Length Sensing & Control Subsystem Design Requirements Review

J. Camp, L. Sievers, M. Zucker

4/30/96

LSC DRR

Charge

1) Determine whether the requirements identified in the Design Requirements Document (DRD) are complete; advise whether proposed requirement values are appropriate; if needed, recommend additional requirements to be specified, and recommend other appropriate actions. Some specific points to consider are:

- definition of the scope and objectives
- delineation of interfaces
- performance requirements
- physical and environmental requirements
- documentation
- testing criteria

2) Evaluate the conceptual design of the LSC subsystem to determine if it is

- consistent with the DRD
- sufficiently developed to proceed with a Preliminary Design

LSC DRR

Agenda

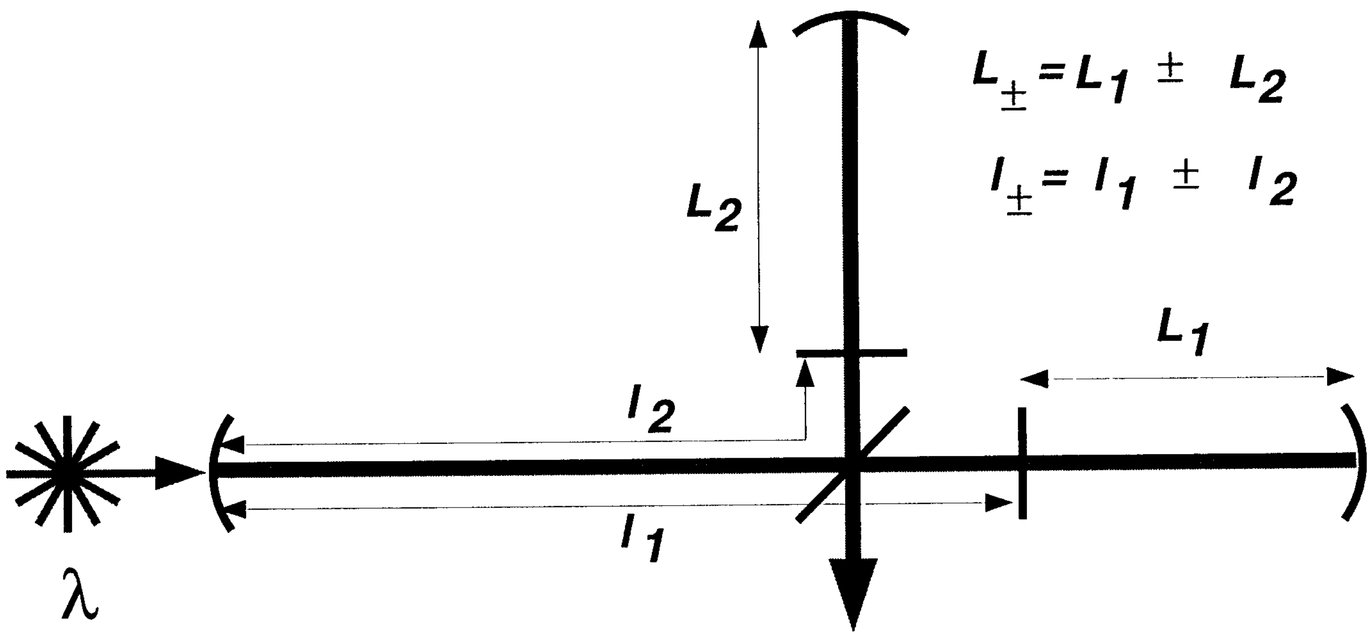
09:00-09:05	Charge, Introduction (DHS, 5 min)
09:05-09.30	LSC Overview (Zucker)
09.30-10:15	Requirements, Part I: Control Loop Constraints (Camp)
10:15-10:45	Conceptual Design, Part I: Control Loop Design (Sievers)
10:45-11:30	Requirements, Part II: Hardware, Diagnostics and Calibration (Camp)
11:30-12:00	Conceptual Design, Part II: Hardware, Diagnostics and Calibration (Zucker)
13:00-13:30	Summary; Open Issues and Focus Areas for Preliminary Design (Zucker)
13:30-14:30	Document Review and Closeout (DHS)

