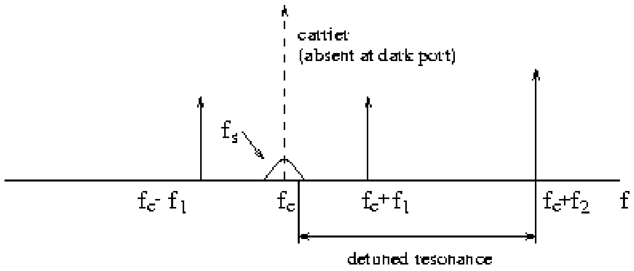


# Controlling the signal mirror

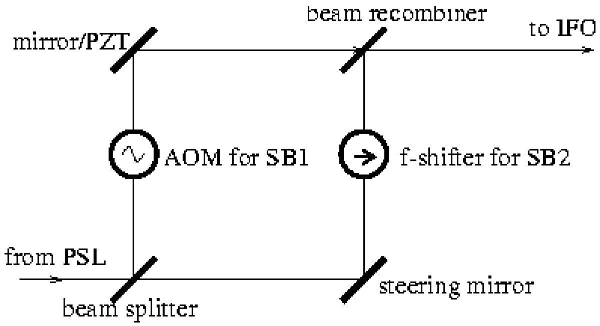
- The other 6 mirrors (LIGO-I configuration) are controlled by reflection-locking: beat carrier (resonant in all cavities) off of RF sidebands
- Here, with no GW, there is no carrier in signal cavity!
- One solution: add another RF sideband; make one RF sideband resonant in signal cavity, the other isn't; then, reflection locking will work.
- Both RF sidebands must be resonant in PRC; and both must pass through the MC
- Want to change the tune $\phi = 2kl_s$ at will
- This is a difficult, constrained problem – no good (simple) solution yet!

# RSE control scheme

- Simple scheme (Jim Mason):
  single sideband (RF2) at $3f_{RF1}$



- applied via frontal modulation with input M-Z IFO



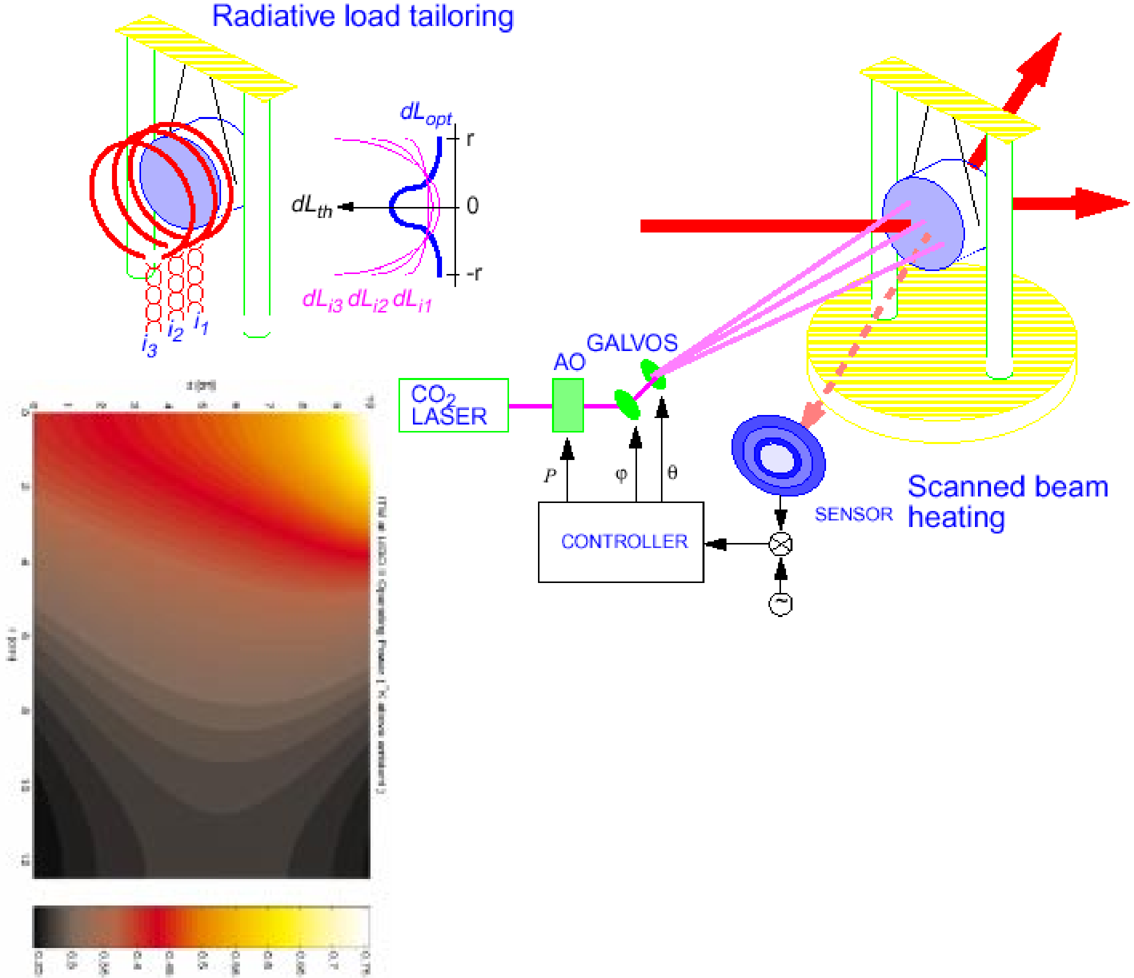
Resonance conditions:

- Carrier resonant in ARMs, PRC
- Carrier resonant (broadbanded) or de-tuned in SRC
- RF1 resonant in PRC
- RF2 resonant in PRC, SRC

# Thermal compensation (de-lensing) methods

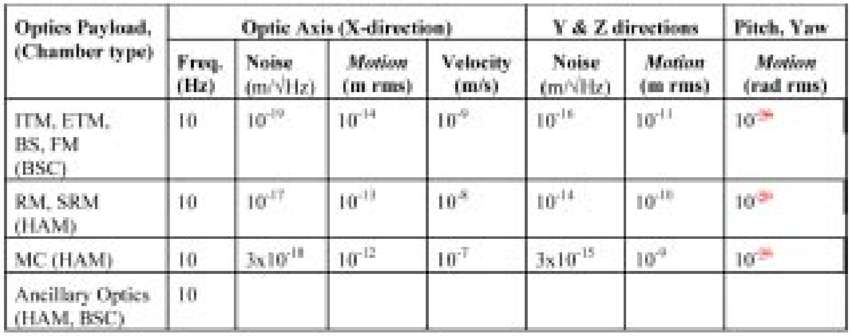
- Beam heating at center of optic distorts the optic due to thermal expansion, changing ROC, index of refraction, etc.

- Compensate by heating the optic from the circumference in, to give uniform and constant-in-time thermal loading as the IFO is operated.

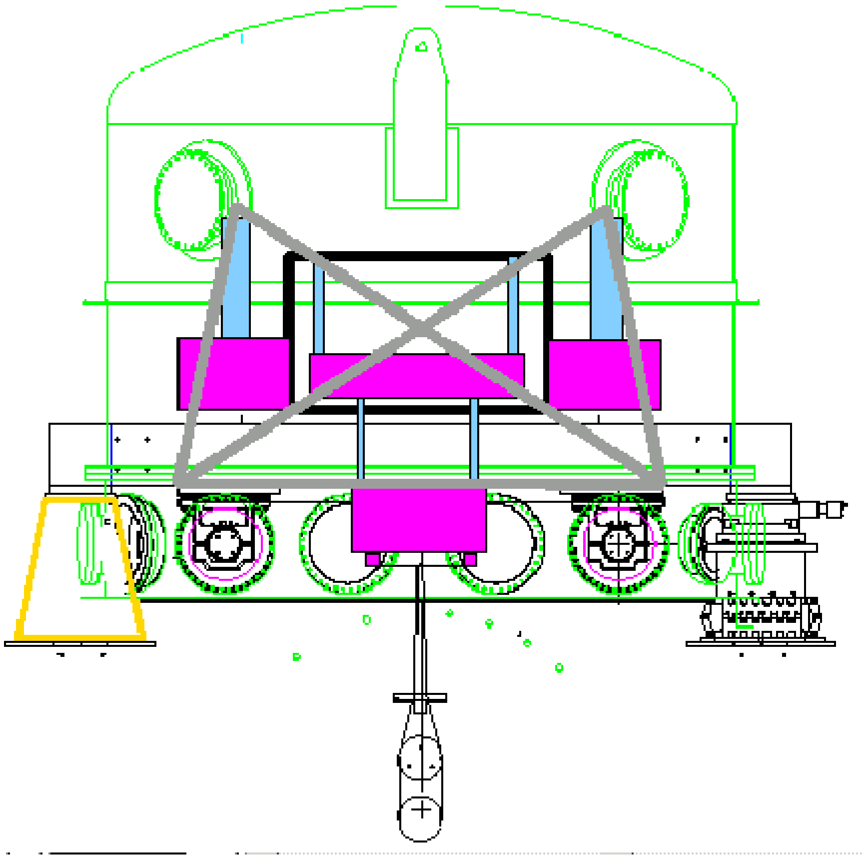


# LIGO II Active seismic isolation and multiple pendulum suspension

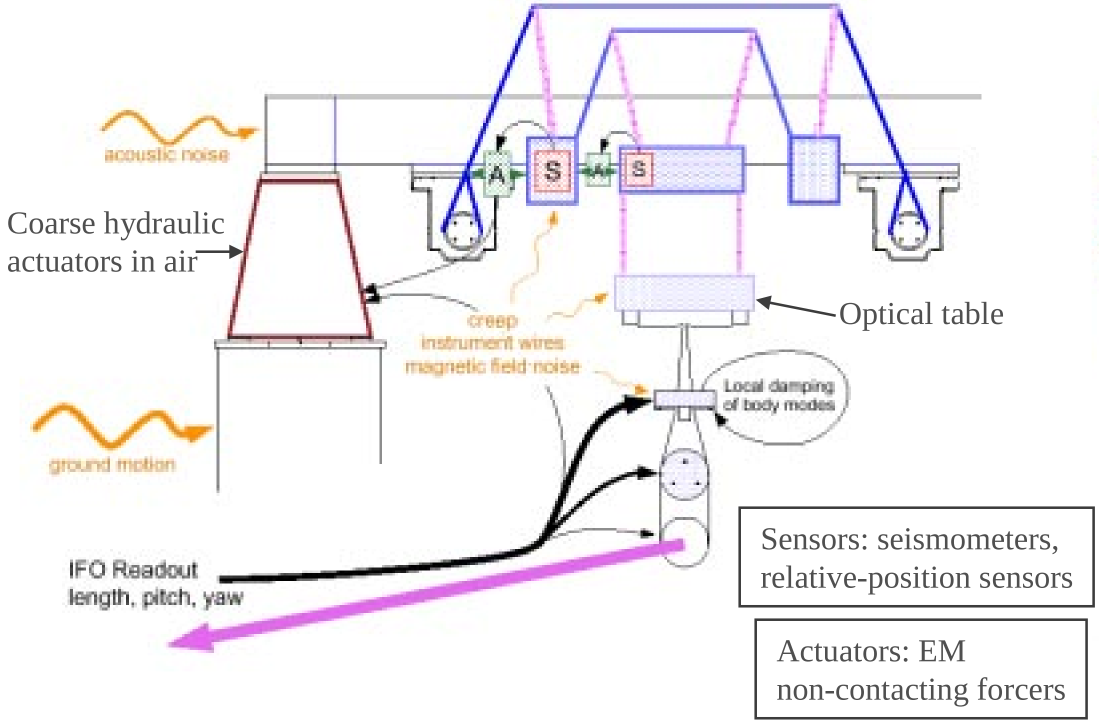
- Must support LIGO test mass optic at the beamline.
- Must fit inside existing vacuum chambers, and be fully vacuum compatible.
- Must provide full control system.
- Must satisfy specs:



| Optics Payload, (Chamber type) | Optic Axis (X-direction) | | | | Y & Z directions | | Pitch, Yaw |
|---|---|---|---|---|---|---|---|
| | Freq. (Hz) | Noise (m/√Hz) | *Motion* (m rms) | Velocity (m/s) | Noise (m/√Hz) | *Motion* (m rms) | *Motion* (rad rms) |
| ITM, ETM, BS, FM (BSC) | 10 | $10^{-19}$ | $10^{-14}$ | $10^{-9}$ | $10^{-16}$ | $10^{-11}$ | [illegible] |
| RM, SRM (HAM) | 10 | $10^{-17}$ | $10^{-13}$ | $10^{-8}$ | $10^{-14}$ | $10^{-10}$ | [illegible] |
| MC (HAM) | 10 | $3x10^{-18}$ | $10^{-12}$ | $10^{-7}$ | $3x10^{-15}$ | $10^{-9}$ | [illegible] |
| Ancillary Optics (HAM, BSC) | 10 | | | | | | |



# Active control of SEI system

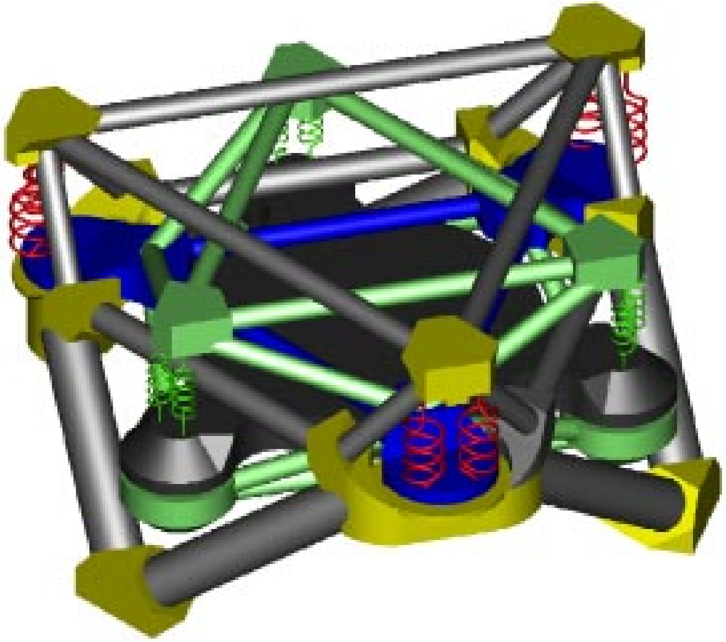


Coarse hydraulic
actuators in air

Optical table

Sensors: seismometers,
relative-position sensors

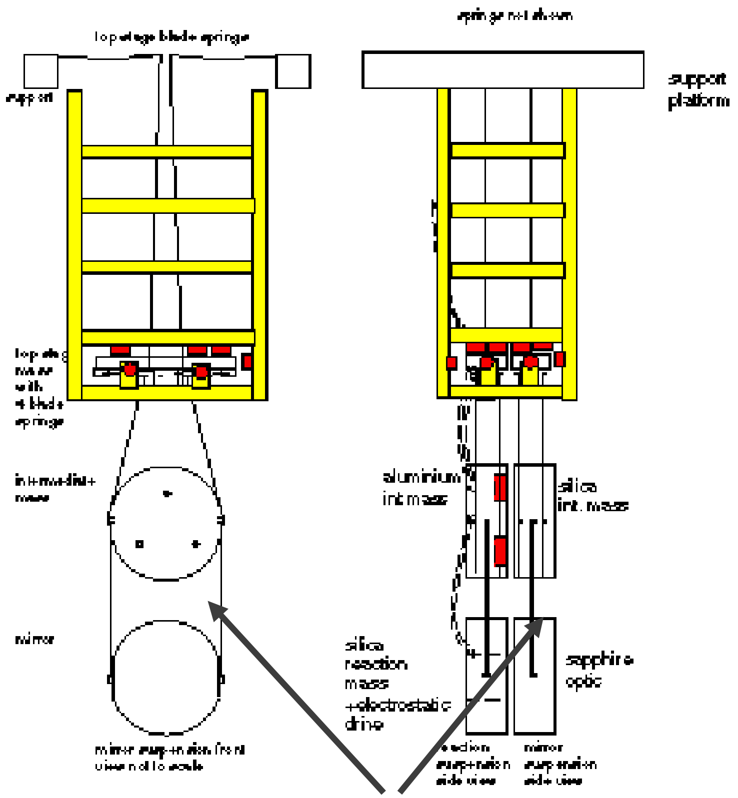
Actuators: EM
non-contacting forcers



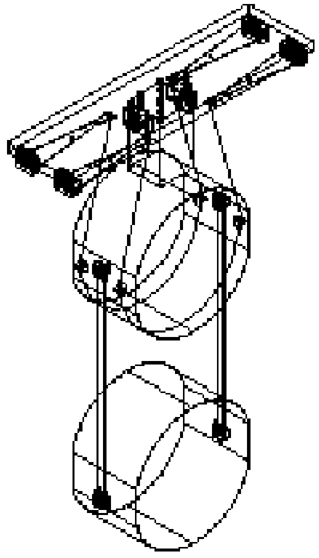
Two active stages: cages, masses, springs, S/A pairs.
All DOF under active control.

