The LIGO Interferometer Sensing and Controls System

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Marcel Grossmann IX Meeting

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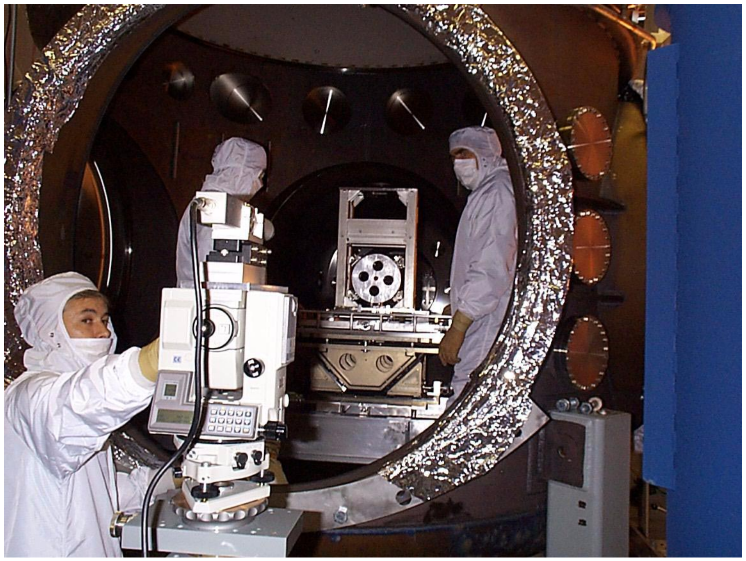
ISC overview

- What is ISC?
  - ◊ Initialize alignment to attain interference in coupled LIGO cavities
  - ◊ Sense optical phase to derive interferometer lengths and laser wavelength
  - ◊ Sense spatial phase gradients to determine mirror alignment errors
  - ◊ Apply feedback controls to maintain and optimize optical resonance
  - ◊ Provide calibrated readout of gravitational wave strain
- Who's responsible?
  - ◊ D. Barker, R. Bork, E. Daw, M. Evans, P. Fritschel, G. Gonzalez, J. Heefner, A. Marin, N. Mavalvala, D. Ouimette, L. Sievers, D. Sigg, B. Ware, M. Zucker

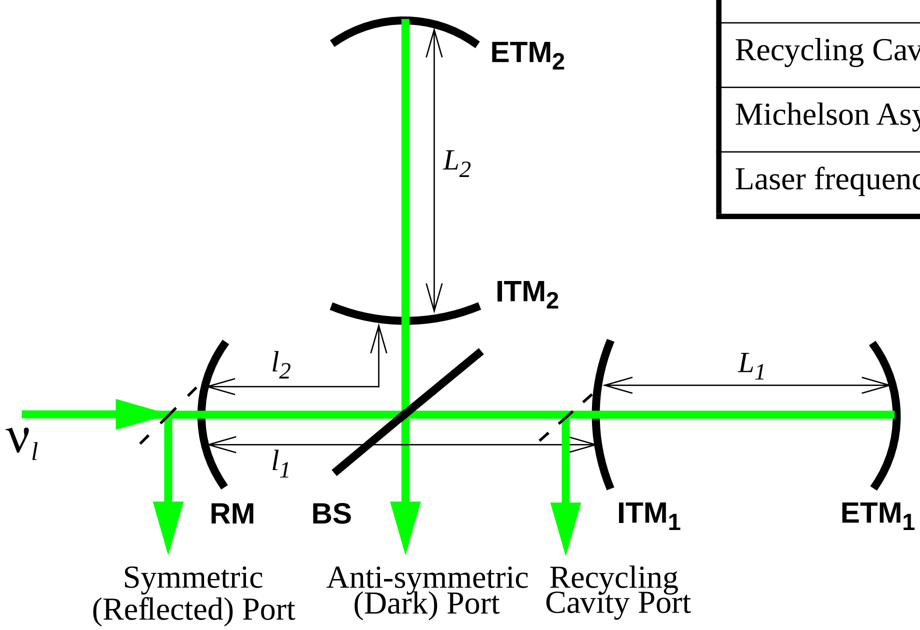
Core Optics Initial Alignment & Positioning



Reference vectors from GPS-based construction survey monuments are transferred to suspended optic normals with autocollimator-equipped theodolite

Lock the laser, open the beamtube gate valves and...

The LIGO I Interferometer



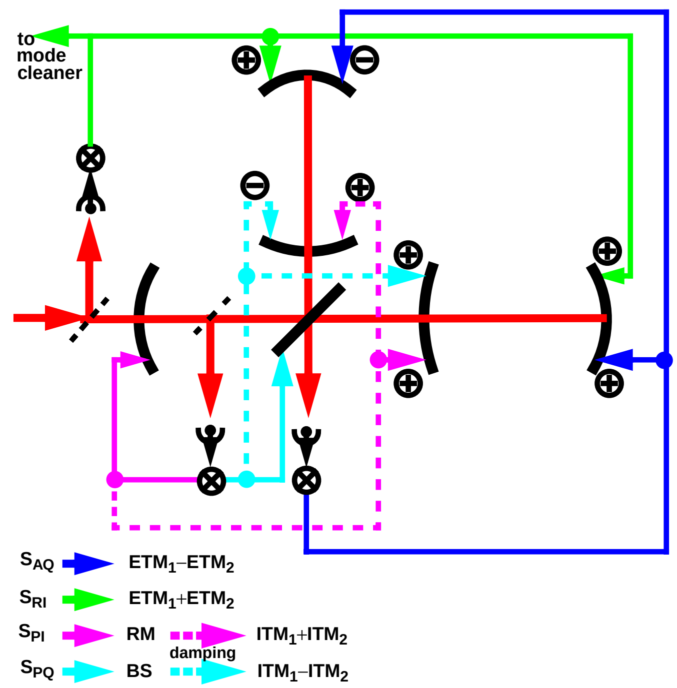
Name	*Symbols*	*Definition*
Differential Arm Length	L_-, L_m	$L_1 - L_2$
Common Arm Length	L_+, L_p	$L_1 + L_2$
Michelson Length	l_-, l_m	$l_1 - l_2$
Recycling Cavity Length	l_+, l_p	$l_1 + l_2$
Michelson Asymmetry	Δl	$(l_1 - l_2)/2$
Laser frequency	ν_l	hc/λ

Modulation & Readout

- Frontal “Schnupp” modulation scheme
  - ◊ Front (recycling) cavity mean length l_+ chosen to resonate with common phase-modulation sidebands; arm cavities only resonant with carrier
  - ◊ Macroscopic asymmetry Δl_- (fraction of RF wavelength) couples sidebands out dark port, where they beat with residual carrier returning from arms
  - ◊ Detected/demodulated beat note reveals phase difference between arms (L_-)
  - ◊ Auxiliary degrees of freedom (l_+ , l_- , L_+ / ν_l) are similarly sensed by sampling reflected and circulating fields & demodulating with appropriate reference phases