II. LSC Overview

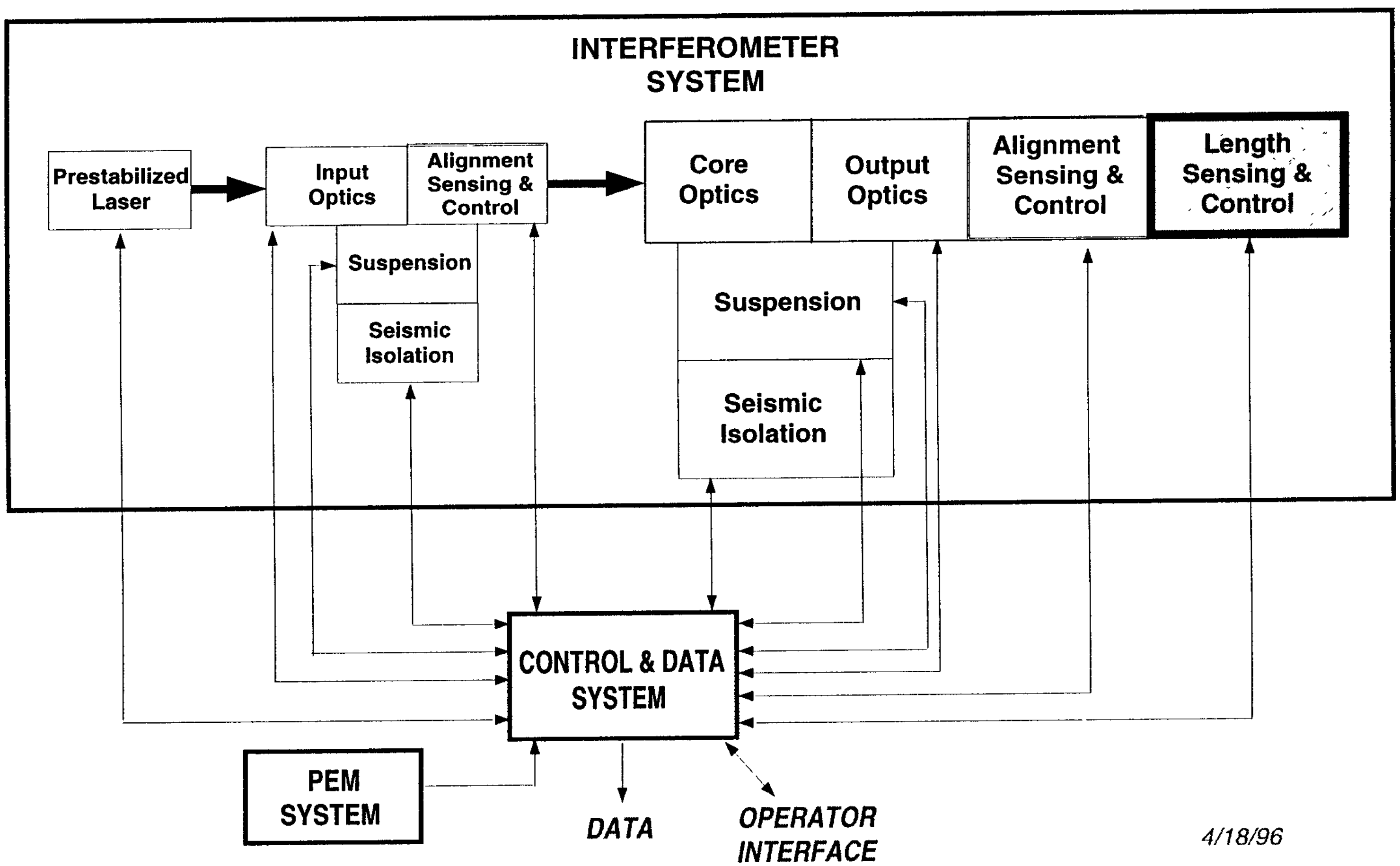
THE LSC MISSION:

- Acquire and maintain optical resonance in LIGO cavities, providing a linear optical phase response to strain;
- Stabilize cavity lengths and laser wavelength to minimize susceptibility to laser and environmental noise;
- Provide filtered strain readout *consistent with SRD sensitivity and availability*, suitable for recording and analysis;
- Support commissioning, test and diagnostics of itself and other subsystems.