# GEO multiple pendulum design

- 3 or 4 pendulum stages; each provides $1 / f^2$ filtering for $f > f_0$
- Top stage has 6 OSEMs for 6-dof control (“marionetta”), relative to support cage.
- Normal modes of the multiple pendulum (~24) must not have nodes at the top, so they can be controlled from the top.
- Blade springs at the very top provide tuned vertical isolation.
- Lower stages must control w.r.t. stage above it; so the actuators must push against a “reaction mass” which is as quiet as the stage above it
- lowest stage (test mass optic) is attached to stage above it with fused silica fibers.



Fused silica fibers

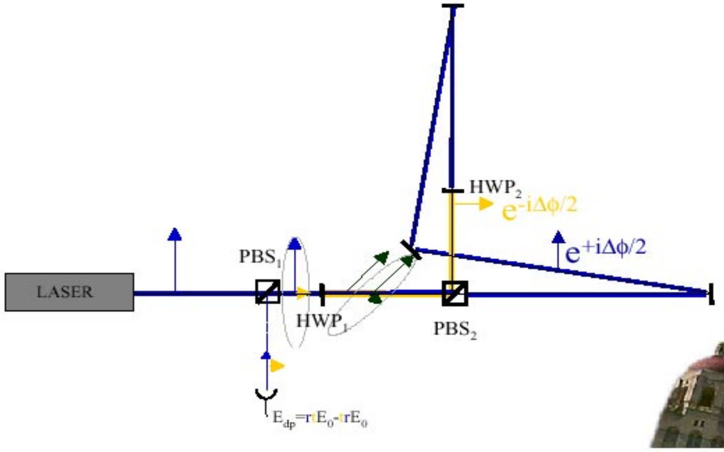


# LIGO III

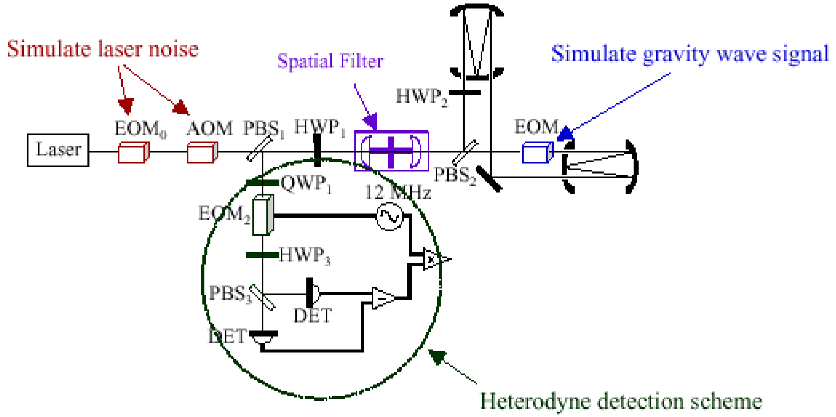
- More advanced optical design (Sagnac?)
- non-transmissive optics (Sagnac)
- quantum non-demolition?
- Photon drive?

# The polarization Sagnac IFO

- All reflective optics to minimize thermal distortions
- Common path for interfering beams
- Grating beam splitter (double-pass, to null dispersion)
- Delay line arms
- Heroic efforts to minimize noise due to scattered light
- Polarization allows the light to exit the IFO at the symmetric port of the beam splitter
- Many clever tricks to ensure robust control, low noise



THE Stanford GRAVITATIONAL WAVE GROUP



# Prototype IFOs

- **40 meter (Caltech)** :
  full engineering prototype for optical and control plant for LIGO II
- **Thermal Noise Interferometer (TNI, Caltech)** :
  measure thermal noise in LIGO II test masses
- **LIGO Advanced Systems Testbed IFO (LASTI, MIT)** :
  full-scale prototyping of LIGO II seismic isolation & suspensions
- **Engineering Test Facility (ETF, Stanford) :**
  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)
- Several table-top (non-suspended) IFOs for development of RSE/DR – Caltech (Jim Mason), UFla, ANU

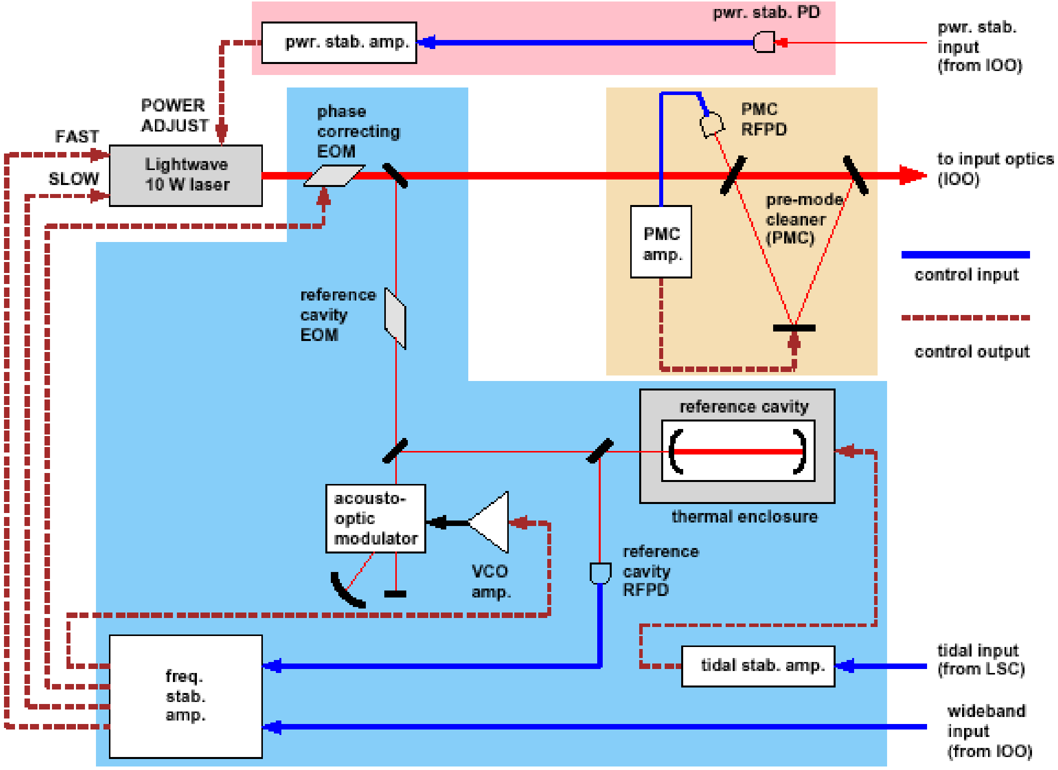
# LIGO Subsystems

- 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!

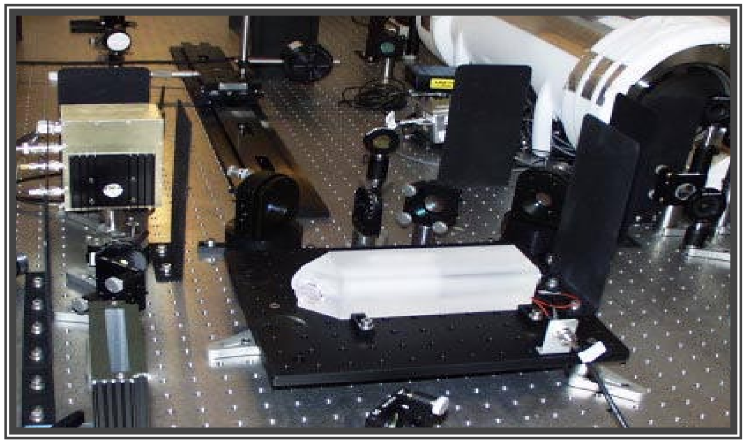
# Pre-Stablized Laser (PSL)

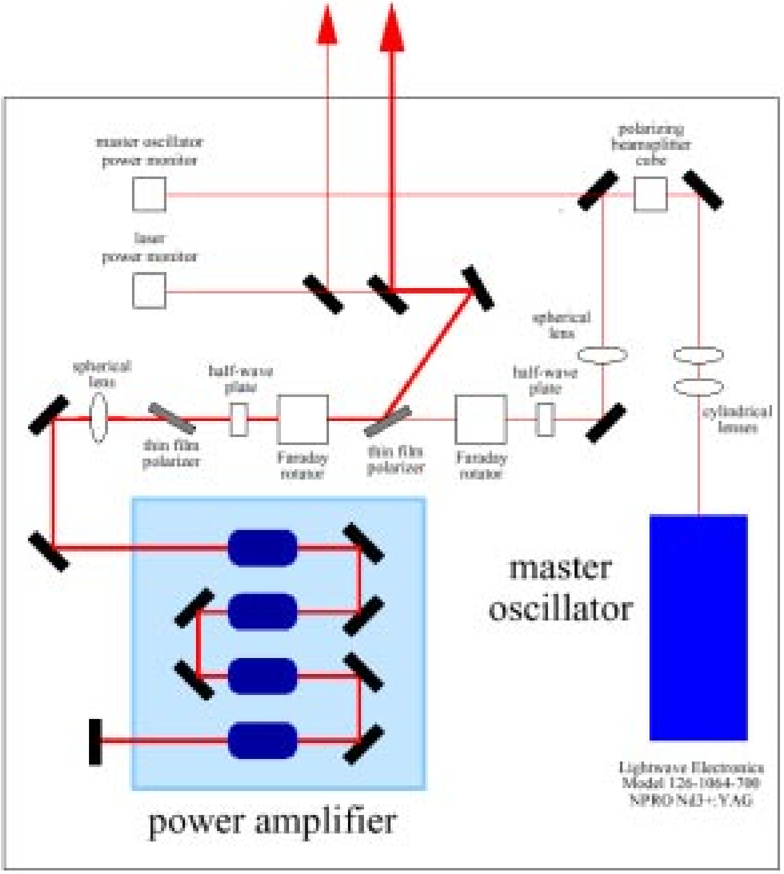
- Start with high-power (10watt) CW Nd:YAG IR (1.064 um) MOPA laser
- Frequency stabilization
  - (fast and slow)
- Power stabilization
- Transverse “mode cleaning”
- Phase correction



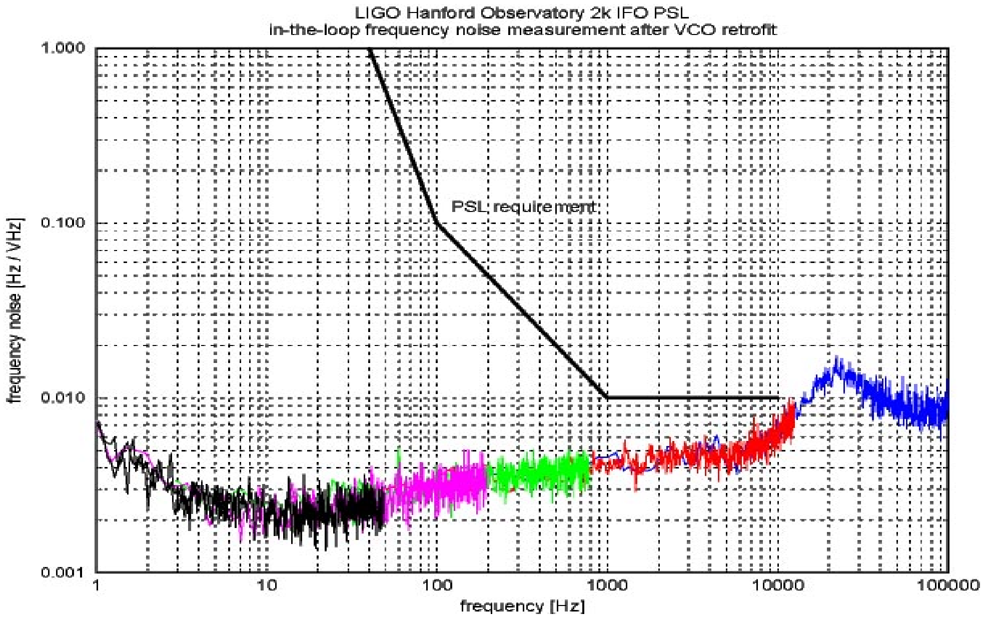
# Pre-stabilized laser (PSL)

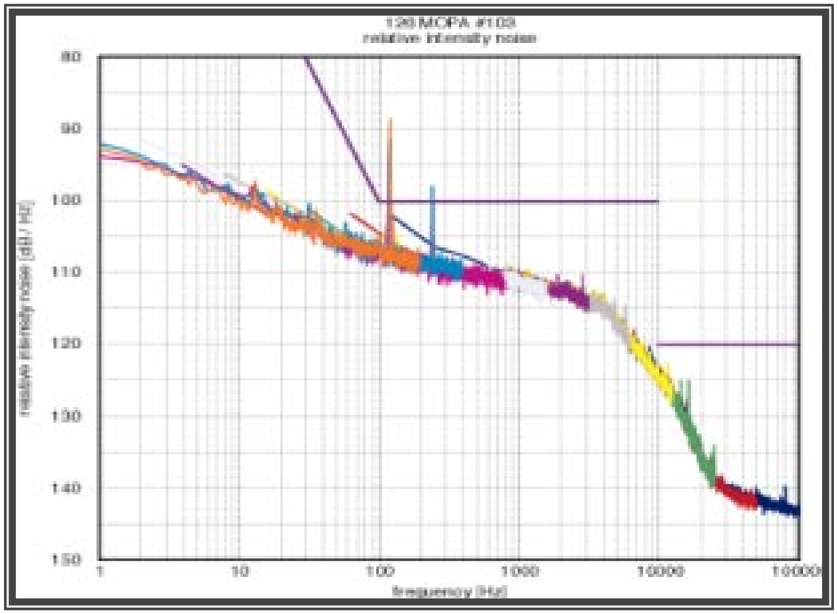
- Nd:YAG MOPA (Master Oscillator Power Amplifier)
- 1.064 µm
- Output power > 8W in TEM00 mode