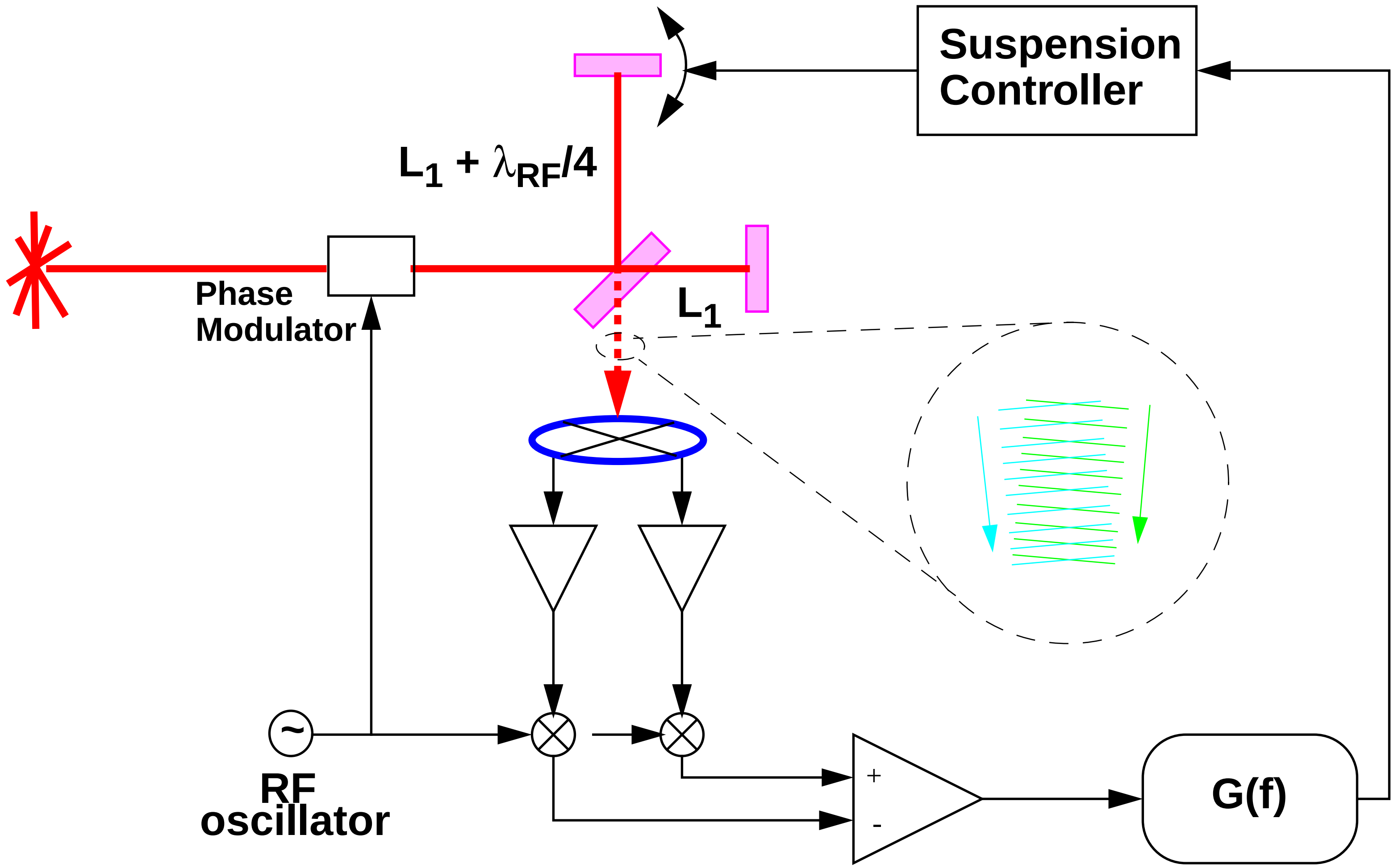
Length Sensing Matrix Elements & Chosen Control Signals

Signal port	ϕ_{RF}	*Symbol*	*Degree of Freedom*			
			L_+	l_+	L_-	l_-
Reflection	I	S_{RI}	–62000	–560	0	0
Rec. cav. PO	I	S_{PI}	520000	17000	0	0
Anti-symm.	Q	S_{AQ}	0	0	23000	180
Reflection	Q	S_{RQ}	0	0	0	19
Rec. cav. PO	Q	S_{PQ}	0	0	0	4900

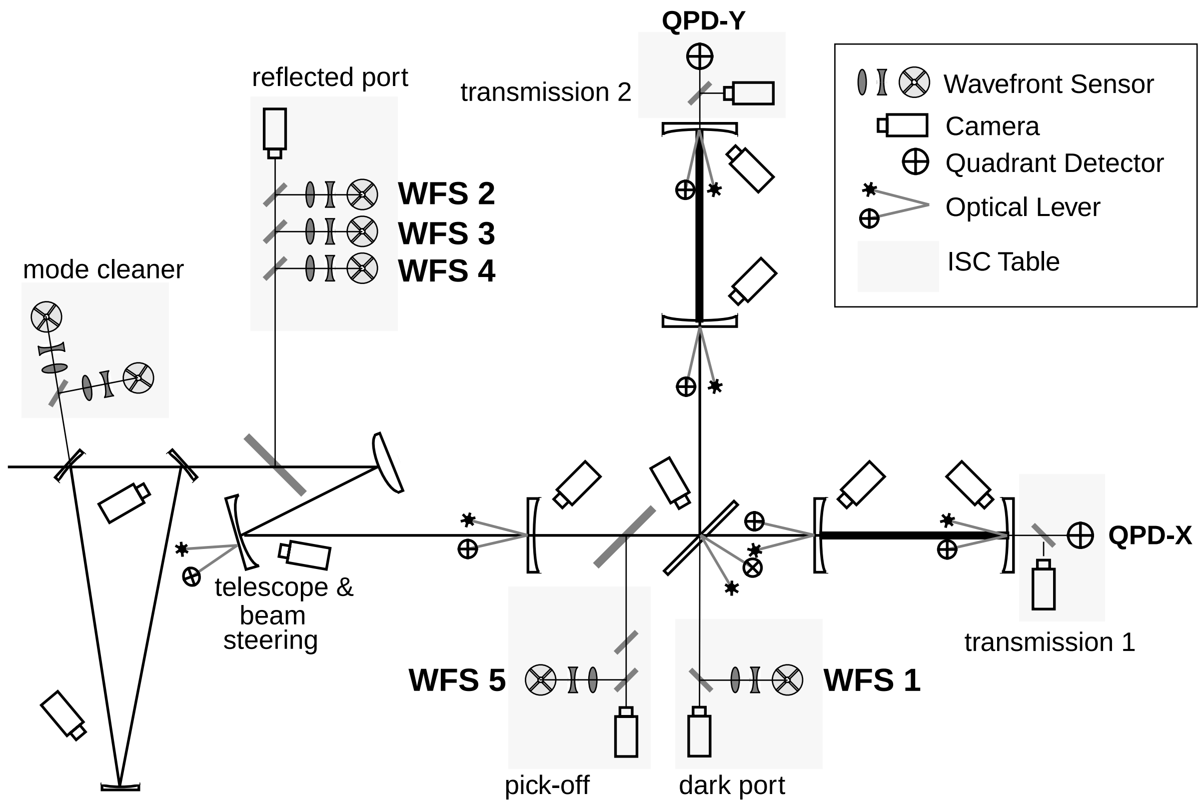


Alignment: Wavefront Sensing

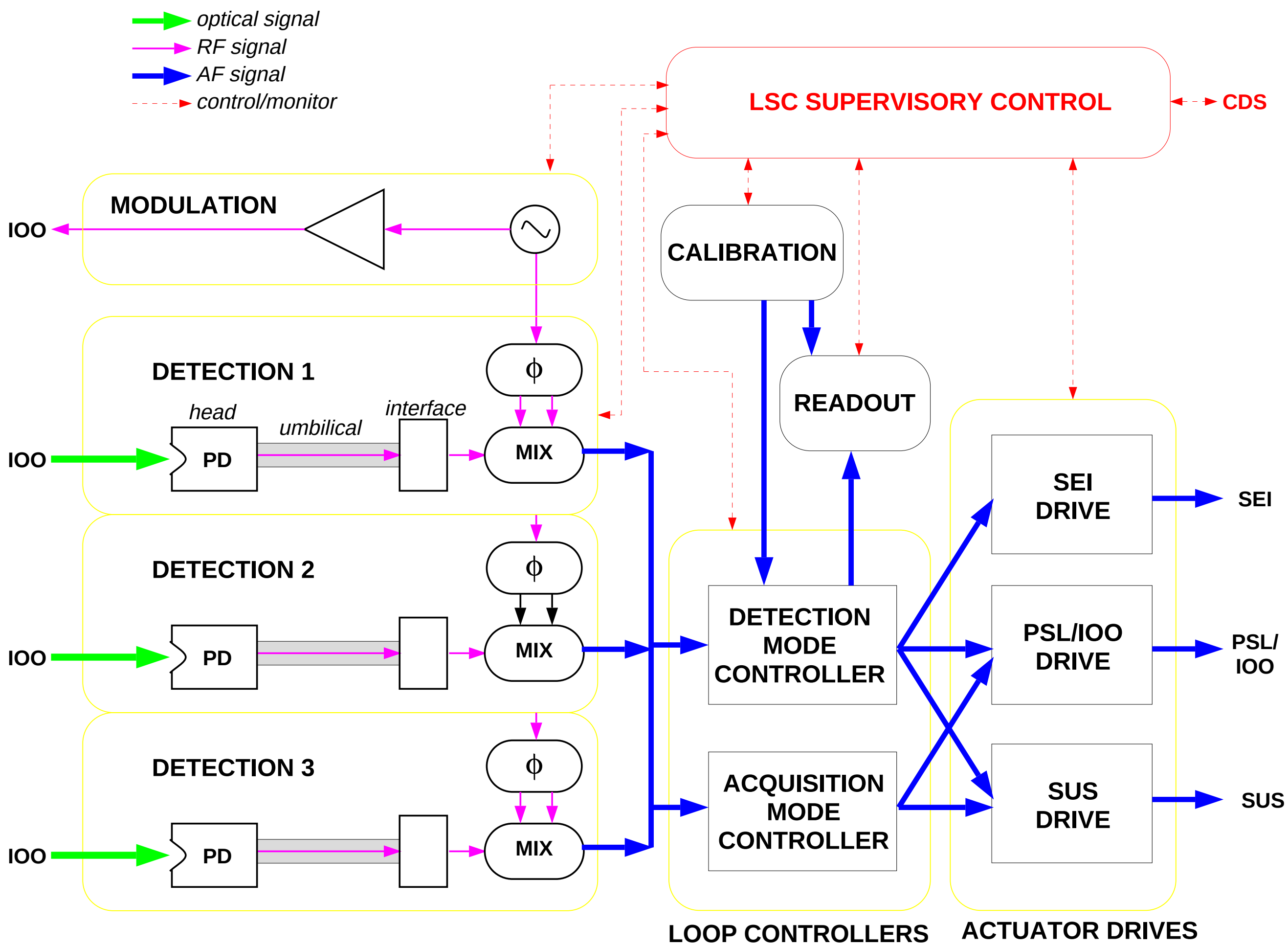
Simple Michelson interferometer with deliberate arm asymmetry