Interferometer Lengths: Definitions

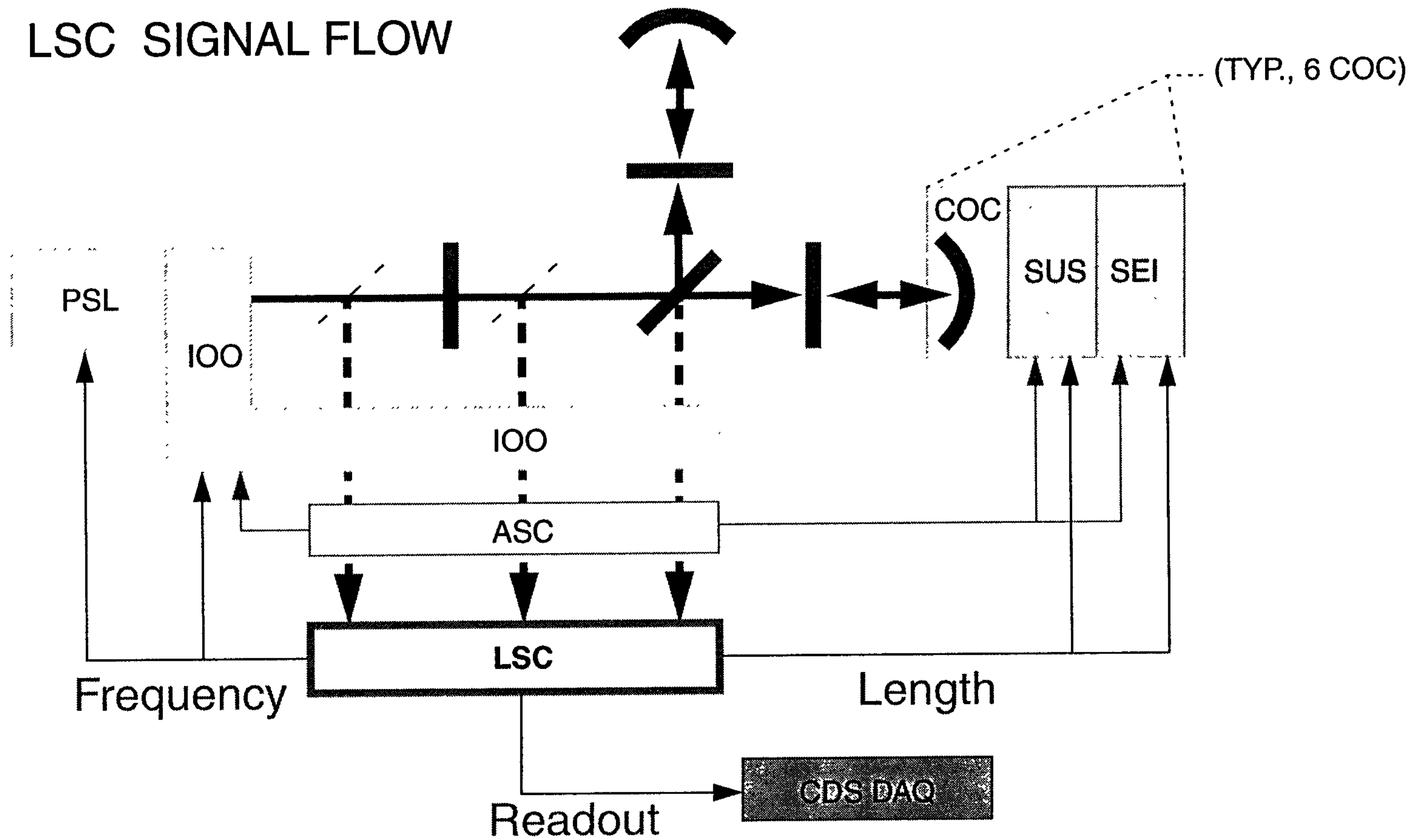


LSC Detector Context



LSC Context (Cont'd)