# Laser noise pre-stablization

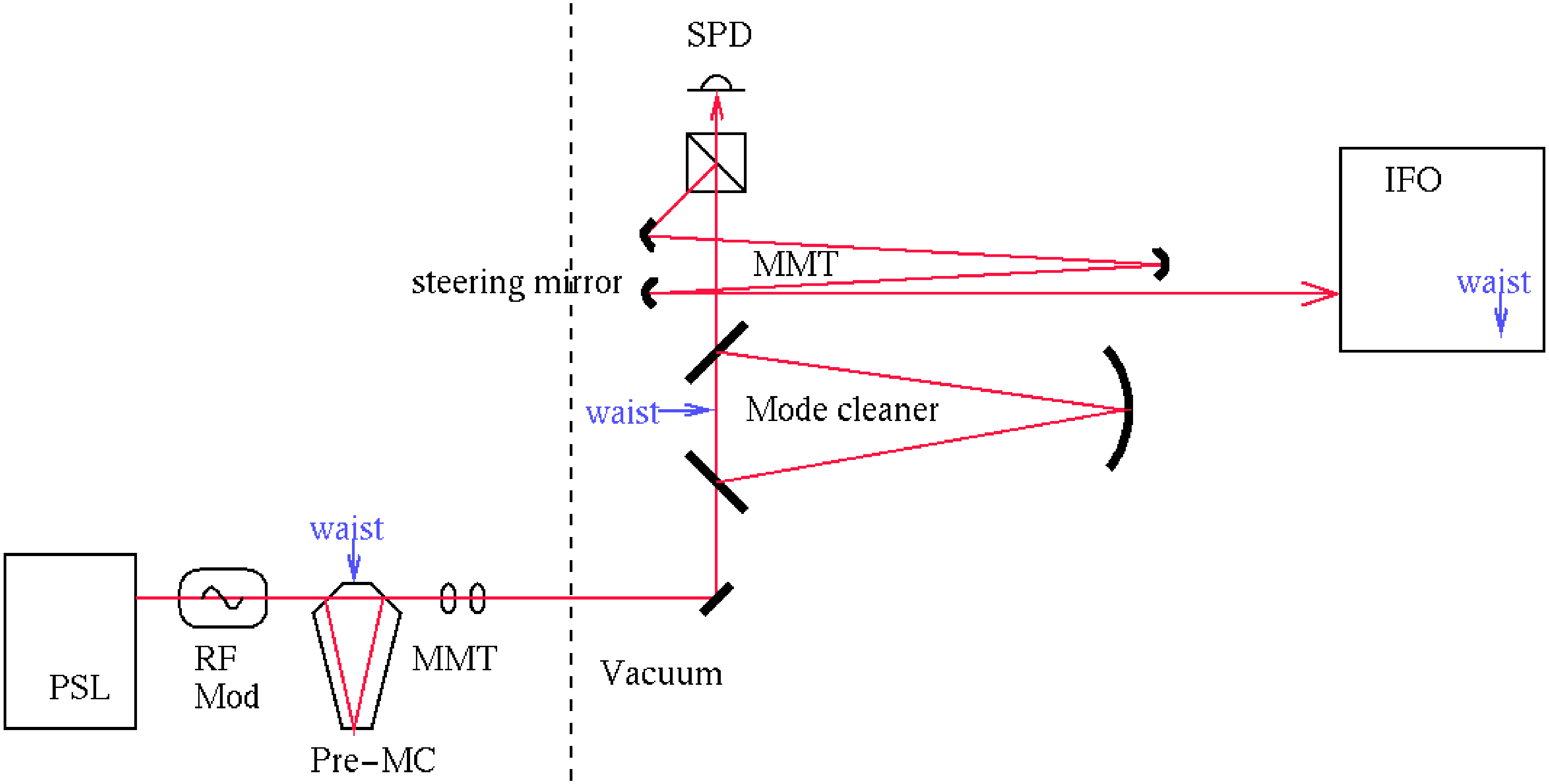




- **frequency noise:**
- $\delta\nu(f) < 10^{-2}\,\mathrm{Hz/Hz^{1/2}}$ 40Hz<f<10KHz

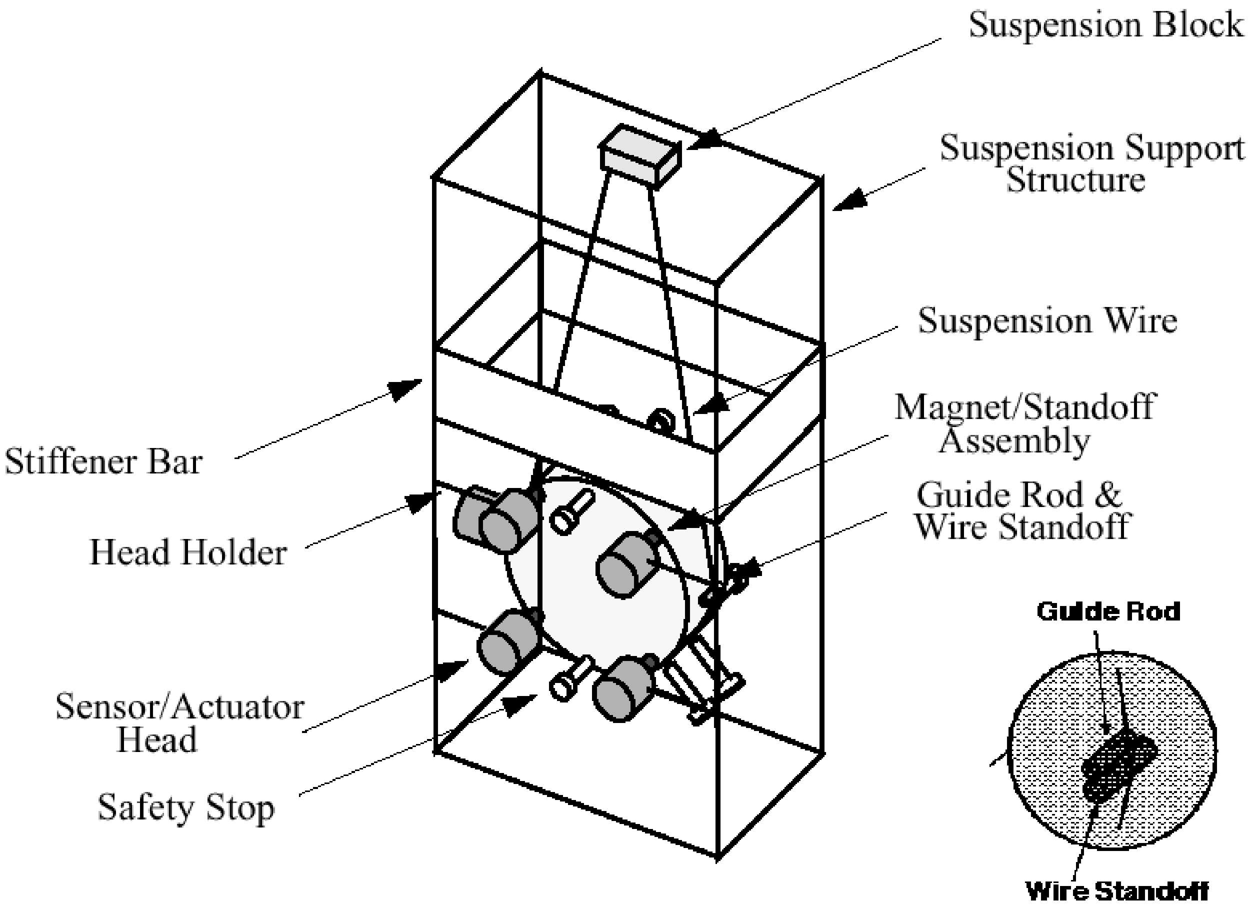
- **intensity noise**:
- $\delta I(f)/I < 10^{-6}/\mathrm{Hz}^{1/2}$, 40 Hz<f<10 KHz

# Input Optics (IOO)



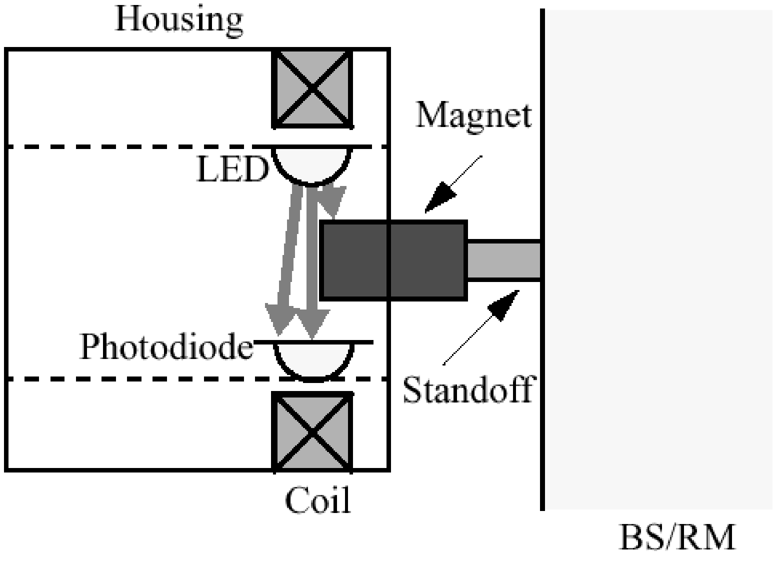
# LIGO I Suspensions

- 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



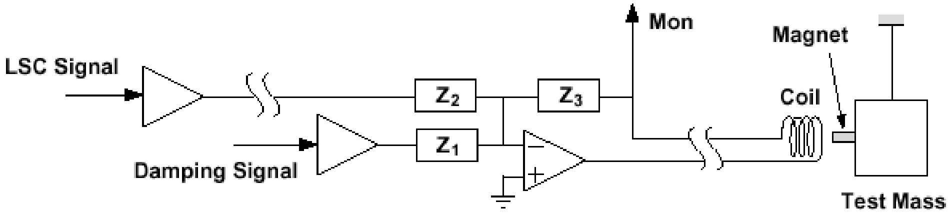
# OSEMs

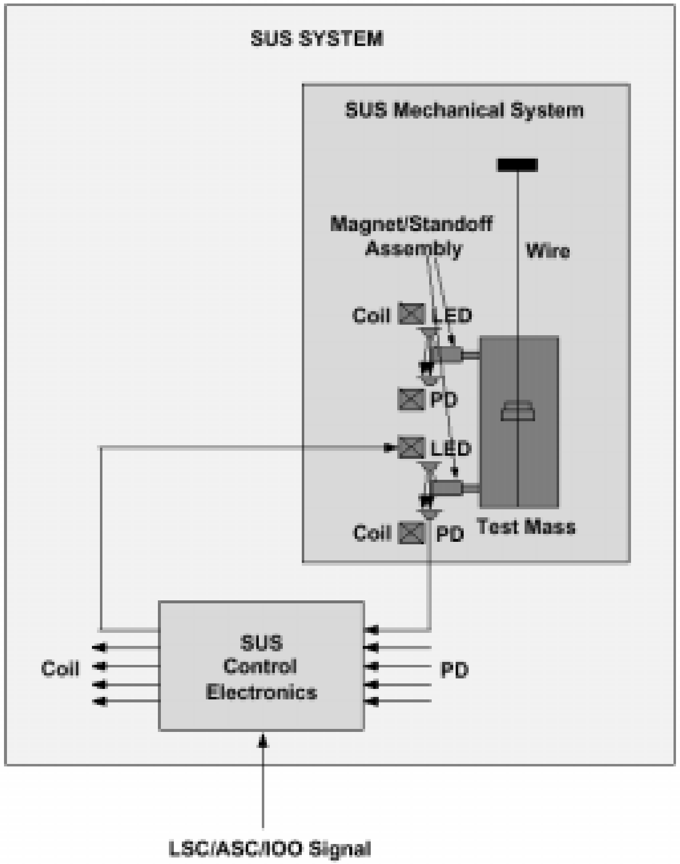
- Five magnets glued to fused Si optic
  - (this ruins the thermal noise properties of the optic – a big problem!)
- LED/PD pair senses position
- Coil pushes/pulls on magnet, against pendulum



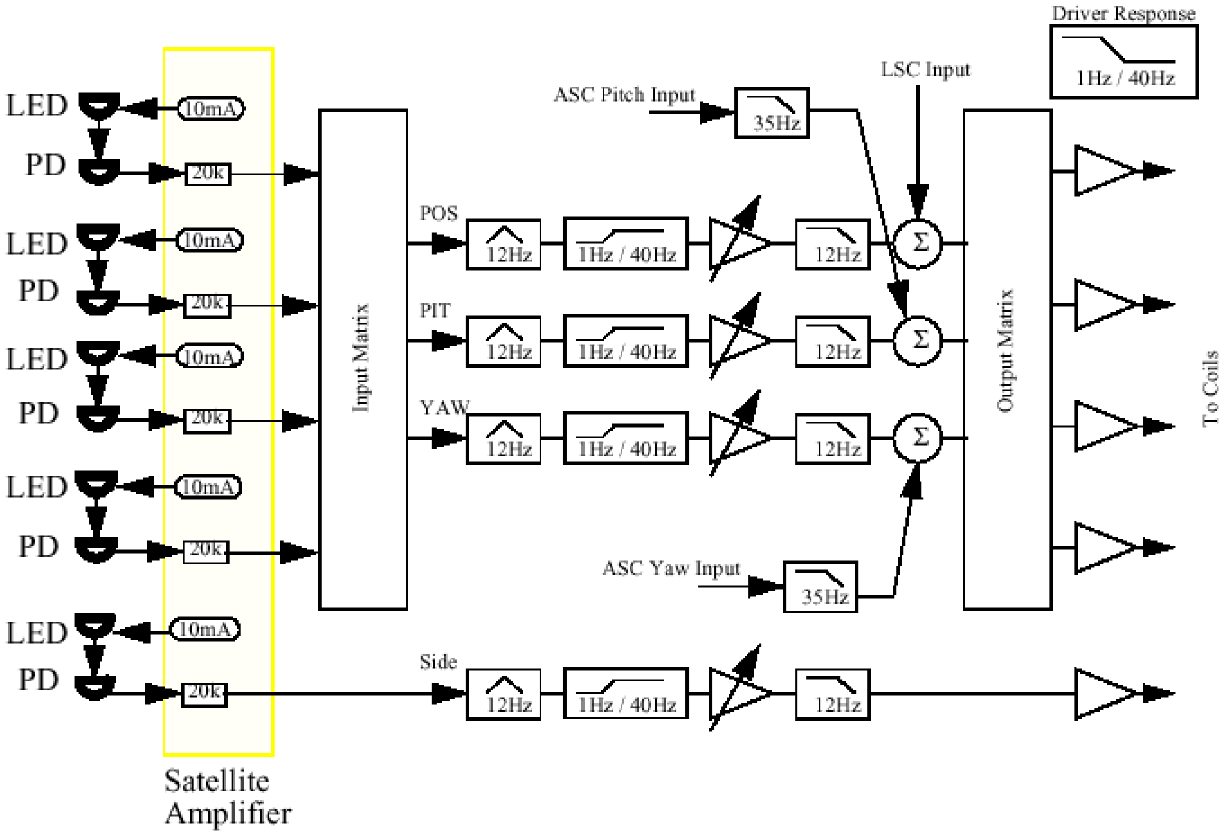
# Suspension control system

- 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)

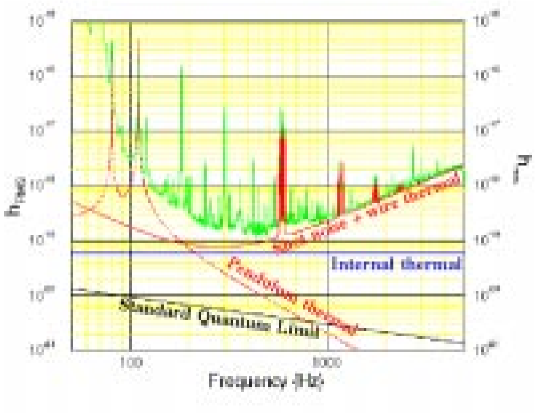


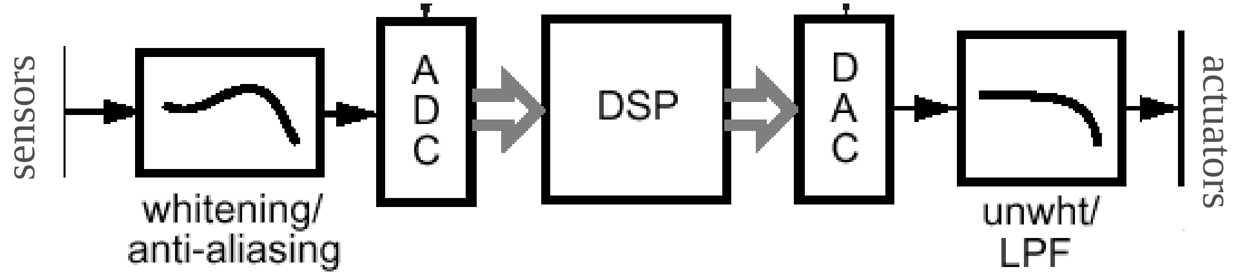
# Digital servo electronics chain

- **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.