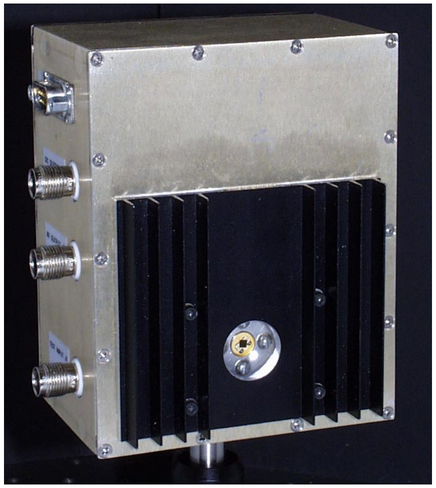
WFS Application

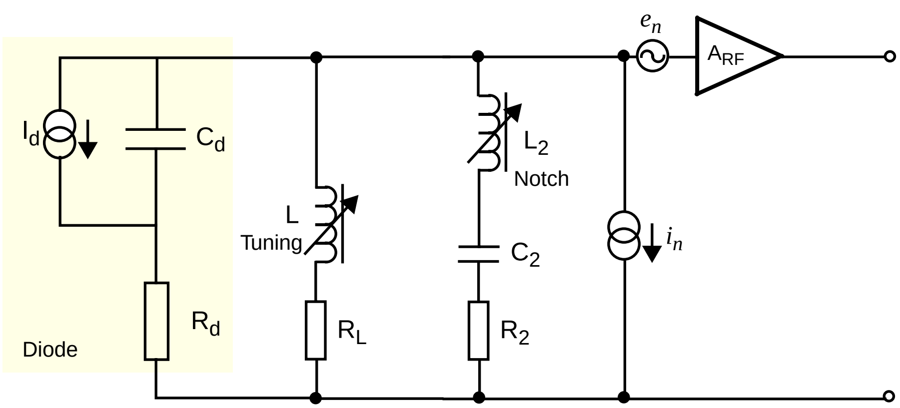


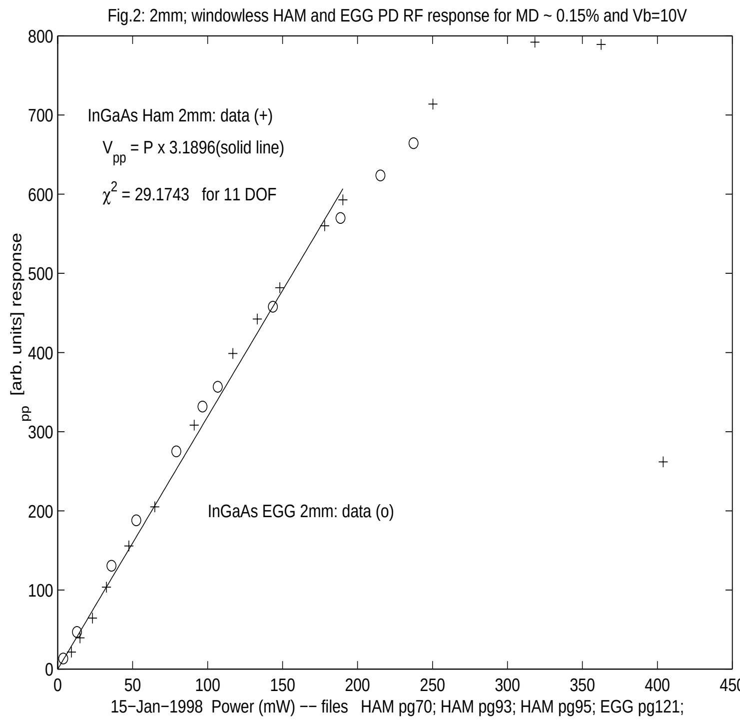
Functional Block Diagram



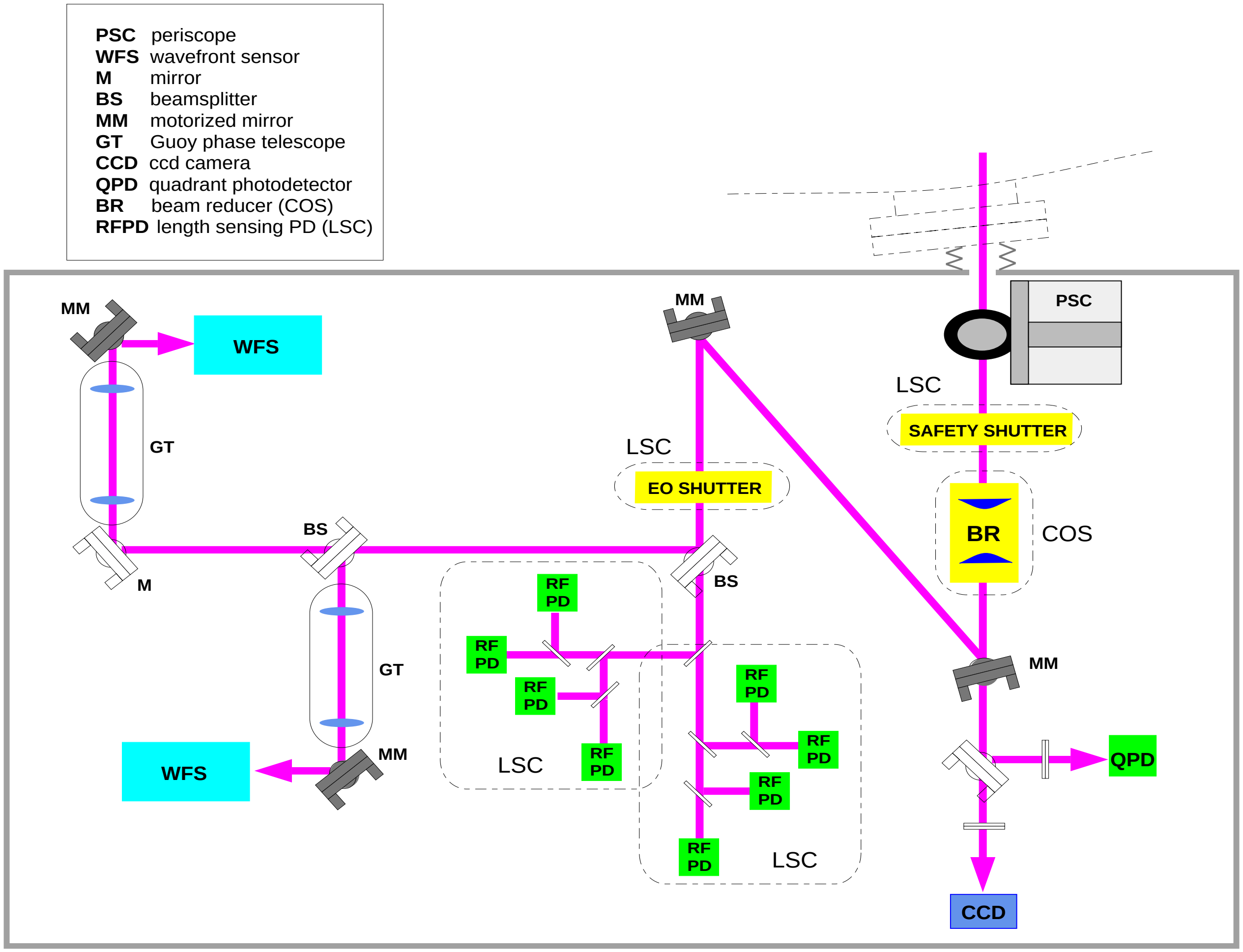
RF Photodetectors



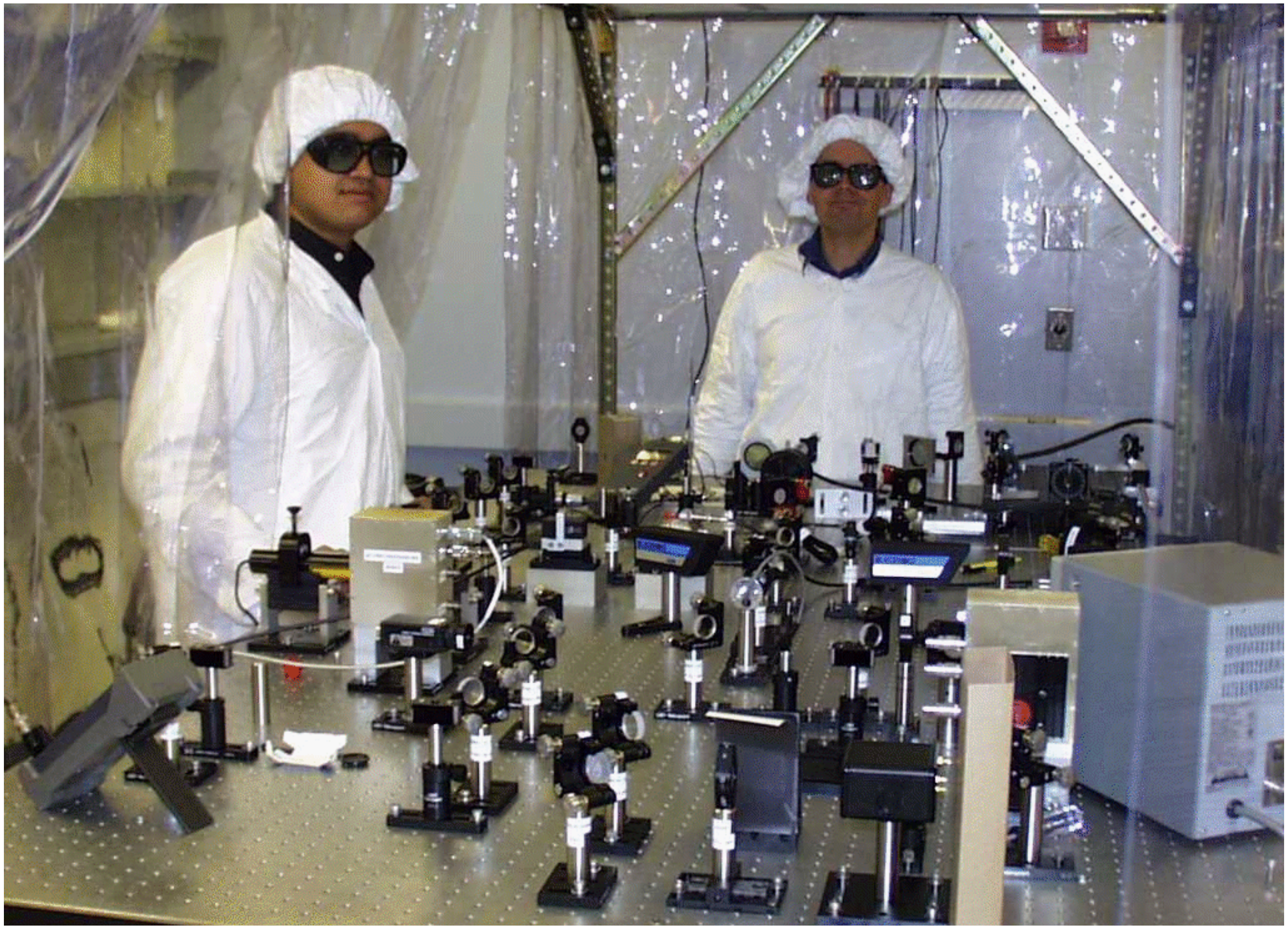