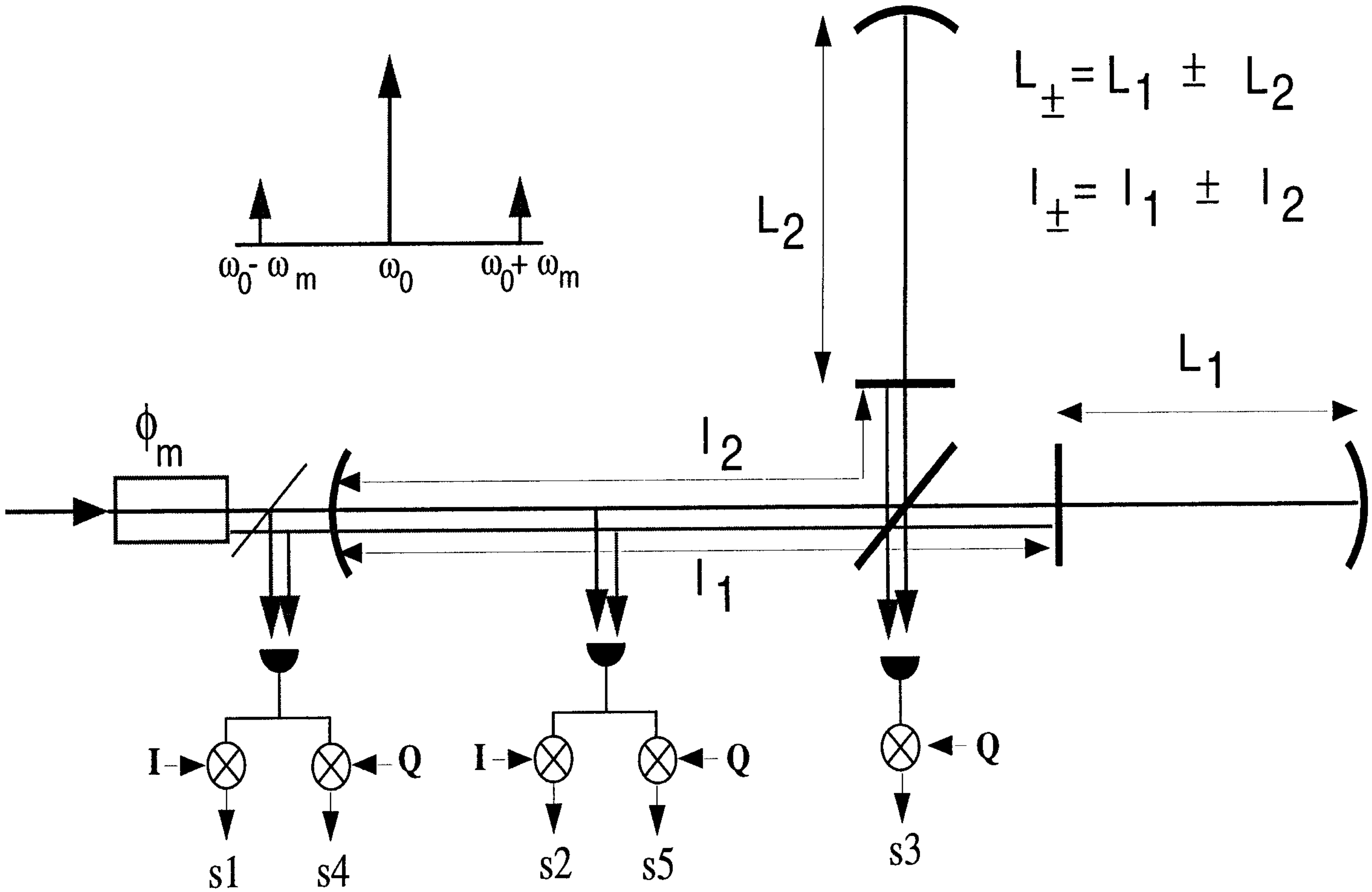
LSC SIGNAL FLOW



LSC Modulation and Readout

- Baseline:
  - ››Single carrier, single-frequency phase modulation
  - ››Asymmetry readout
  - ››Sensing matrix “diagonalized” by loop gain hierarchy: $G(L_+) >> G(l_+)$
- Option:
  - ››Additional nonresonant sideband
- Fallbacks:
  - ››Frequency-shifted subcarrier (FSSC)
  - ››Auxiliary Mach-Zehnder