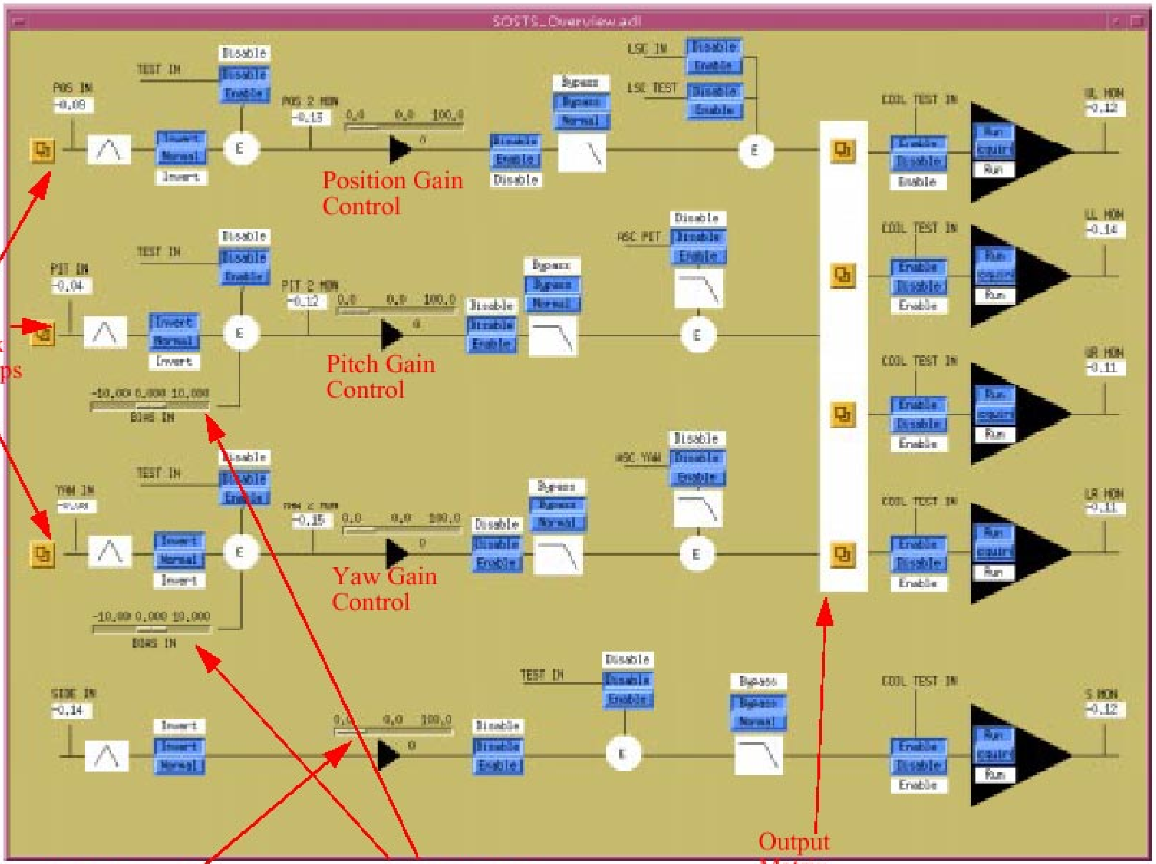
⇒Must whiten:  de-emphasize high-noise low-f part of data stream, emphasize higher-f signal

- **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



Position Gain Control

Pitch Gain Control

Yaw Gain Control

Input Matrix Pop Ups

Side Gain Control

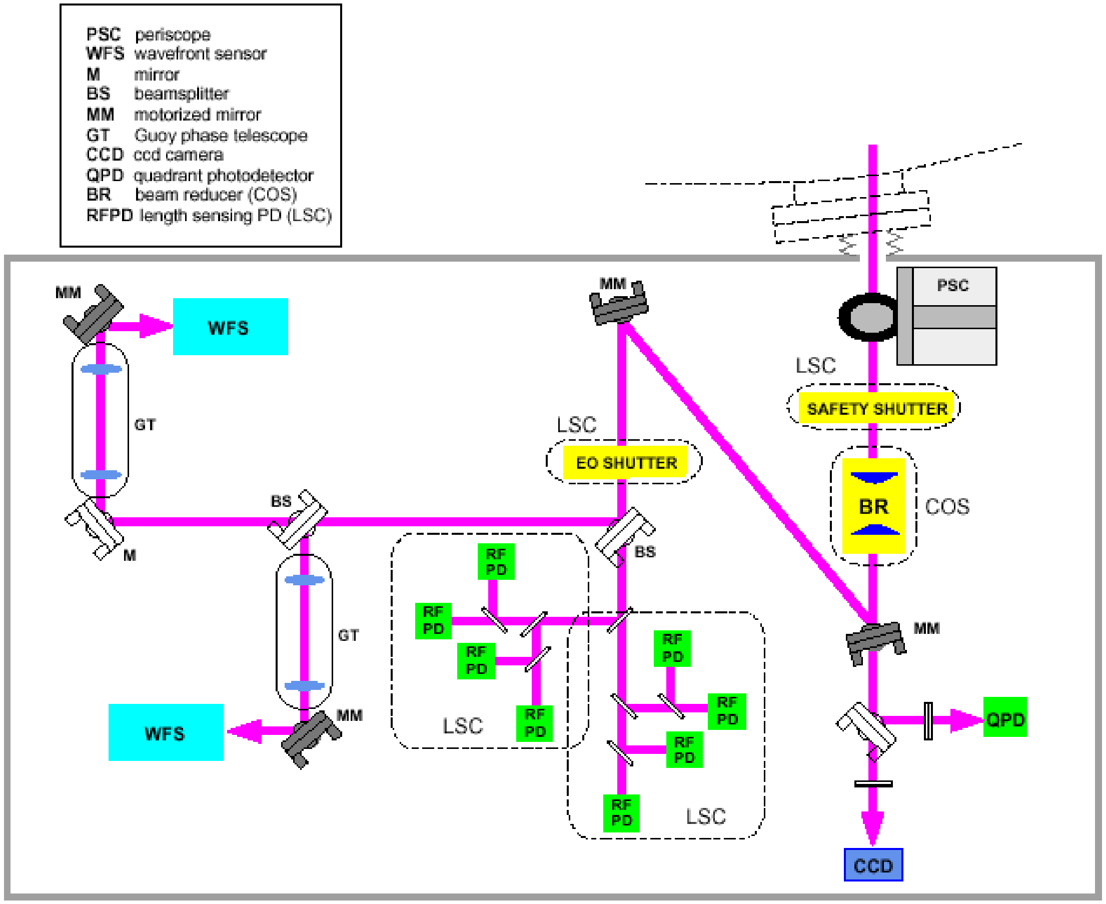
Pitch & Yaw Bias Adjust

Output Matrix Pop Ups

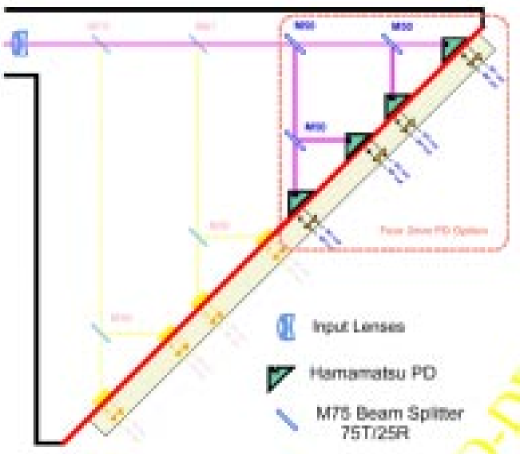
# Digital control, DAQS, EPICS

- 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!)



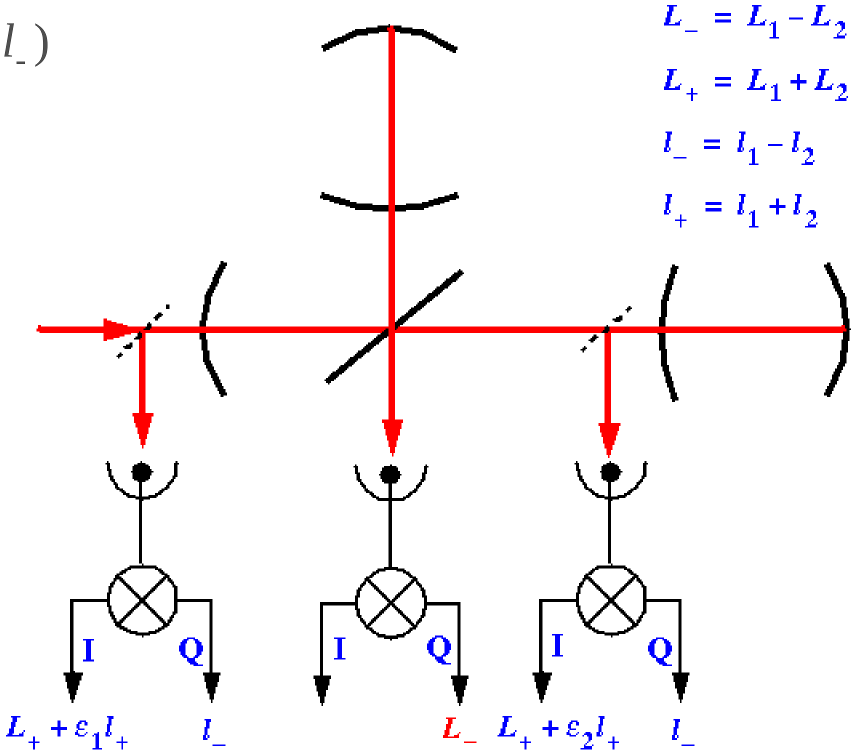
| | |
|---|---|
| **PSC** | periscope |
| **WFS** | wavefront sensor |
| **M** | mirror |
| **BS** | beamsplitter |
| **MM** | motorized mirror |
| **GT** | Guoy phase telescope |
| **CCD** | ccd camera |
| **QPD** | quadrant photodetector |
| **BR** | beam reducer (COS) |
| **RFPD** | length sensing PD (LSC) |



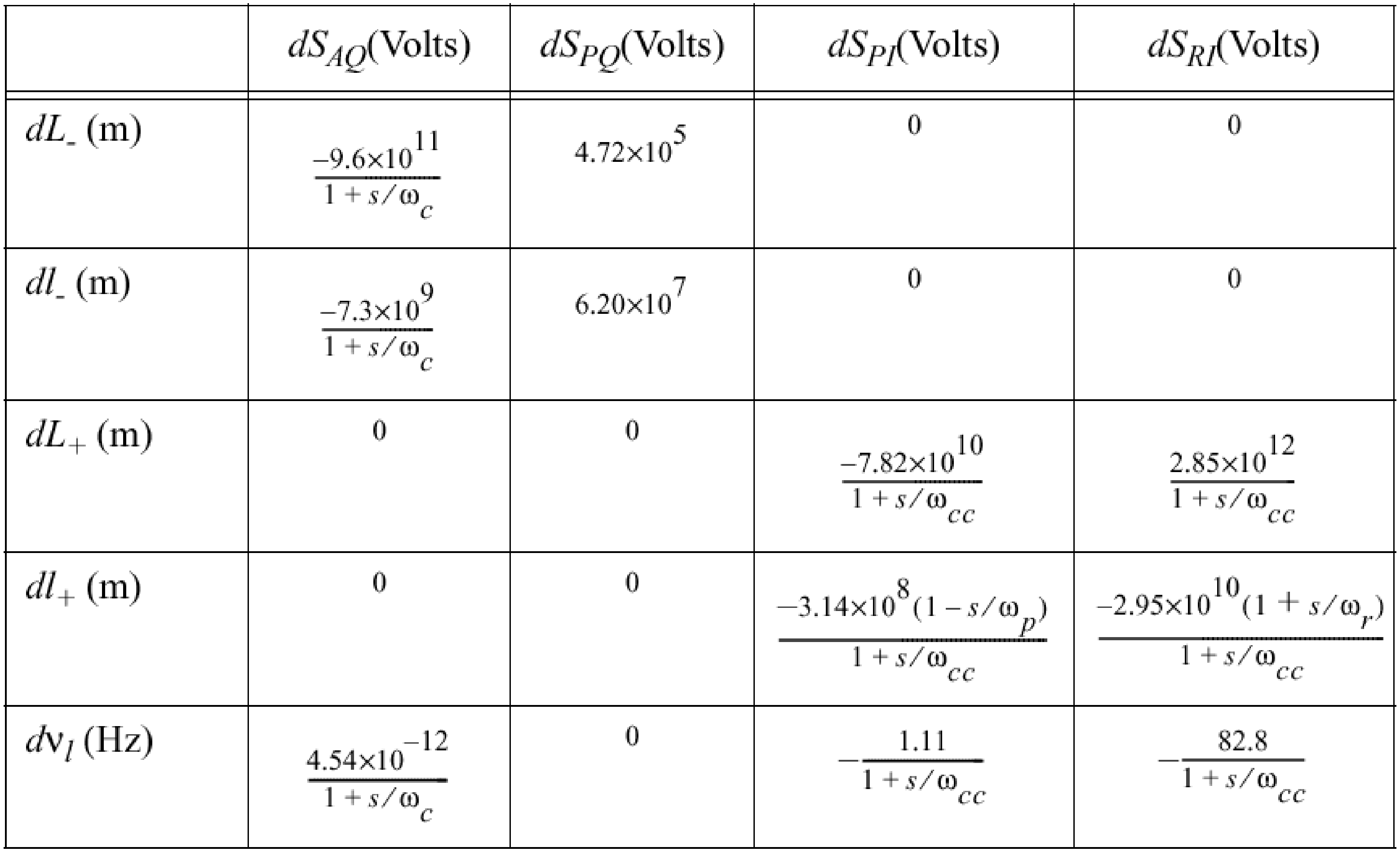
# Length Sensing and Control (LSC)