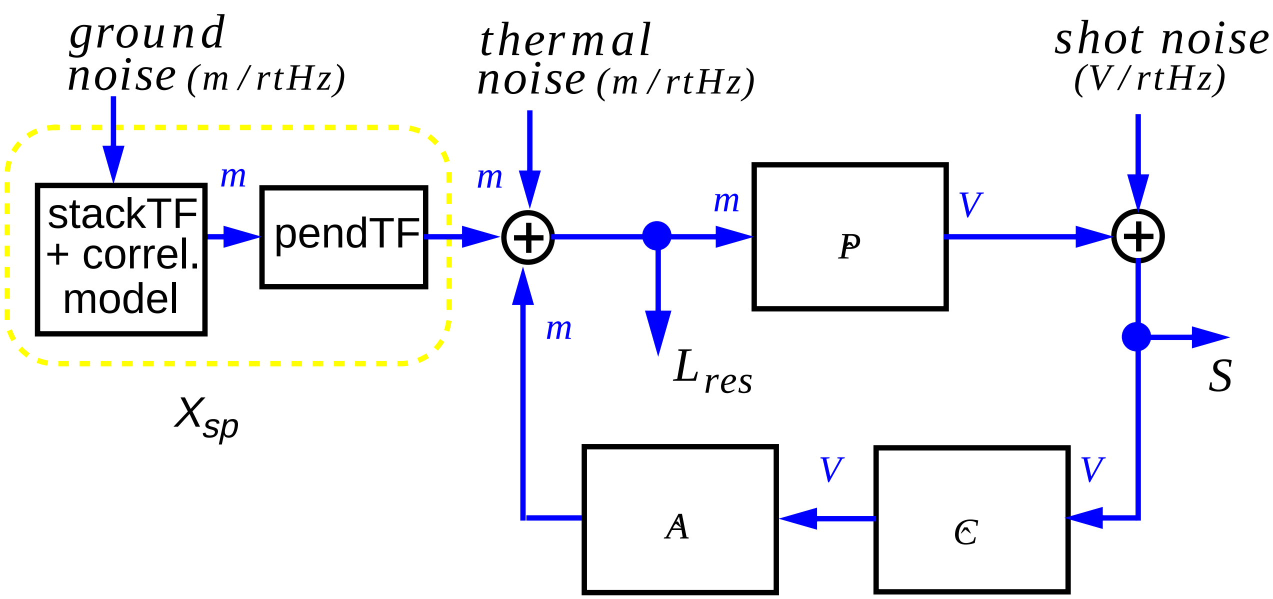
ISC Sensing Table Schematic



ISC Table Assembly/Test



Control Model and Residual Motion Requirements



$$\vec{L}_{res} = M^{-1}(X_{sp}\vec{L}_{gnd} + \vec{L}_{therm} + AC\vec{S}_{shot})$$