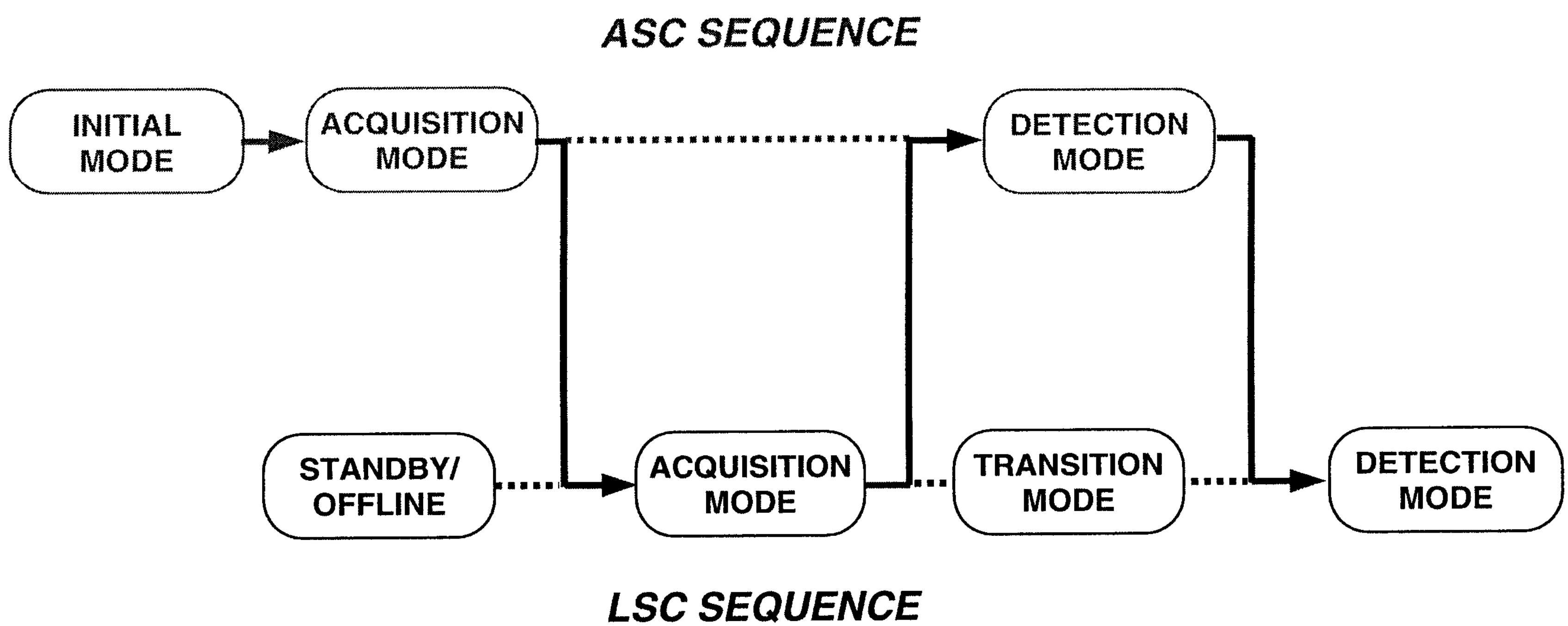
LSC Modulation and Readout (cont'd)



LSC Modes of Operation

- Acquisition mode
  - ››Optical response nonlinear
  - ››High dynamic reserve; noise, gains noncritical
  - ››Sequencing "intelligence," nonlinear damping --> *fast acquisition*
- Transition mode
  - ››Settle transients & signal ASC transition (e.g. apply WFS signals); self-test
  - ››Linear operation, high dynamic reserve, moderate noise
- Detection mode
  - ››Optical response linear (cavities "resonant," circulating fields in equilibrium)
  - ››Low noise required, loop gain critical