## 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

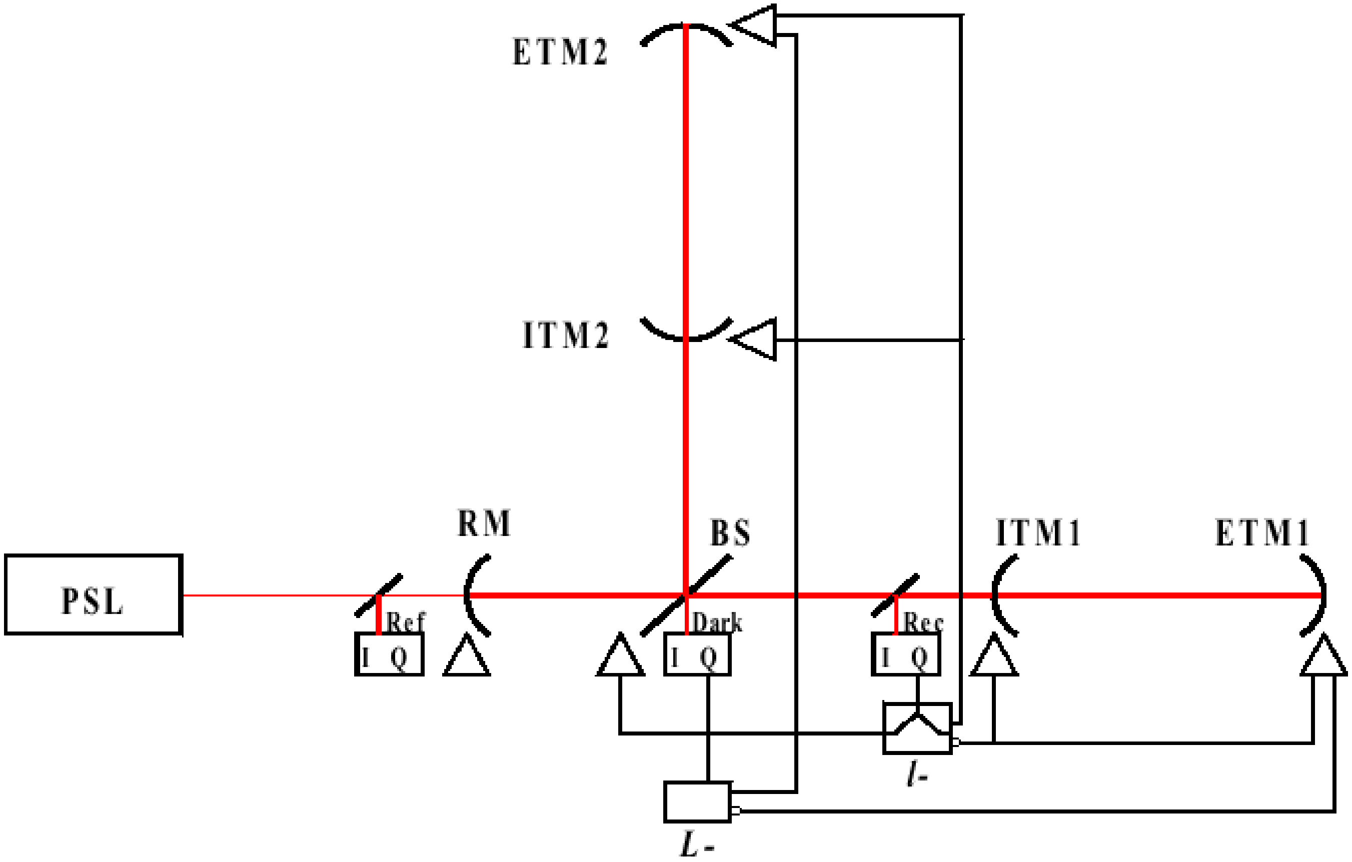


# Length control matrix

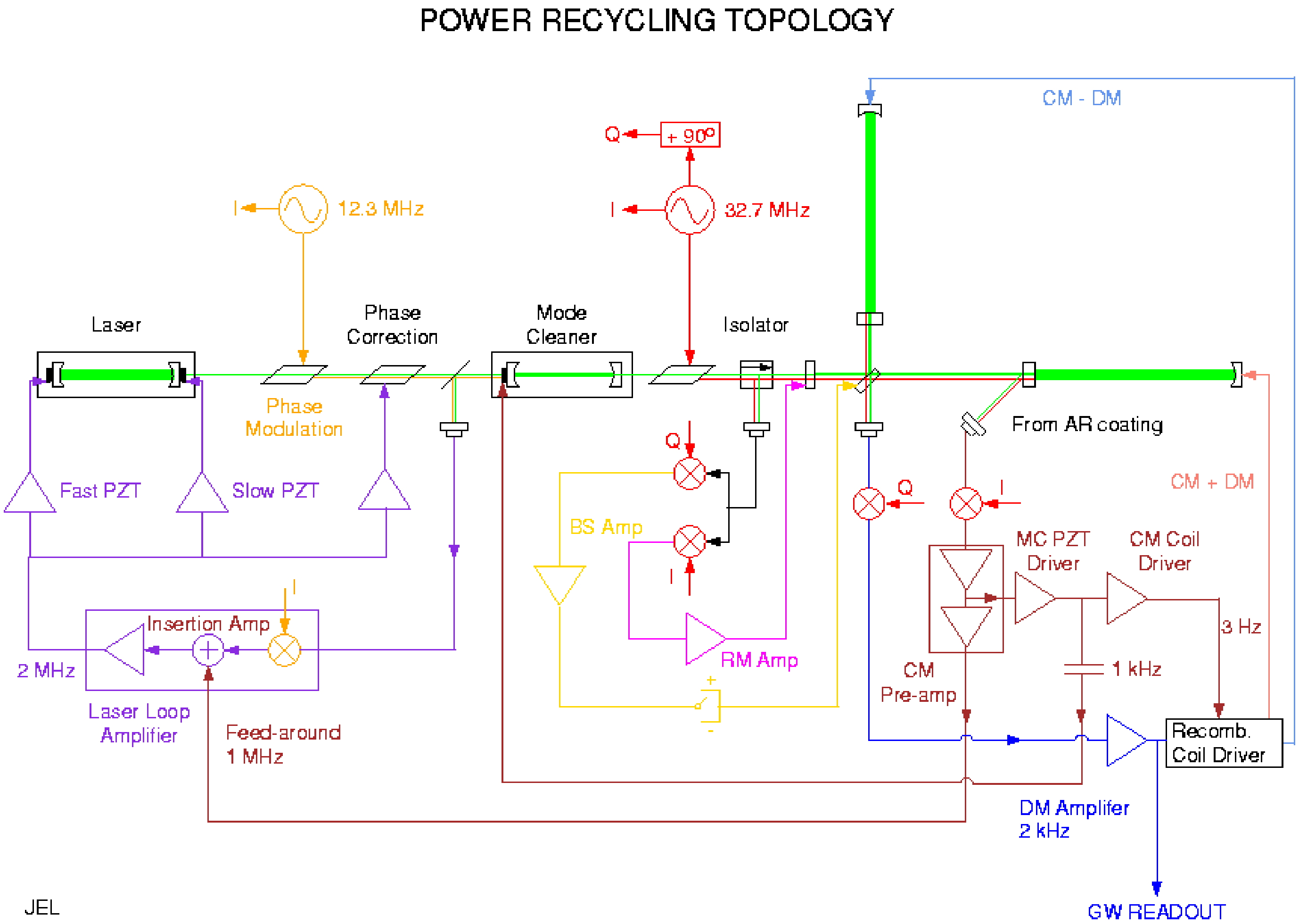


| | $dS_{AQ}$(Volts) | $dS_{PQ}$(Volts) | $dS_{PI}$(Volts) | $dS_{RI}$(Volts) |
|---|---|---|---|---|
| $dL_-$ (m) | $\frac{-9.6\times10^{11}}{1+s/\omega_c}$ | $4.72\times10^{5}$ | 0 | 0 |
| $dl_-$ (m) | $\frac{-7.3\times10^{9}}{1+s/\omega_c}$ | $6.20\times10^{7}$ | 0 | 0 |
| $dL_+$ (m) | 0 | 0 | $\frac{-7.82\times10^{10}}{1+s/\omega_{cc}}$ | $\frac{2.85\times10^{12}}{1+s/\omega_{cc}}$ |
| $dl_+$ (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)

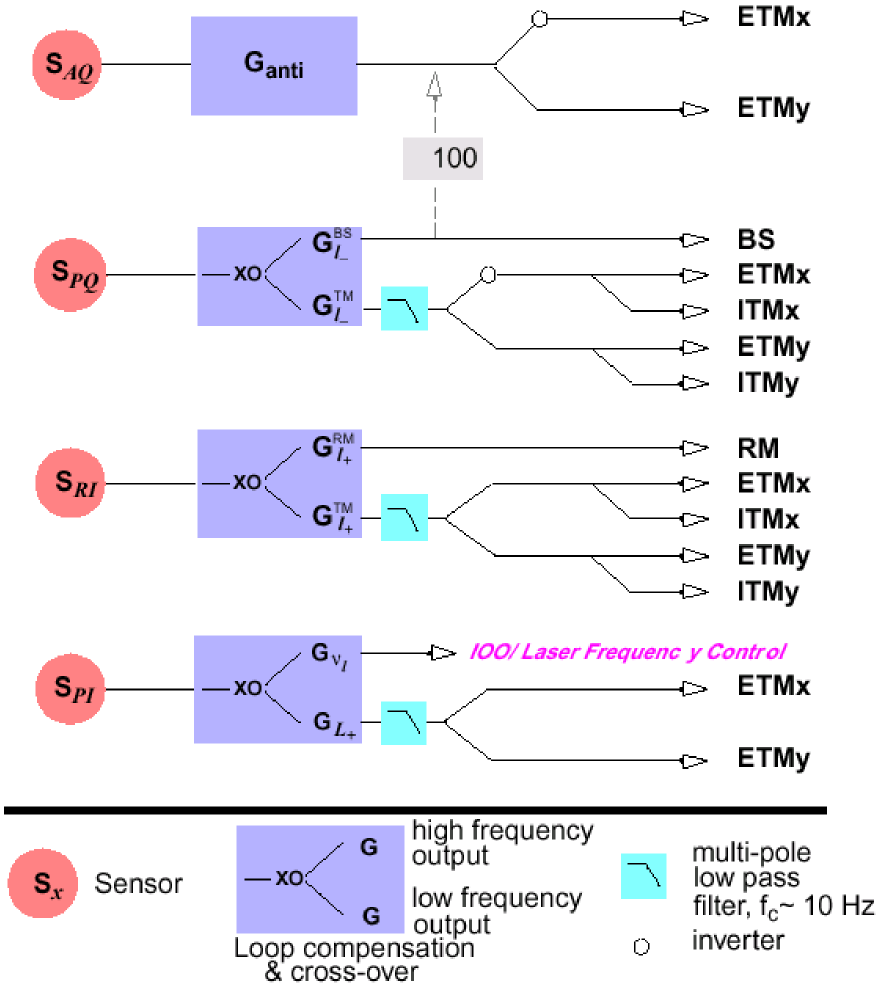


# Length Control system topology

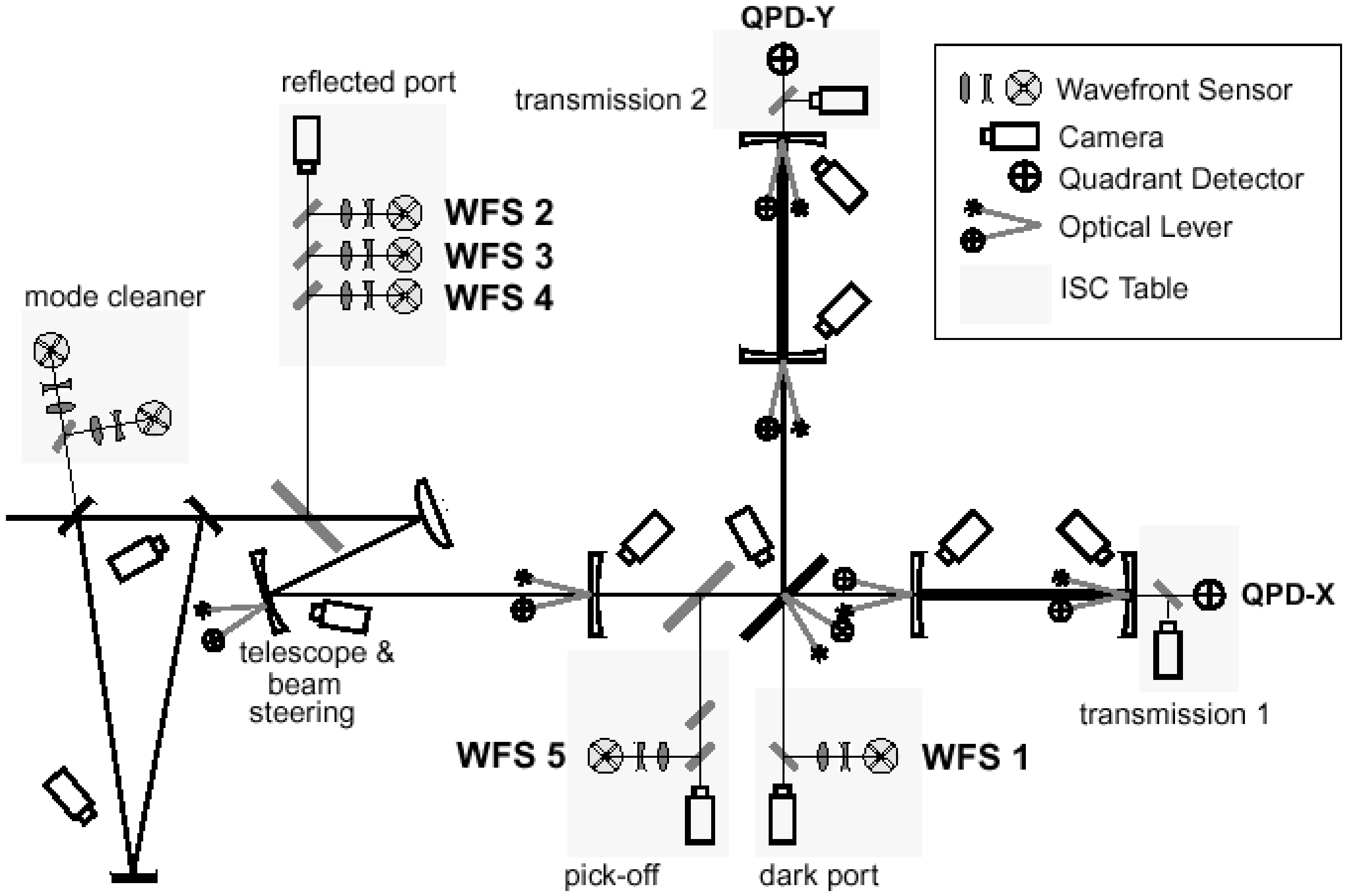


JEL

# Servo gains and bandwidth



# Alignment Sensing and Control (ASC)

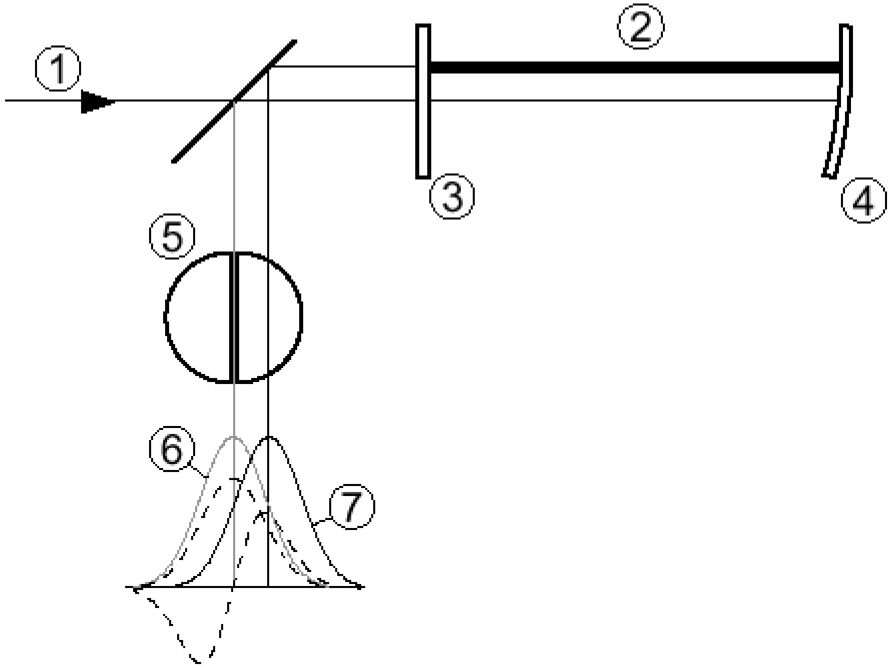


# Wavefront sensing (WFS)

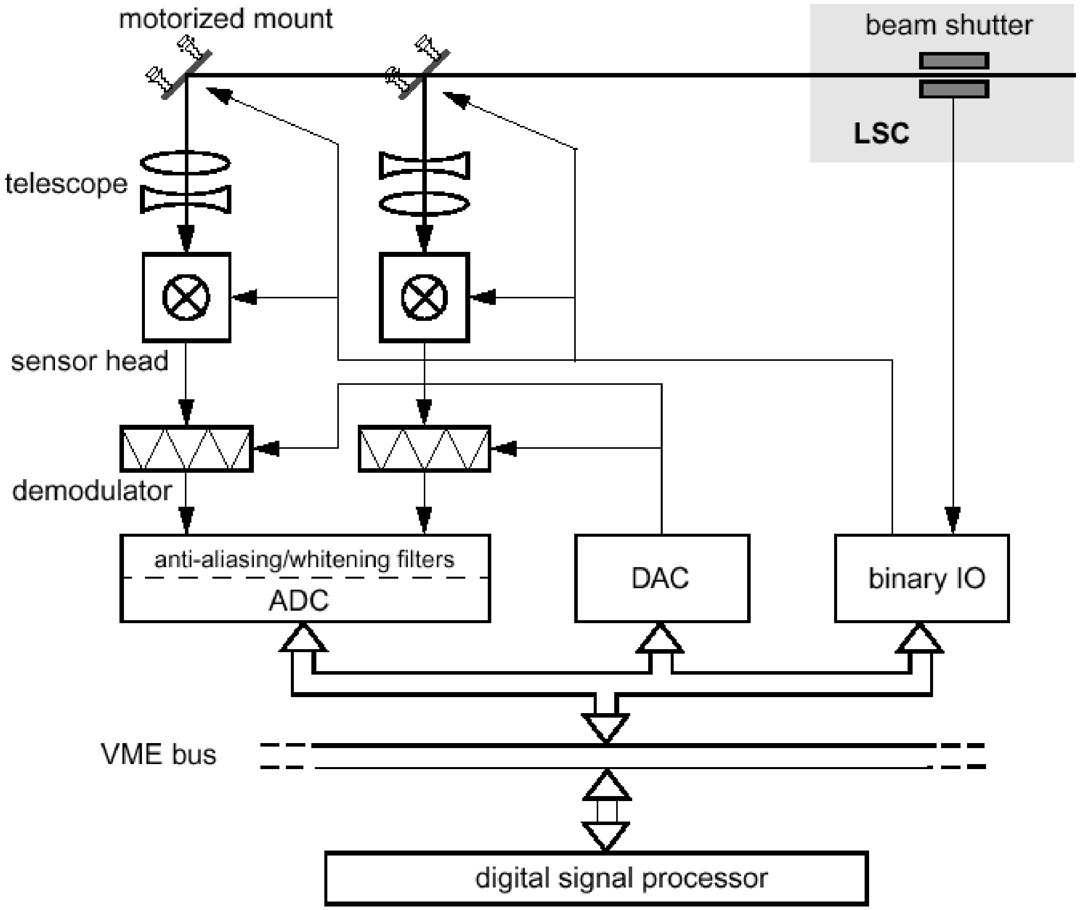
- Sense transverse beam profile in cavity;