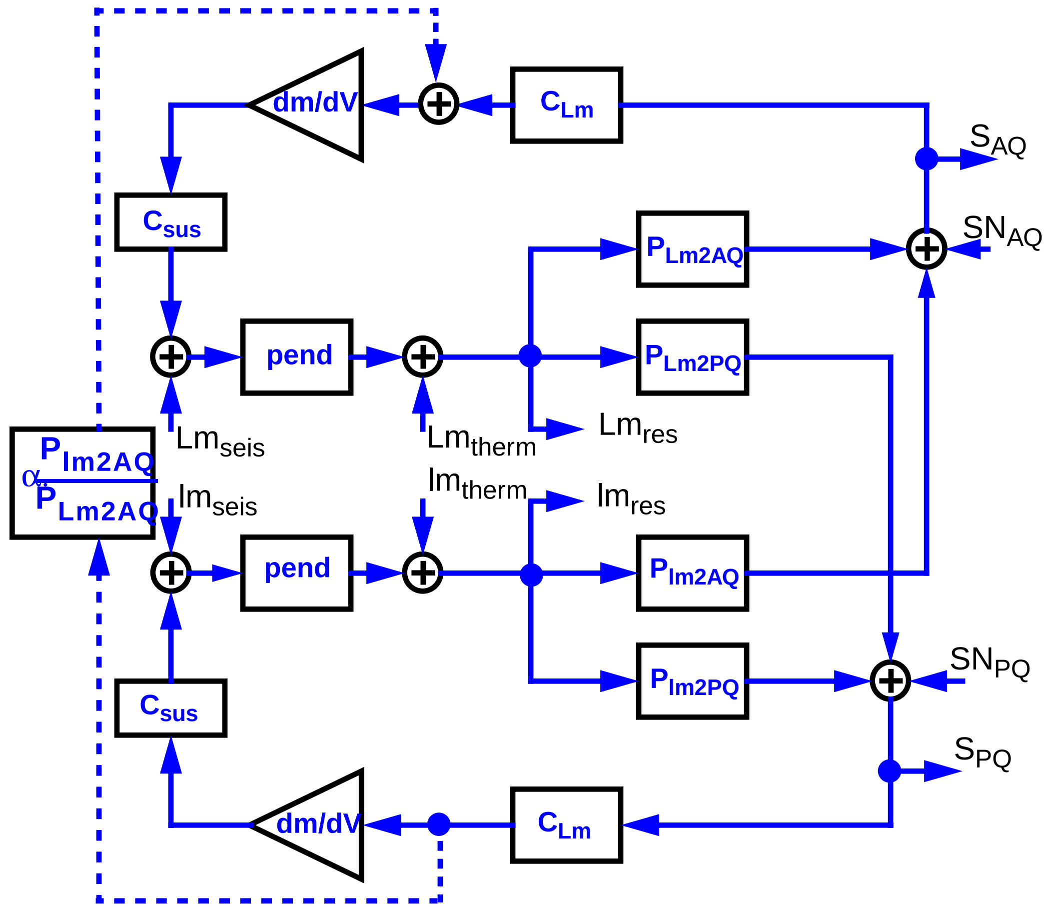
$$M = 1 - ACP$$

Gain, Residual Motion & Noise Constraints

Degree of freedom	*Residual deviation*	*Units*	*Coupling mechanism*
$\delta Lm + (\pi/(2F))\delta lm$	1×10^{-13}	m_{rms}	Amplitude noise coupling
$\delta lm + (\pi/(2F))\delta Lm$	1×10^{-9}	m_{rms}	Amplitude noise coupling
$\delta(k_l \cdot Lp)$	9×10^{-6}	rad_{rms}	Arm cavity power reduction
$\delta(k_l \cdot lp)$	7×10^{-4}	rad_{rms}	Arm cavity power reduction

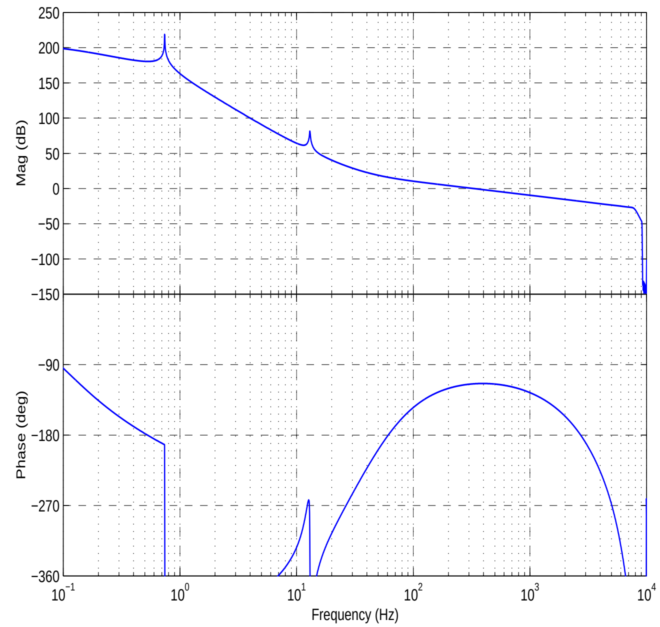
- Gain limits: TM internal resonances (f ~ 6.8 kHz, Q ~ 10^7)
- Bleedthrough of shot noise from “noisy” d.o.f. (e.g., l_-)
- Electronics noise and dynamic reserve

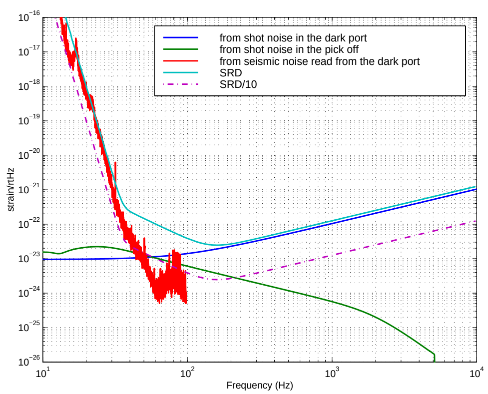
Differential-mode loop model



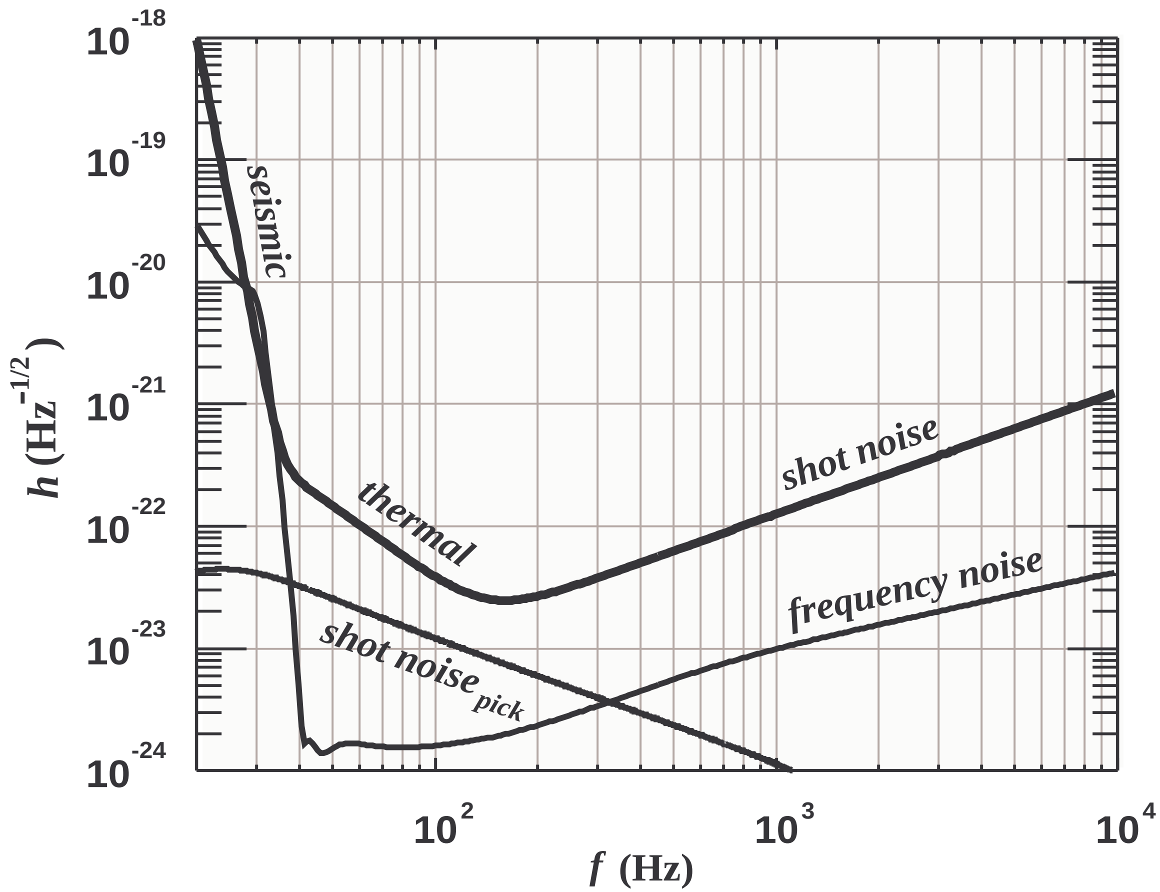
Differential loop design and performance

Performance Data	Lm	lm	Units
Gain at DC	205	110	dB
Unity gain bandwidth	330	43	Hz
Phase margin	66	55	deg
Gain at 9.48 kHz (5.58 kHz)	–140	(–141)	dB
Residual length deviation	10^{-14}	5×10^{-12}	m_{rms}
Control signal at coil driver	3.1	0.13	μm_{rms}