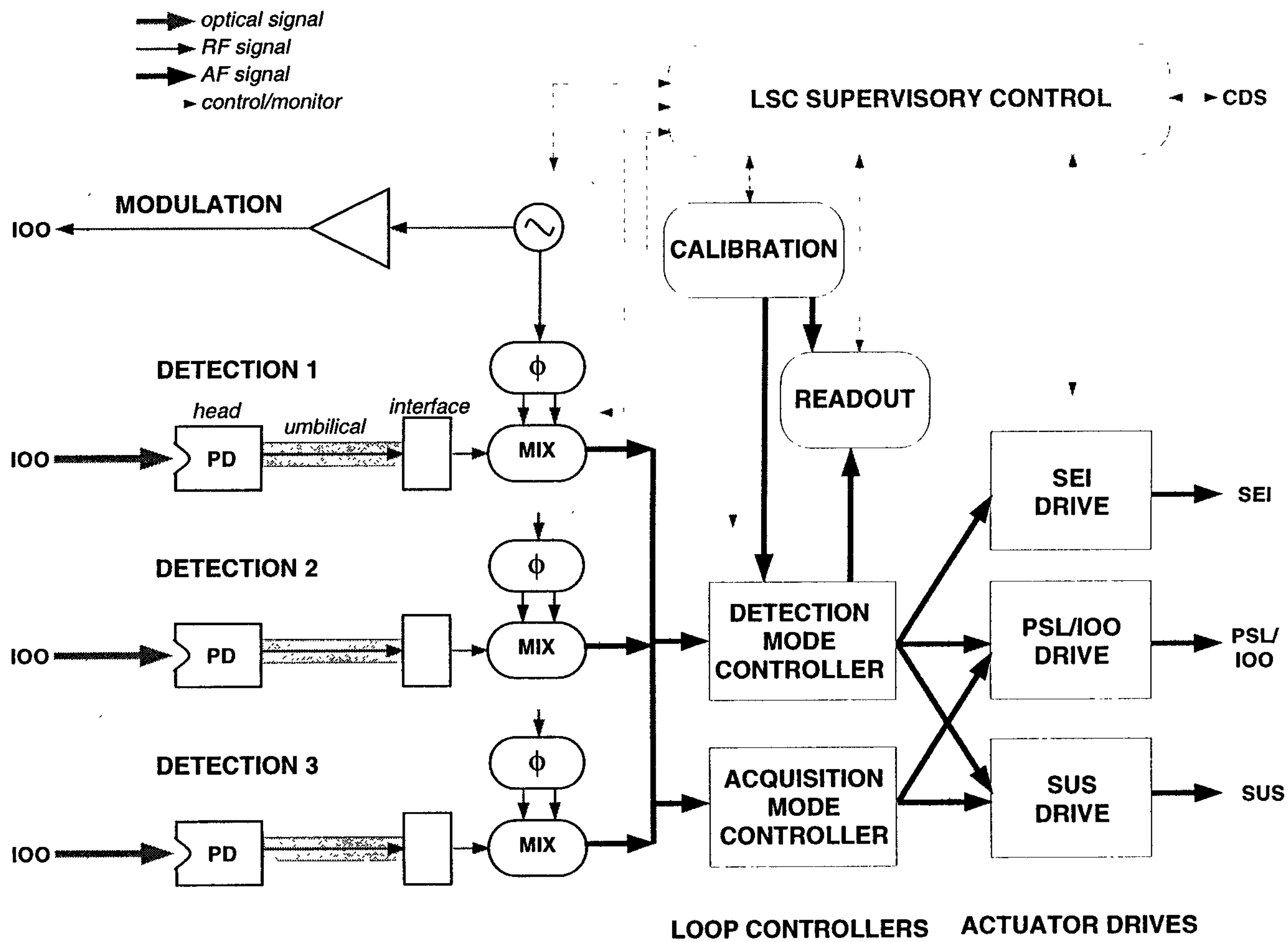
LSC Modes (cont'd): LSC/ASC sequencing



LSC Modes (cont'd)

- Diagnostic/Calibration mode(s)
  - ››Stimulus/Response tests:
    - –Frequency response measurements (e.g. readout frequency response calibration)
    - –Parametric tests (e.g. laser AM coupling vs. fringe offset)
  - ››Variations in Control Topology
  - ››Variations in Optical Topology

LSC Functional Block Diagram



III. - V. Requirements and Conceptual Design Presentations

III. Control Requirements and Constraints (J. Camp)

IV. Sample Control Design (L. Sievers)

V. Other Requirements (J. Camp)

VI. Hardware, Diagnostics, and Calibration (M. Zucker)

VII. Key Preliminary Design Issues (M. Zucker)

LSC Design Requirements Control Loop Constraints

Jordan Camp

Lisa Sievers

Mike Zucker

Constraints and Assumptions

- **LIGO Scientific Requirements Document**
  - ››x (100 Hz) = 10^{-19} m / $Hz^{1/2}$
  - ››x (10 kHz) = 4 x 10^{-18} m / $Hz^{1/2}$

- SYS DRD
  - ››IFO input power - 6 W
  - ››arm knee frequency ~ 90 Hz
  - ››also flowdown of following subsystem parameters:

- IOO Output Light Noise
  - ››$\delta\nu/\nu$ ~ 1 x 10^{-4} Hz / $Hz^{1/2}$ at f = 100 Hz (Thermal noise)
  - ›› ~ 1 x 10^{-5} Hz / $Hz^{1/2}$ at f = 10 kHz (" ")
  - ››$\delta I/I$ < 10^{-8} Hz / $Hz^{1/2}$ for f > 40 Hz

Assumptions and Constraints (cont.)

- Core Optics parameters

  ››Loss per optic (‘bare losses’ and microroughness)- 50 ppm

  ››Arm storage time mismatch ~ 1% (--> FREQUENCY NOISE)

  ››Contrast defect < 0.1%

  ››DC power: ~600 mW sideband at GW port, ~80 mW IFO reflected port (-->SHOT NOISE)

  ››accrued cavity losses < 100 ppm contamination

- Seismic Excitation of Test Mass

  ››4 layer Viton seismic stack; $Q_{layer} = 5$

  ››Livingston Parish seismic spectrum

  ››Single pendulum suspension: f=0.74 H

  ››open loop Δx_{rms} ~ 1 micron (over 7 sec period)