  presence of higher-order

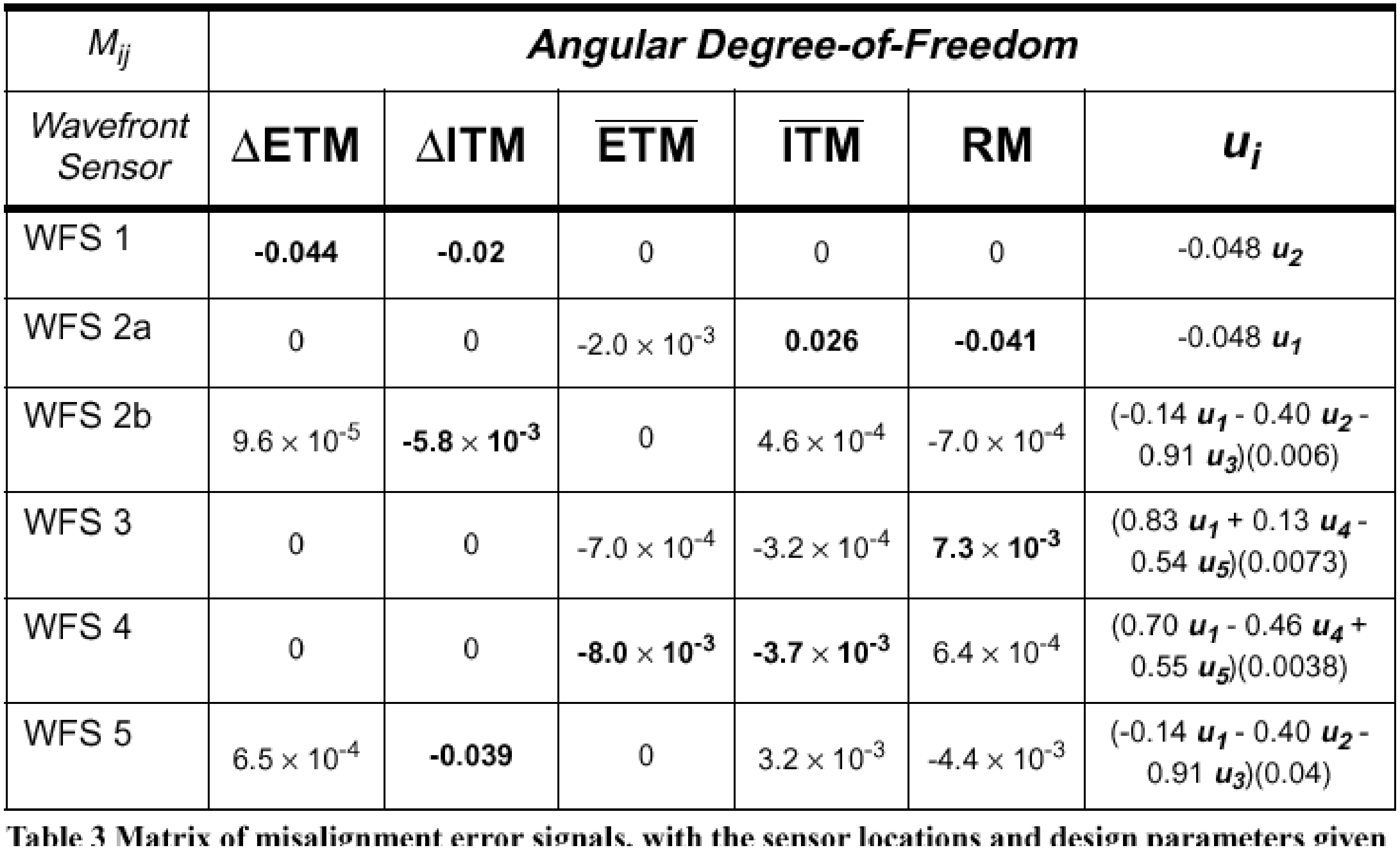
  *Hermite-Gaussian* (TEM$_{01}$, TEM$_{10}$) transverse profiles
- Distinguish misalignment of multiple mirrors at only a few output ports, by use of *Guoy phase telescopes*



# Wavefront Processing Unit (WPU)



# WFS misalignment error signals

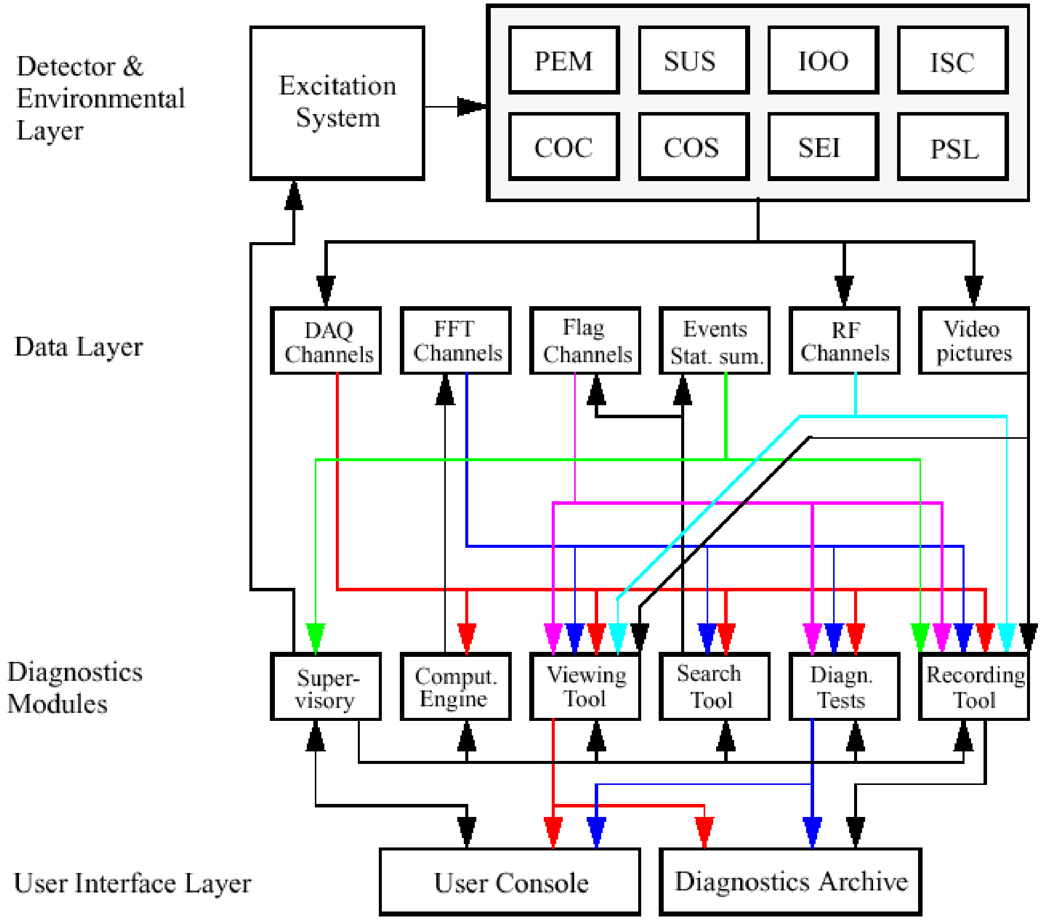


| $M_{ij}$ | Angular Degree-of-Freedom | | | | | |
|---|---|---|---|---|---|---|
| *Wavefront Sensor* | **$\Delta$ETM** | **$\Delta$ITM** | **$\overline{\text{ETM}}$** | **$\overline{\text{ITM}}$** | **RM** | $\boldsymbol{u_i}$ |
| WFS 1 | **-0.044** | **-0.02** | 0 | 0 | 0 | -0.048 $\boldsymbol{u_2}$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

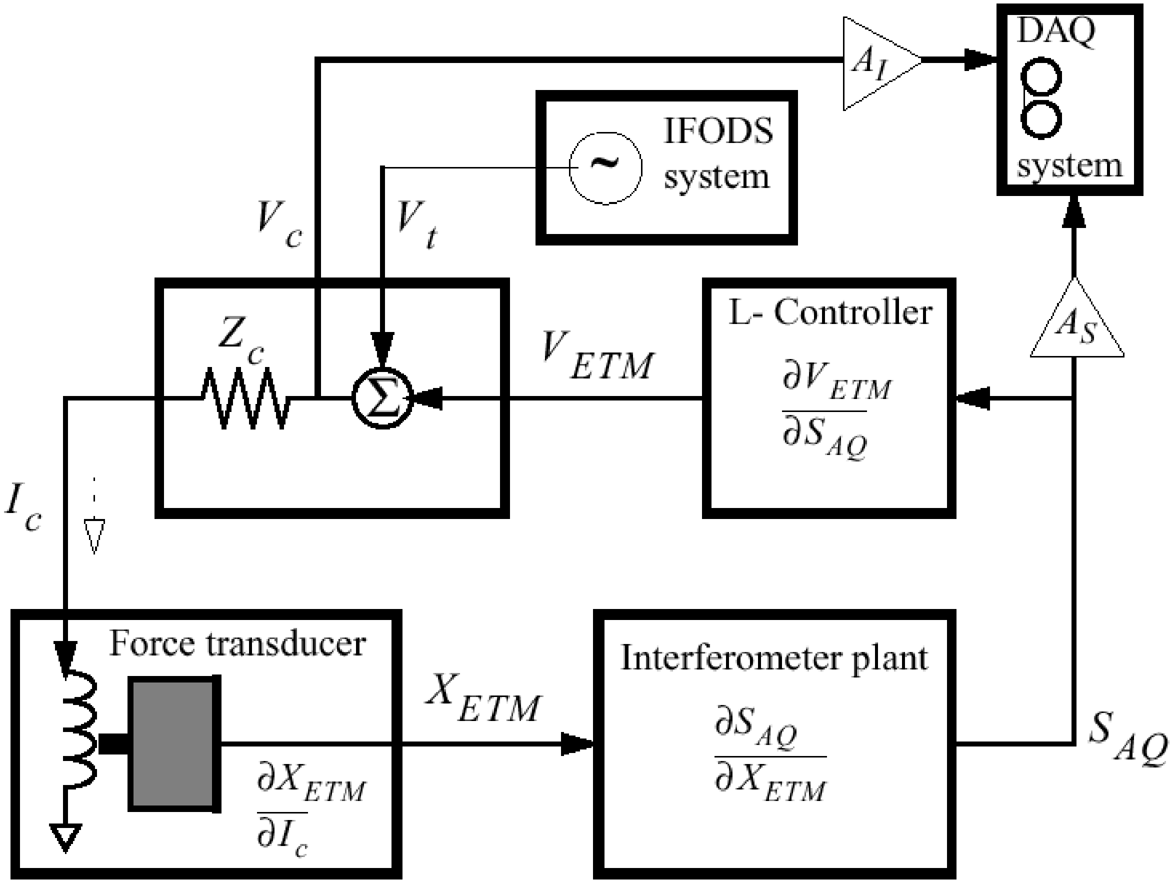
**Table 3** Matrix of misalignment error signals, with the sensor locations and design parameters given

# Global Diagnostics System (GDS)

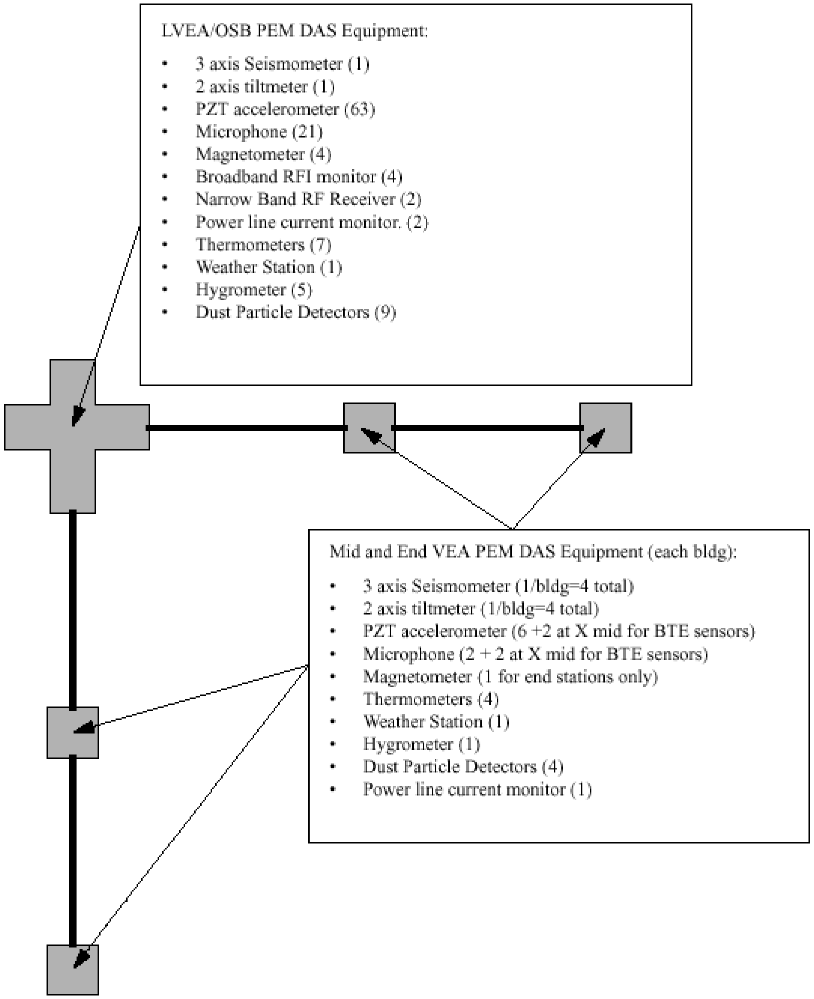
- Swept-sine transfer functions with excitation engine
- Lock acquisition, status and monitoring
- environmental monitoring
- correlating IFO signals
- identifying transients (bumps in the night)
- triggers, alarms
- maintain detector meta-database



# Calibration



# Physical Environment Monitoring (PEM)



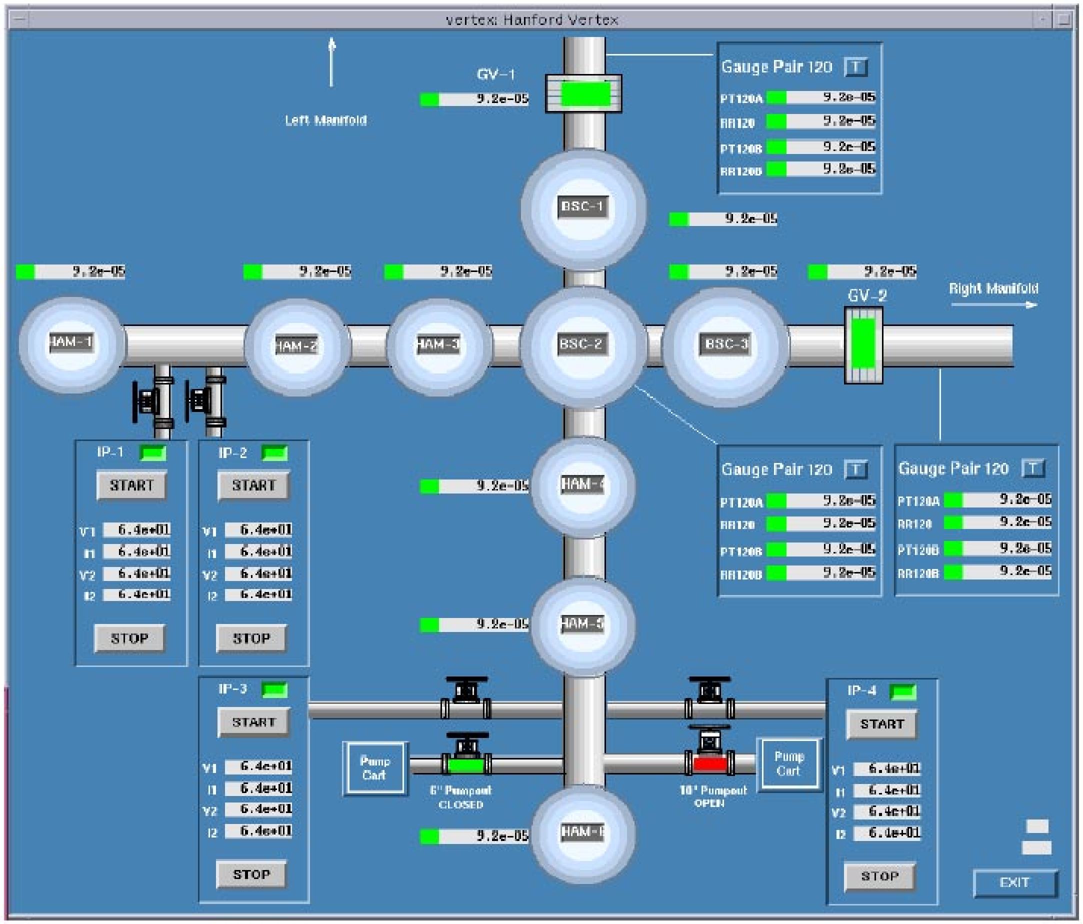
LVEA/OSB PEM DAS Equipment:

- 3 axis Seismometer (1)
- 2 axis tiltmeter (1)
- PZT accelerometer (63)
- Microphone (21)
- Magnetometer (4)
- Broadband RFI monitor (4)
- Narrow Band RF Receiver (2)
- Power line current monitor. (2)
- Thermometers (7)
- Weather Station (1)
- Hygrometer (5)
- Dust Particle Detectors (9)

Mid and End VEA PEM DAS Equipment (each bldg):

- 3 axis Seismometer (1/bldg=4 total)
- 2 axis tiltmeter (1/bldg=4 total)
- PZT accelerometer (6 +2 at X mid for BTE sensors)
- Microphone (2 + 2 at X mid for BTE sensors)
- Magnetometer (1 for end stations only)
- Thermometers (4)
- Weather Station (1)
- Hygrometer (1)
- Dust Particle Detectors (4)
- Power line current monitor (1)

# Vacuum control system



Gauge Pair 120
PT120A 9.2e-05
RR120 9.2e-05
PT120B 9.2e-05
RR120B 9.2e-05

IP-1
V1 6.4e+01
I1 6.4e+01
V2 6.4e+01
I2 6.4e+01

IP-2
V1 6.4e+01
I1 6.4e+01
V2 6.4e+01
I2 6.4e+01

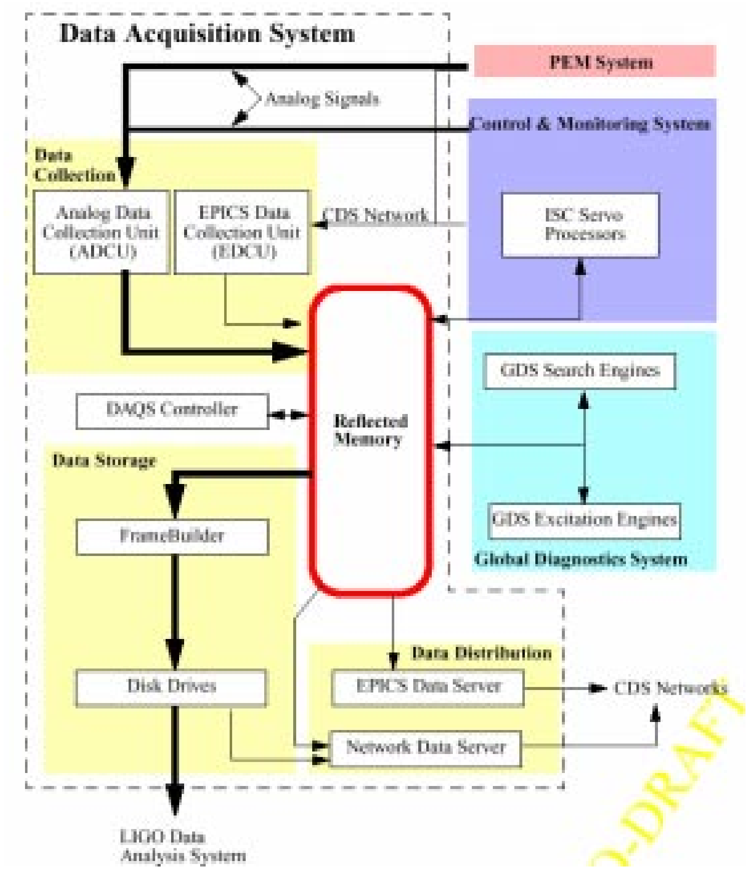
IP-3
V1 6.4e+01
I1 6.4e+01
V2 6.4e+01
I2 6.4e+01