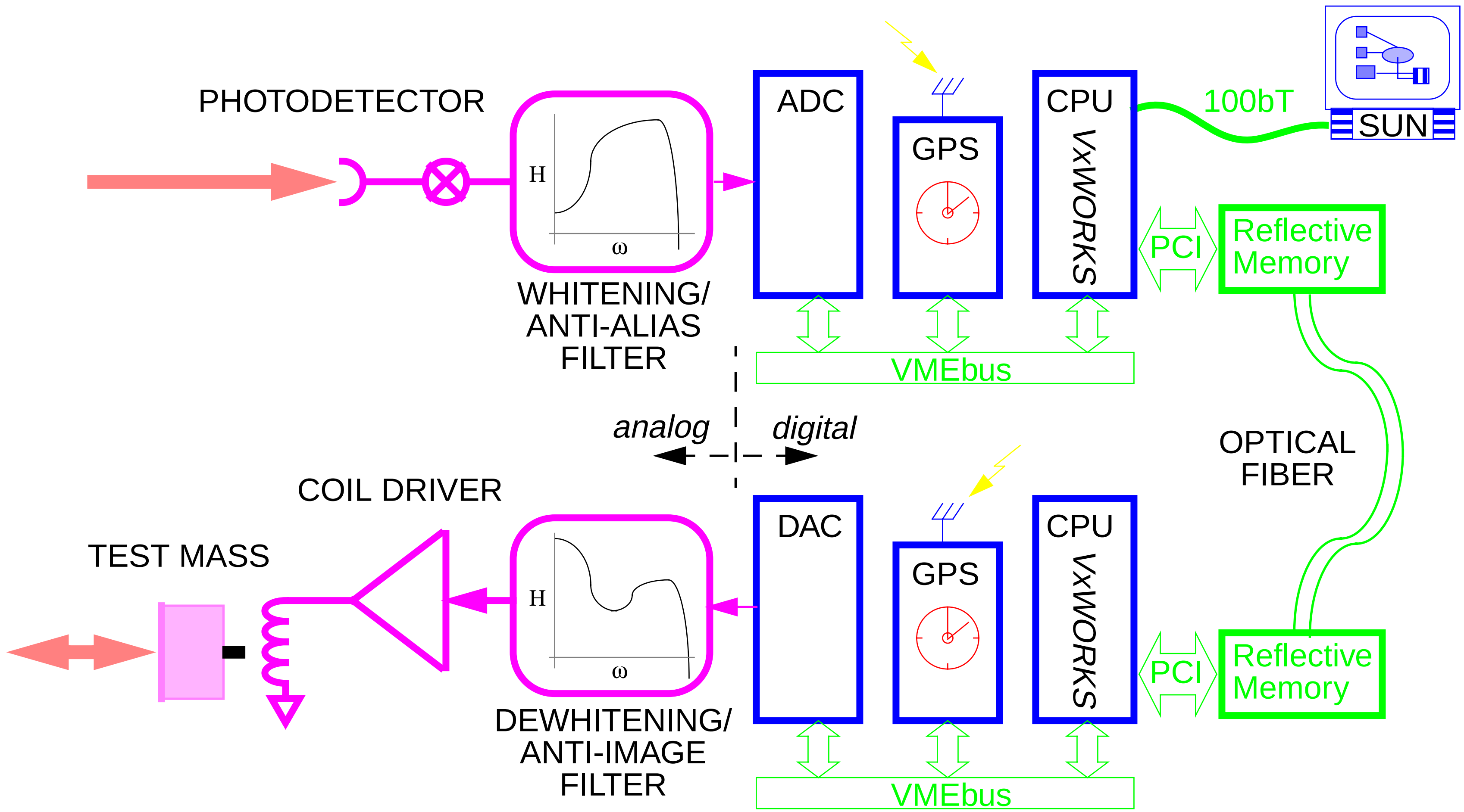
Residual contribution to noise



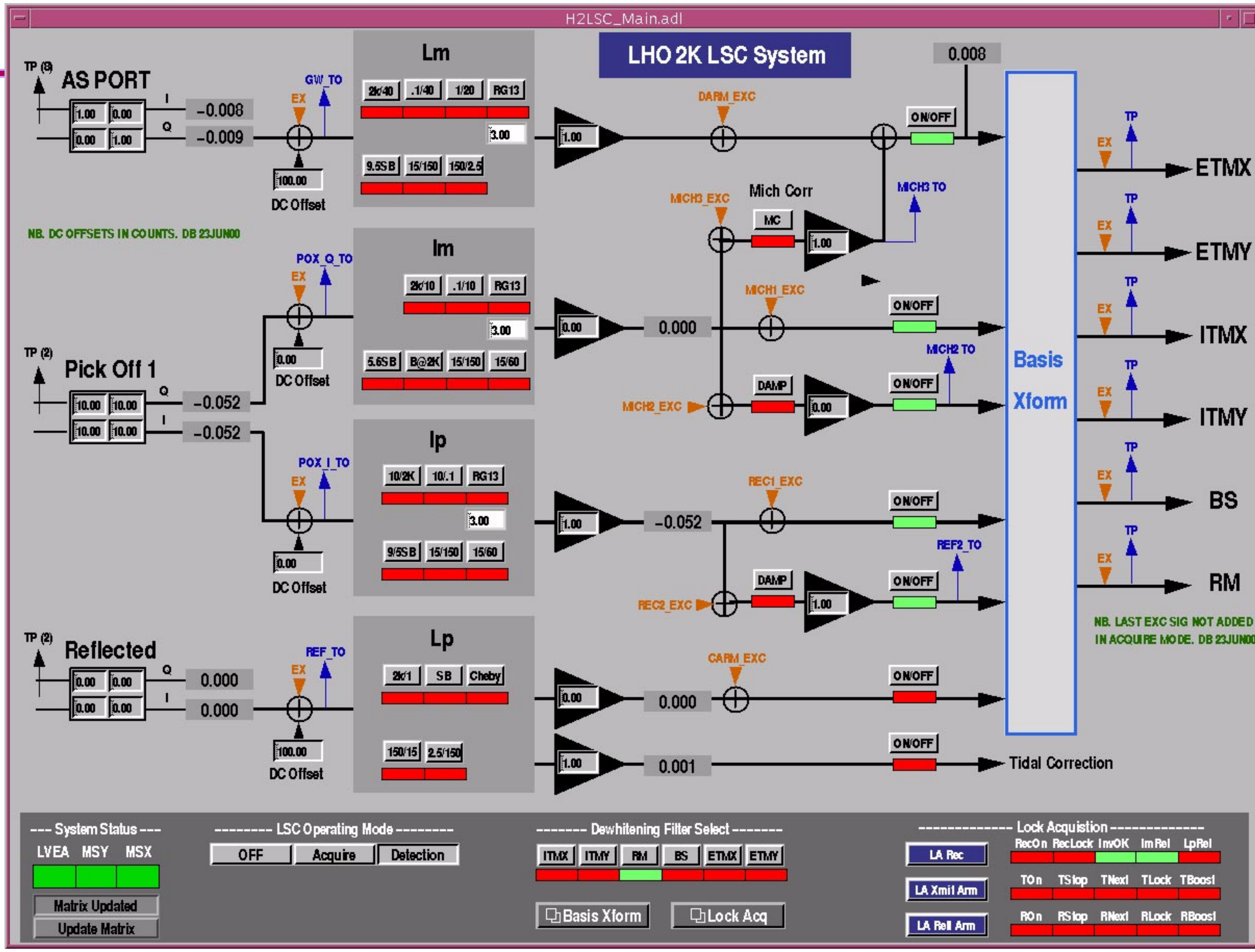
Controls Implementation: Digital Signal Processing

- Superior filter performance, flexibility, and stability, but with some tricky issues:
  - ◊ dynamic range (especially output DAC)
  - ◊ speed/bandwidth (one path, high-speed laser feedback, remains analog)
  - ◊ network bandwidth & time delays (local & 4 km)
- Hardware solution:
  - ◊ Pentek 6102 ADC/DAC (16-bit, low pipeline delay); f_S = 16,384 Hz
  - ◊ 550 MHz Pentium CPU running VxWorks operating system
  - ◊ Fiberoptic “Reflective Memory” network
  - ◊ EPICS supervisory command & control via Ethernet