Availability Requirements (Transition Times)

- Acquisition mode to transition mode
  - ››drivers: availability and commissioning
  - ››complicated SYS issue involving SEI, SUS, ASC, FAC
  - ››requirement: < 40 sec (TBD SYS)
- Transition mode to detection mode
  - ››driver: availability
    - —passive: 2 - 5 minutes (similar Q, ν_{violin} to 40 m)
    - —active: < 2 minutes
  - ››requirement: < 2 minutes (TBD SYS)
- Above requirements -> 2 % impact on availability for loss of lock every 2 hours

Detection Mode Requirements

- We derive all noise requirements below assuming that the related noise amplitude spectral density is held to 10% of the LIGO sensitivity *h(f)* at all in-band frequencies.
  - ››40 - 10000 Hz defines “in-band”

Residual RMS Motion

Table 1: Requirements on RMS Deviations from Resonance

Length	*Allowed RMS deviation*	*Noise Mechanism*	*GW S/N degradation*
1. L_-	1×10^{-12} m	intensity noise -> strain noise	0.5 %
2. L_+	2.5×10^{-12} m	loss of 1% arm stored power	0.5 %
3. l_-	1.3×10^{-10} m	intensity noise -> strain noise	0.5 %
4. l_+	1.6×10^{-10} m	loss of 1% arm stored power	0.5 %

1. $x_{noise} = L_{-(rms)}\ (\Delta I / I)$ (Noise on RF sidebands)
2. Deviation from fringe center causes lower arm/recycling cavity field.
3. Noise coupling reduced by factor $2/(1-r_F) \sim 130$
4. Noise coupling reduced by factor $1/(1-r_F) \sim 65$

Other constraints:

- Contrast defect requirement ($P_C < 1\%\ P_{DC}$)