IP-4
V1 6.4e+01
I1 6.4e+01
V2 6.4e+01
I2 6.4e+01

*Figure 2: Hanford Vertex Section Display*

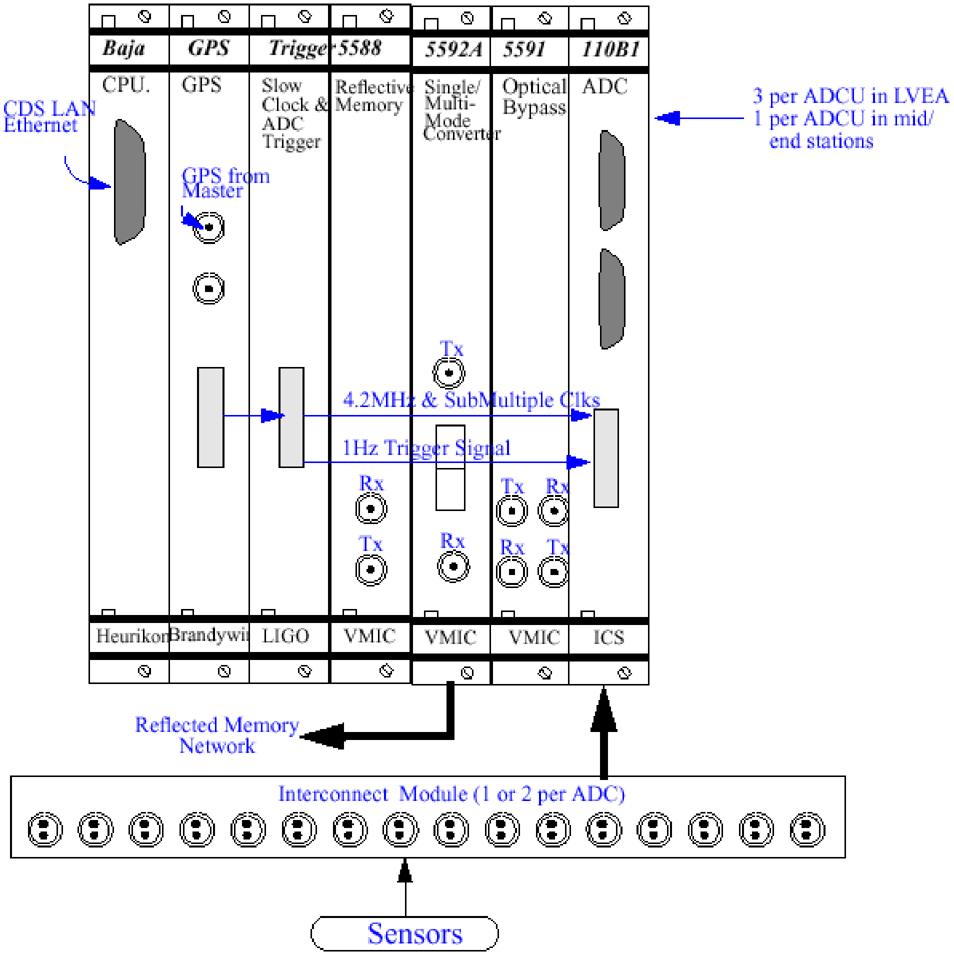
# DAQS overview

- 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

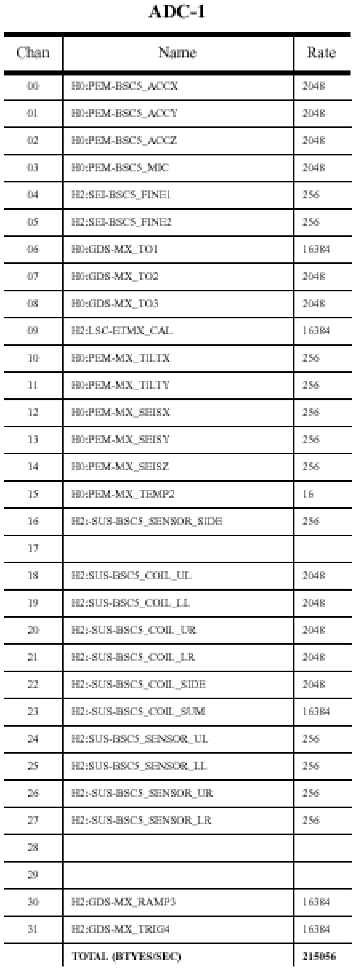


# Analog Data Collection Unit (ADCU)

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

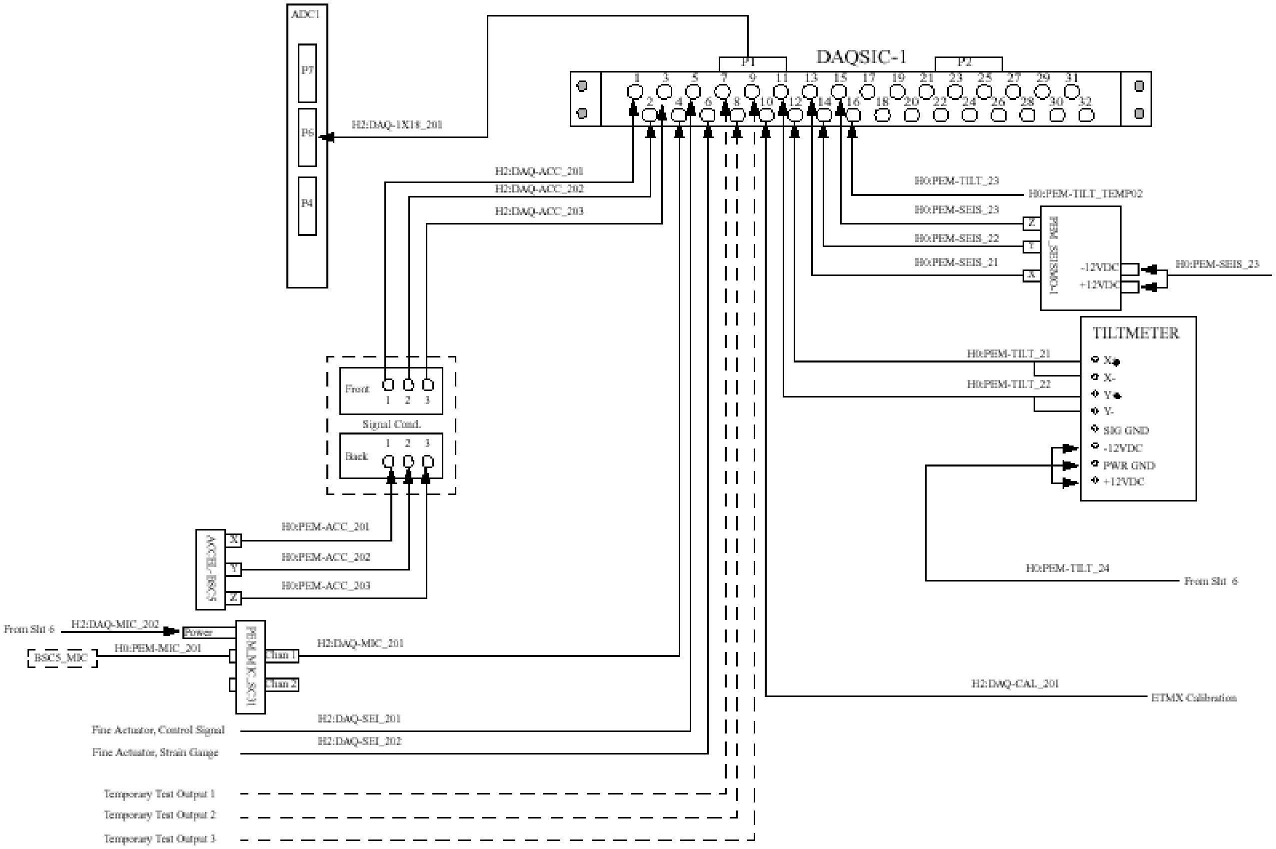


# Typical example of what's in an ADCU

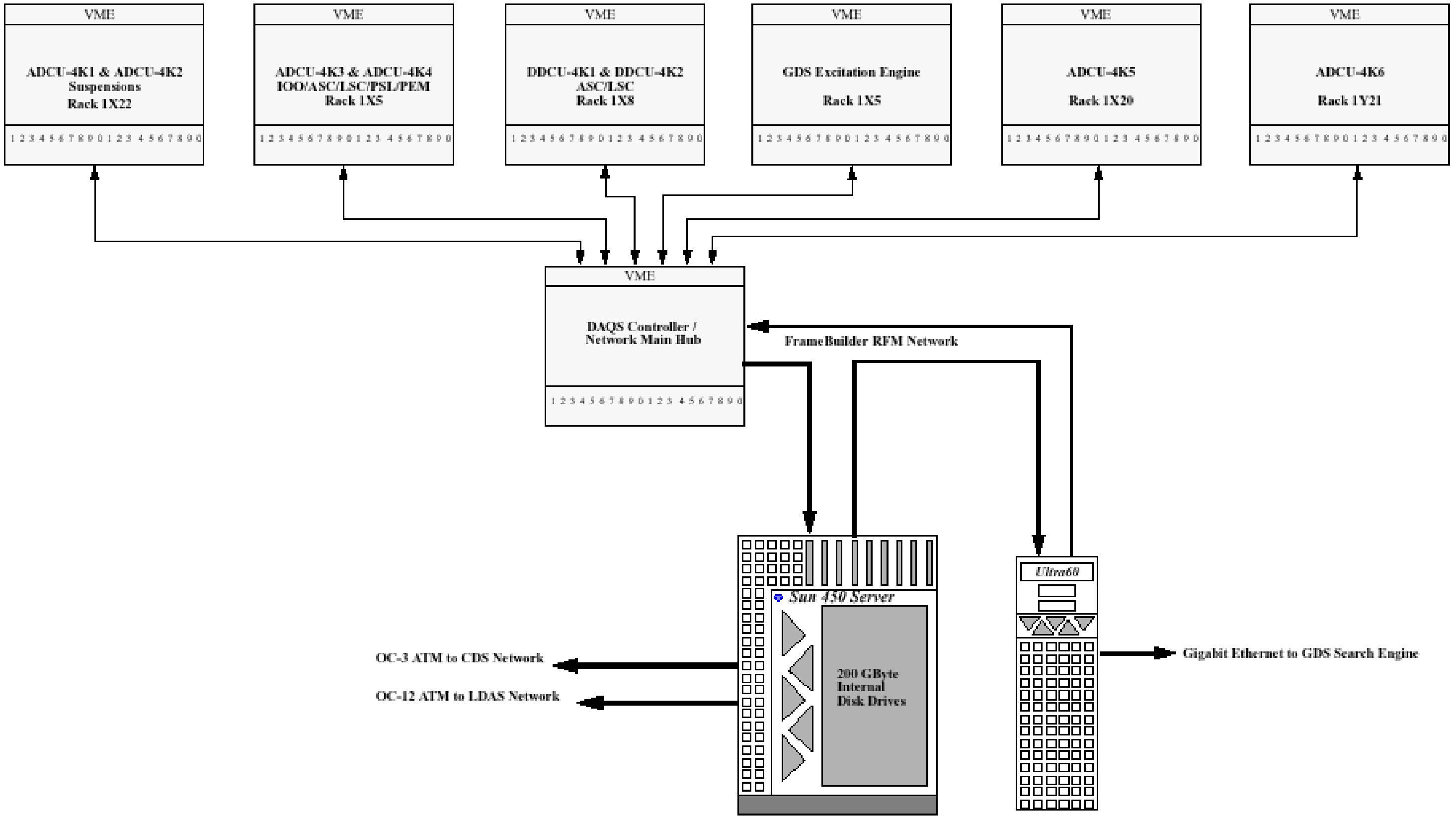


**ADC-1**

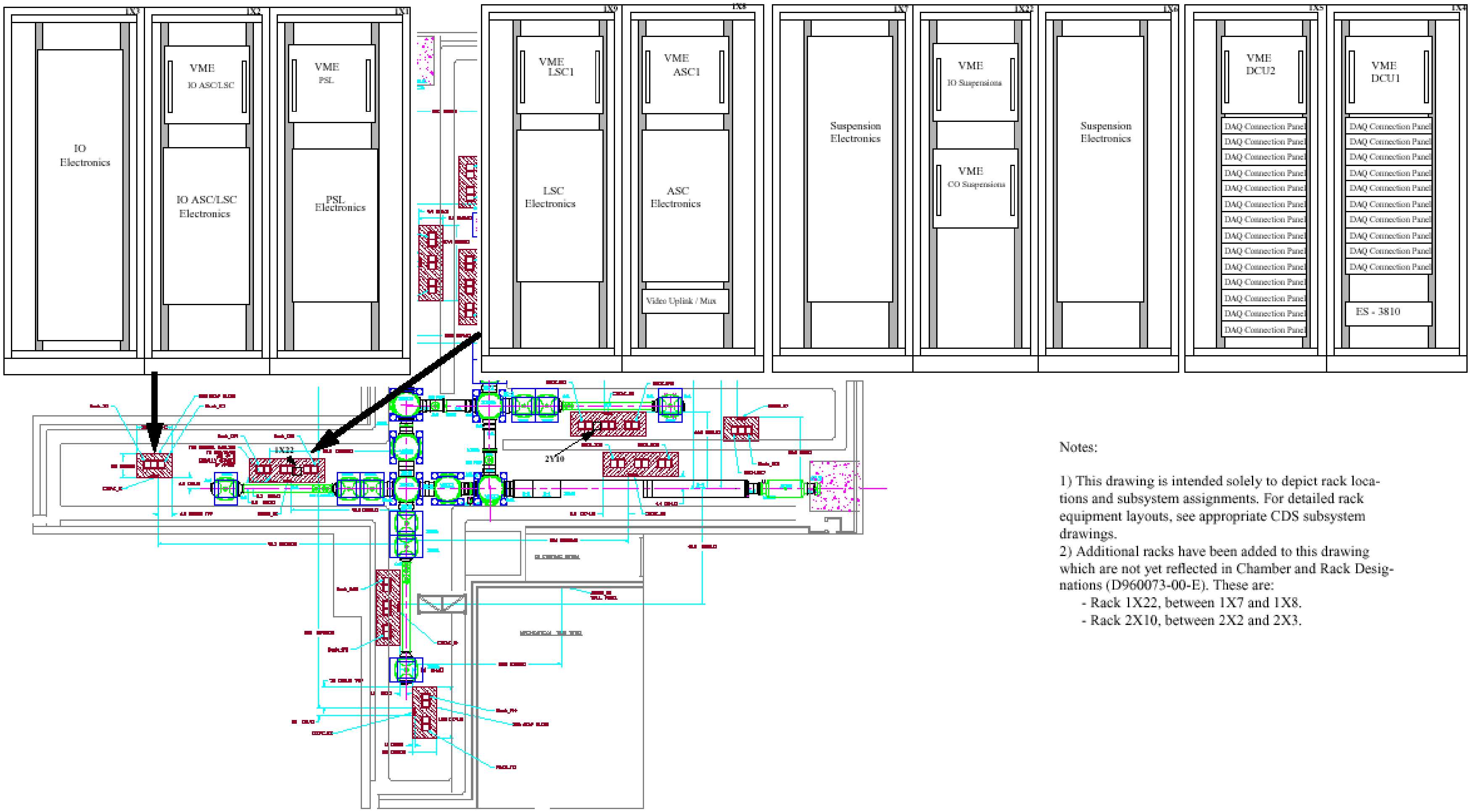
| Chan | Name | Rate |
|---|---|---|
| 00 | H0:PEM-BSC5_ACCX | 2048 |
| 01 | H0:PEM-BSC5_ACCY | 2048 |
| 02 | H0:PEM-BSC5_ACCZ | 2048 |
| 03 | H0:PEM-BSC5_MIC | 2048 |
| 04 | H2:SEI-BSC5_FINE1 | 256 |
| 05 | H2:SEI-BSC5_FINE2 | 256 |
| 06 | H0:GDS-MX_TO1 | 16384 |
| 07 | H0:GDS-MX_TO2 | 2048 |
| 08 | 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

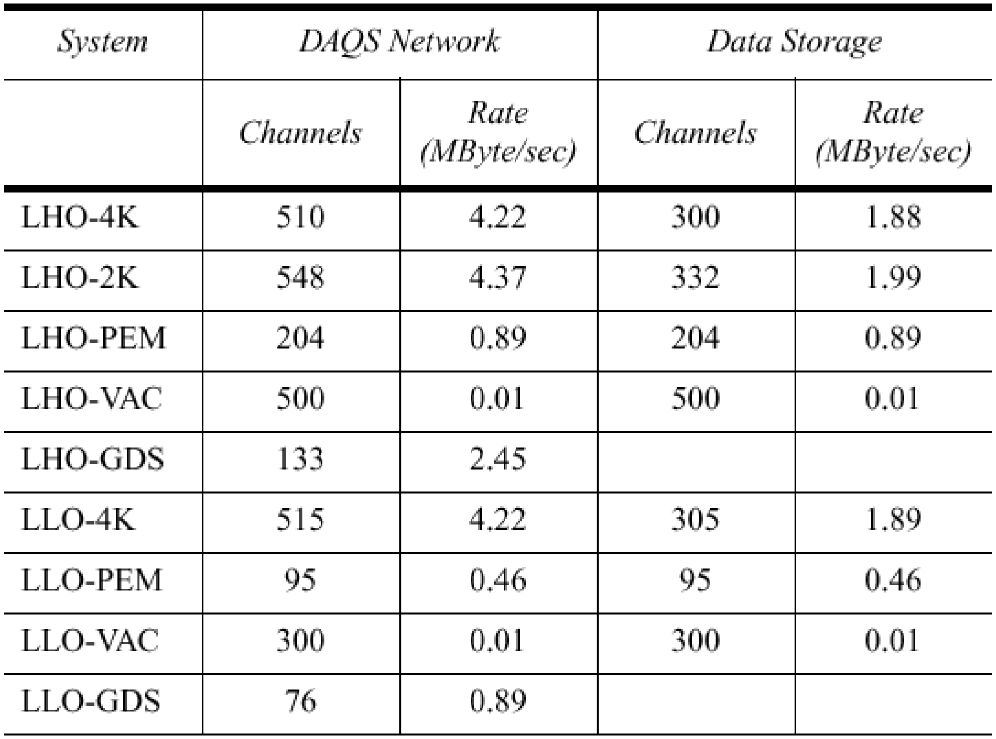


Notes:

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) × ($3 \times 10^7$ 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

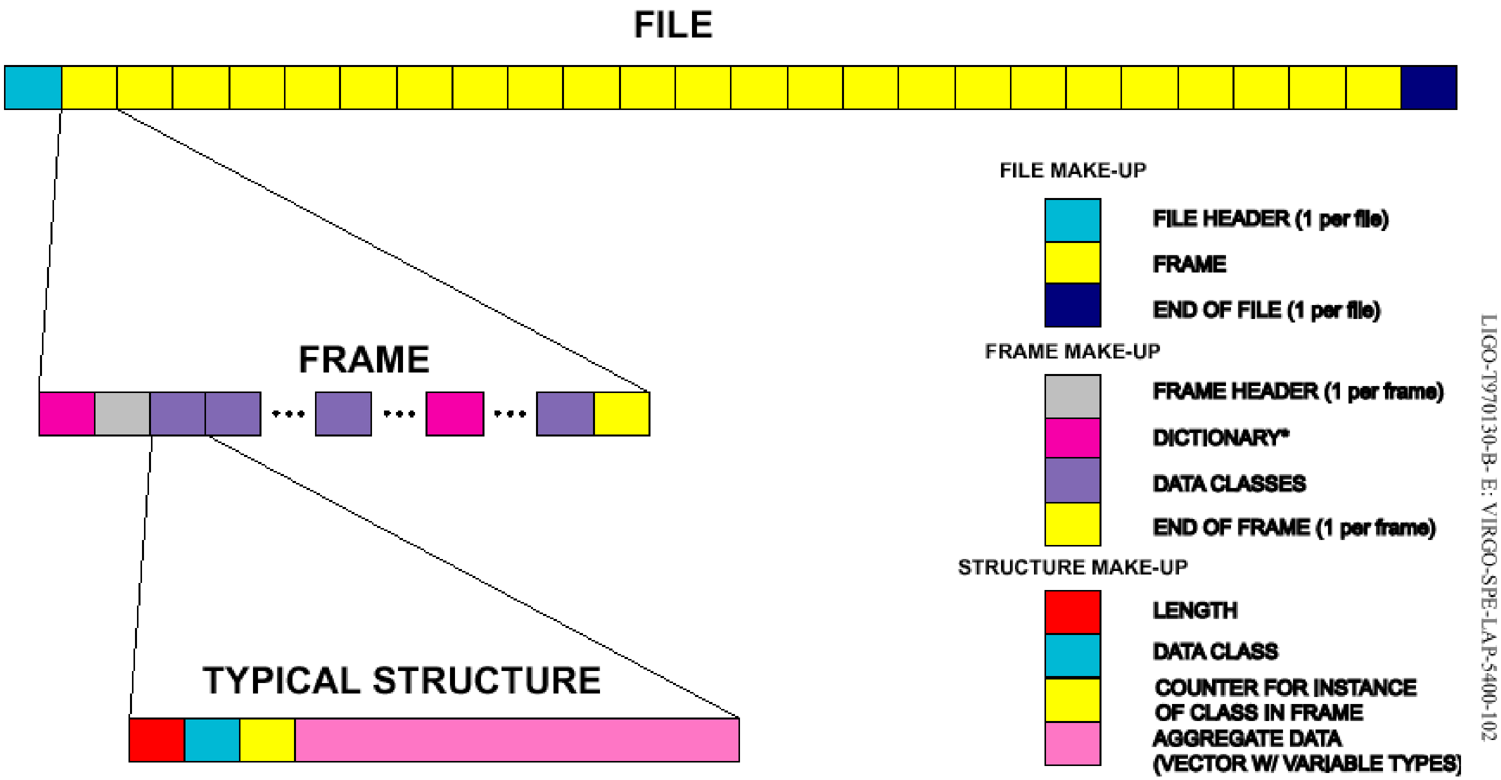


| *System* | *DAQS Network* | | *Data Storage* | |
|---|---|---|---|---|
| | *Channels* | *Rate (MByte/sec)* | *Channels* | *Rate (MByte/sec)* |
| LHO-4K | 510 | 4.22 | 300 | 1.88 |
| LHO-2K | 548 | 4.37 | 332 | 1.99 |
| LHO-PEM | 204 | 0.89 | 204 | 0.89 |
| LHO-VAC | 500 | 0.01 | 500 | 0.01 |
| LHO-GDS | 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



**FILE**

**FRAME**

**TYPICAL STRUCTURE**

FILE MAKE-UP

🟦 **FILE HEADER (1 per file)**
🟨 **FRAME**
⬛ **END OF FILE (1 per file)**

FRAME MAKE-UP

⬜ **FRAME HEADER (1 per frame)**
🟪 **DICTIONARY***
🟪 **DATA CLASSES**
🟨 **END OF FRAME (1 per frame)**

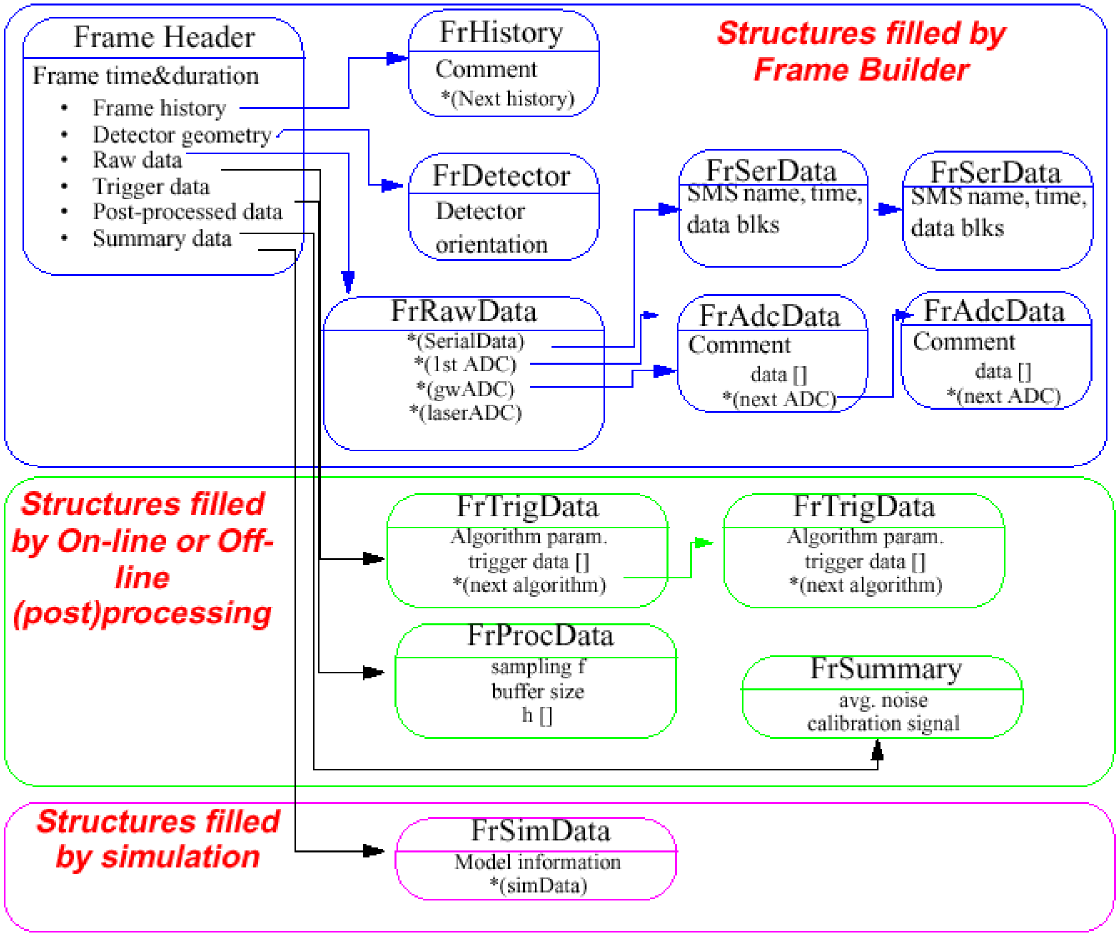
STRUCTURE MAKE-UP

🟥 **LENGTH**
🟦 **DATA CLASS**
🟨 **COUNTER FOR INSTANCE OF CLASS IN FRAME**
🟪 **AGGREGATE DATA (VECTOR W/ VARIABLE TYPES)**

LIGO-T970130-B- E: VIRGO-SPE-LAP-5400-102

* 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



**Structures filled by Frame Builder**

**Frame Header**
Frame time&duration
- Frame history
- Detector geometry
- Raw data
- Trigger data
- Post-processed data
- Summary data

**FrHistory**
Comment
*(Next history)

**FrDetector**
Detector
orientation

**FrRawData**
*(SerialData)
*(1st ADC)
*(gwADC)
*(laserADC)

**FrSerData**
SMS name, time,
data blks

**FrSerData**
SMS name, time,
data blks

**FrAdcData**
Comment
data []
*(next ADC)

**FrAdcData**
Comment
data []
*(next ADC)

**Structures filled by On-line or Off-line (post)processing**

**FrTrigData**
Algorithm param.
trigger data []
*(next algorithm)

**FrTrigData**
Algorithm param.
trigger data []
*(next algorithm)

**FrProcData**
sampling f
buffer size
h []

**FrSummary**
avg. noise
calibration signal

**Structures filled by simulation**

**FrSimData**
Model information
*(simData)