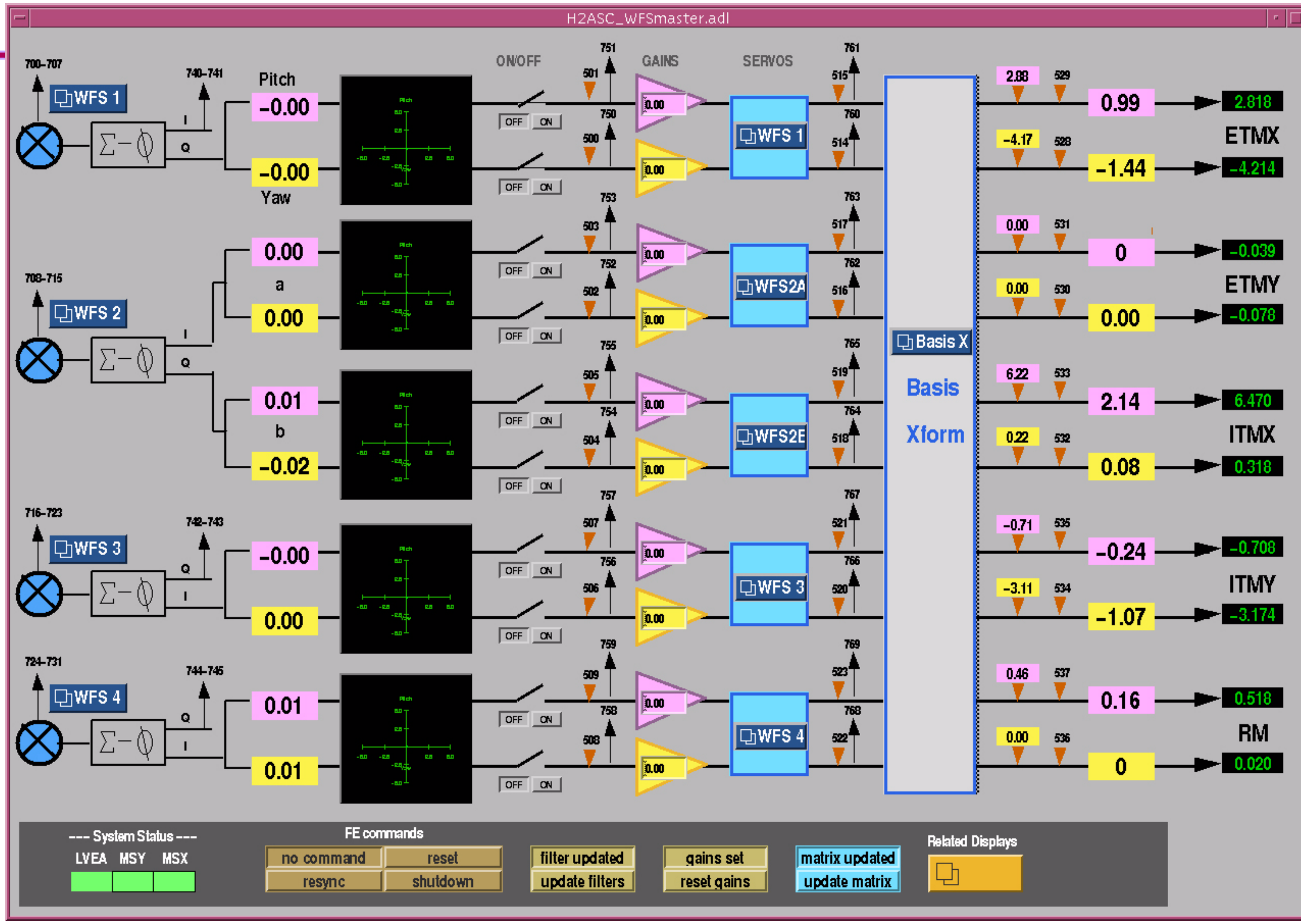
ISC Signal Processing



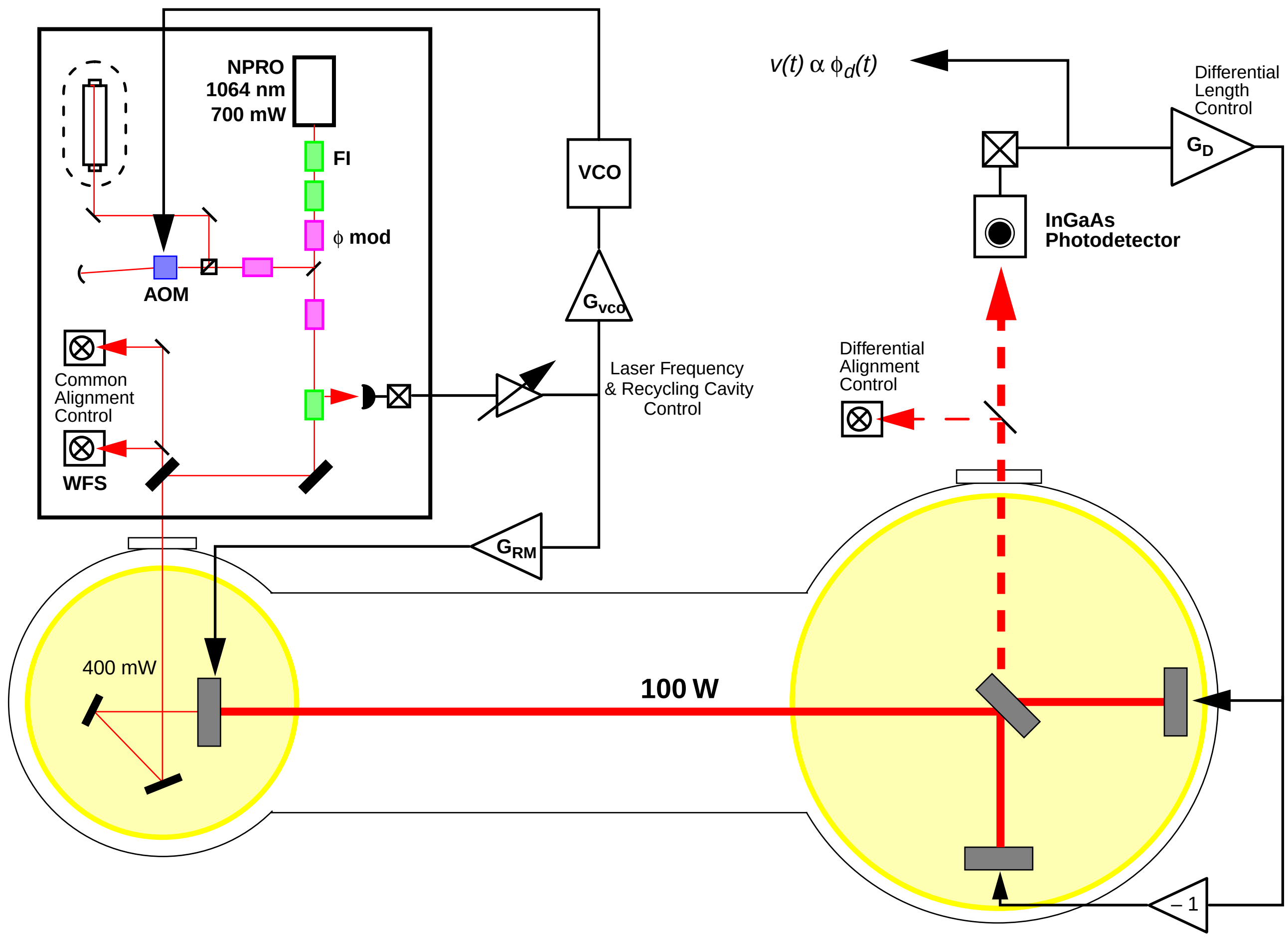
LSC Master Control Screen



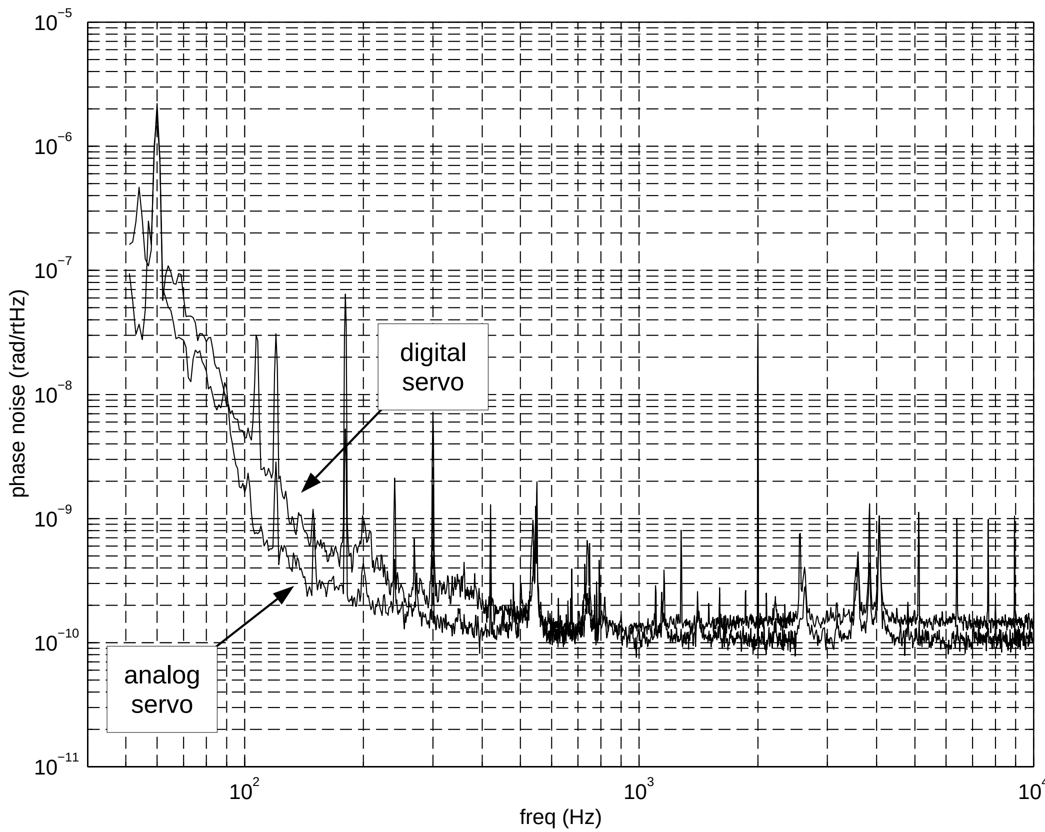
WFS Master Control Screen



Phase Noise Interferometer

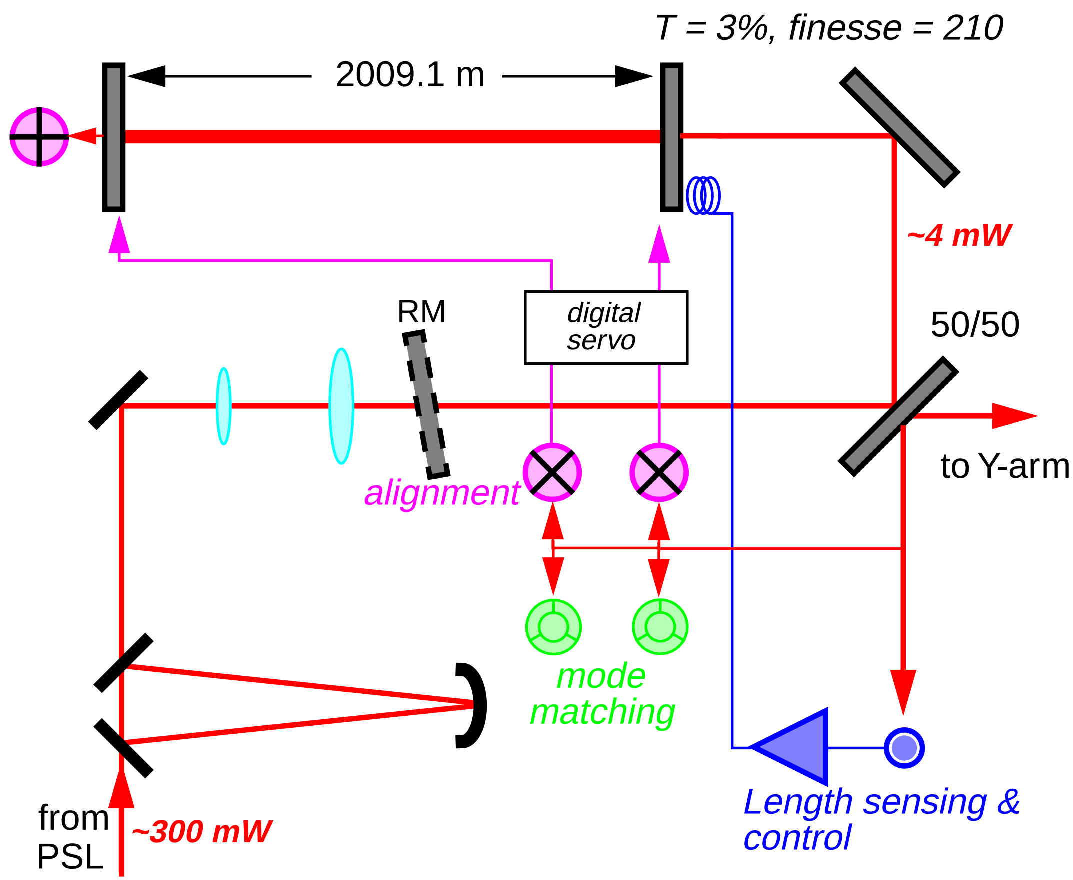


PNI Digital Loop Test Result



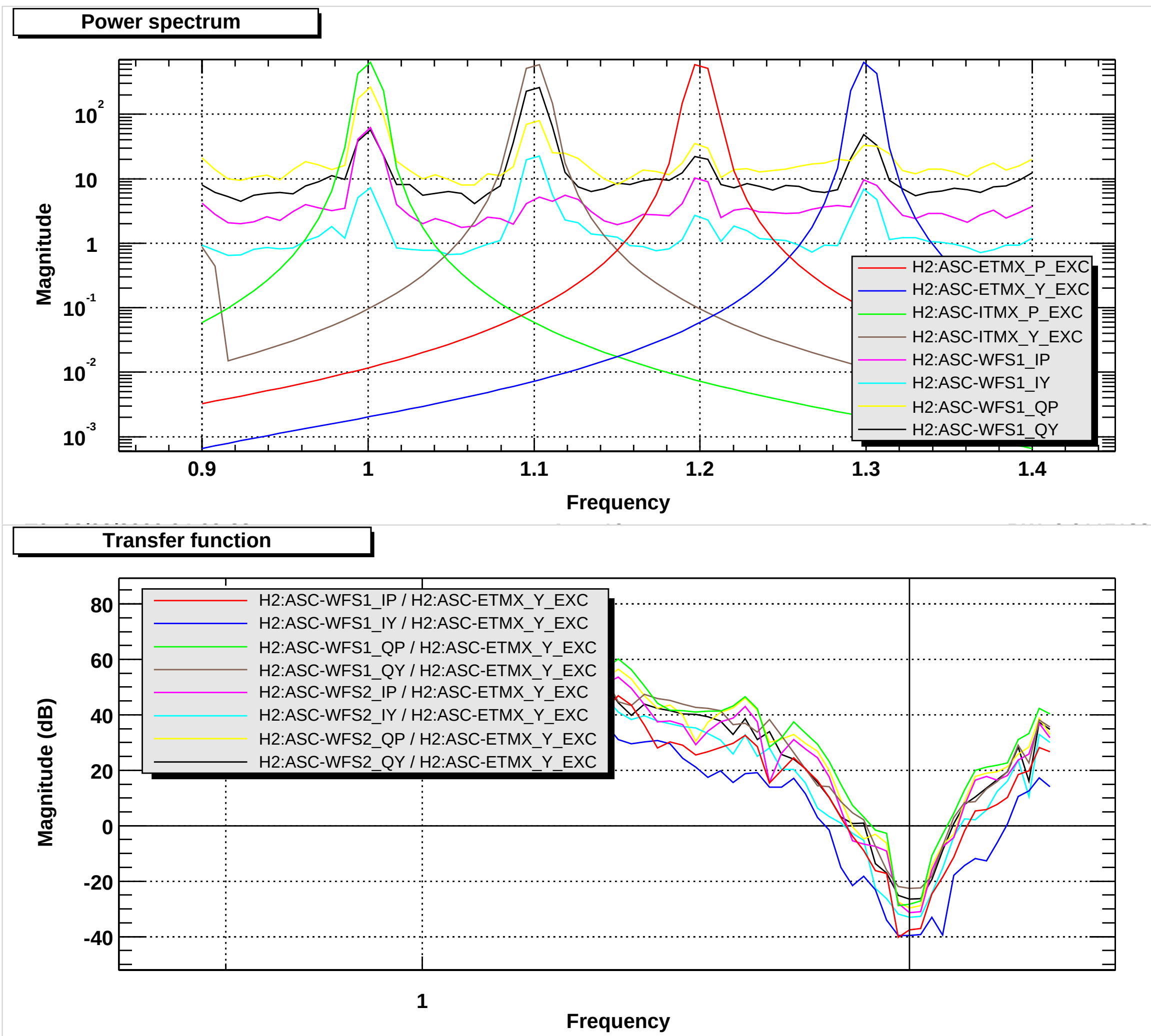
Single-arm cavity test on Hanford 2km X arm

- Tested ~ half of total WFS control system
- Digital controls, net-works & software all worked flawlessly
- Exercised fast ana-log laser frequency controller
- Verified core optics meet specs (!)



WFS Matrix Element Measurement

- Simultaneously excite 4 test masses at different frequencies
- Read out responses of 4 wavefront sensor channels & derive matrix elements



Current Status

- Mode cleaner & laser frequency controls fully operational
- Core optics for recycled Michelson now aligned with arm cavities; *compound interference fringes achieved*
- Remaining electronics & software for full Wa 2k IFO length and alignment installed & tested
- Expect to start locking runs on recycled short Michelson this week
- Livingston 4k following close behind as bugs are worked out at Hanford