  ›› $L_- = 10^{-11}$ m

  ›› $l_- = 10^{-9}$ m

- 1% differential arm storage time requirement

  ›› $L_- = 10^{-10}$ m

Calculation of Noise Couplings

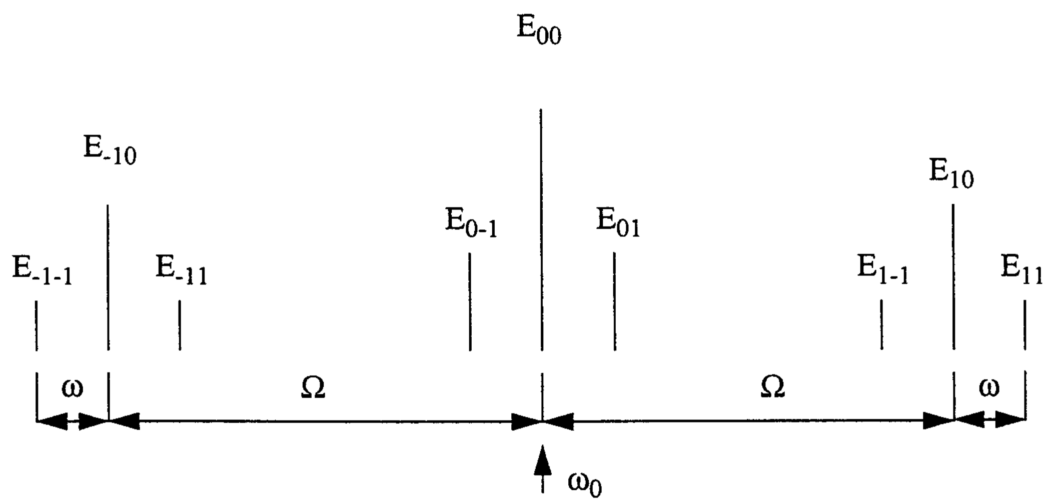


Table 2: Audio sidebands on light

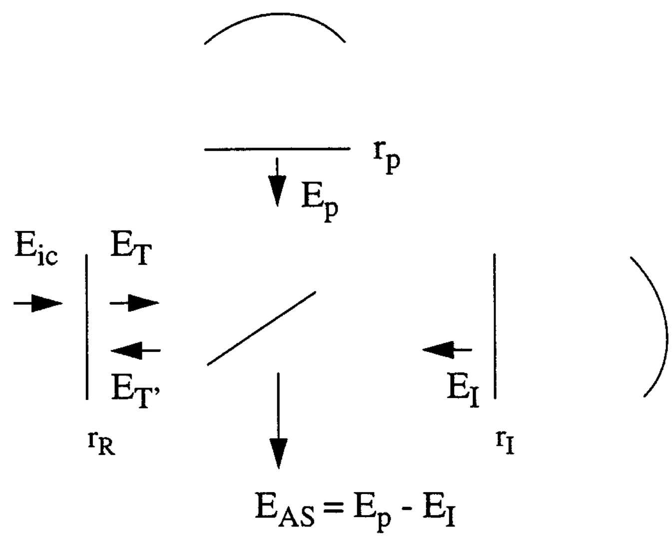
	E_{-1-1}	E_{-10}	E_{-11}	E_{0-1}	E_{00}	E_{01}	E_{1-1}	E_{10}	E_{11}
Laser ν noise	$\frac{-i\Gamma\pi\delta\upsilon}{2\omega}$	$\frac{i\Gamma}{2}$	$\frac{i\Gamma\pi\delta\upsilon}{2\omega}$	$\frac{-\pi\delta\upsilon}{\omega}$	1	$\frac{\pi\delta\upsilon}{\omega}$	$\frac{-i\Gamma\pi\delta\upsilon}{2\omega}$	$\frac{i\Gamma}{2}$	$\frac{i\Gamma\pi\delta\upsilon}{2\omega}$
Laser amp noise	$\frac{i\Gamma\delta E}{4E_0}$	$\frac{i\Gamma}{2}$	$\frac{i\Gamma\delta E}{4E_0}$	$\frac{\delta E}{2E_0}$	1	$\frac{\delta E}{2E_0}$	$\frac{i\Gamma\delta E}{4E_0}$	$\frac{i\Gamma}{2}$	$\frac{i\Gamma\delta E}{4E_0}$
Osc. ν noise	$\frac{\Gamma a_o}{4}$	$\frac{i\Gamma}{2}$	$\frac{\Gamma a_o}{4}$		1		$\frac{-\Gamma a_o}{4}$	$\frac{i\Gamma}{2}$	$\frac{-\Gamma a_o}{4}$
Osc. amp. noise	$\frac{i\Gamma\delta A}{4A}$	$\frac{i\Gamma}{2}$	$\frac{i\Gamma\delta A}{4A}$		1		$\frac{i\Gamma\delta A}{4A}$	$\frac{i\Gamma}{2}$	$\frac{i\Gamma\delta A}{4A}$
Signal		$\frac{i\Gamma}{2}$		ik_0X	1	ik_0X		$\frac{i\Gamma}{2}$	

Noise Propagation through IFO

r_P, r_I : complex arm reflectivities

r_R : recycling mirror reflectivity

E_{AS} : carrier field at dark port



- calculate IFO response to frequency spectrum
- mix electric fields and demodulate
- <u>Assumptions</u> for IFO parameters and imperfections are used

- follows approach of Regehr, Whitcomb, Weiss

Implementation of Detection Mode Requirements

- Control System Loop Gains

  ››sufficient to ensure required RMS deviations from resonance

- Auxiliary Sensor Shot Noise

  ››coupling to GW noise < 10% LIGO sensitivity

Laser Frequency Noise at IFO Input

$\delta\nu\ (f)\ < 1 \times 10^{-7}\ Hz\ /\ Hz^{1/2}$ f=100 Hz

$< 4 \times 10^{-6}\ Hz\ /\ Hz^{1/2}$ f=10 kHz

Require:

- Adequate loop gain
- Limited L_+ sensor shot noise

Control System Robustness and Noise

- All control modes shall be robust and easily adaptable to expected interferometer parameter variations by electronic parameter change.

  ››plan on ~100 ppm accrued losses

  ››affects choice of reflectivities

  ››non-resonant sideband control may enhance robustness of l_+ loop

- Require servo electronic noise at the level of < 10% photodiode shot noise for all signal control loops

LSC Design Requirements Hardware, Diagnostics, Calibration

Jordan Camp

Lisa Sievers

Mike Zucker

RF Modulation

- AM noise
  - ›› <-160 dBc / Hz$^{1/2}$ at f >100Hz
- Phase noise
  - ›› < -70 dBc / Hz$^{1/2}$ at 100 Hz
  - ›› <-120 dBc / Hz$^{1/2}$ at 10 kHz
- modulation depth ~0.5 (TBD)
- mixer phase error (configuration dependent - TBD)

RF Photodiode

- Quantum efficiency > 0.8
- Acceptable DC power level in detection mode of ~0.45 W (TBD SYS)
- Adequate protection provided against power surges during acquisition and loss of lock
- Spatial uniformity $< 10^{-2}$ (TBD)

LSC Diagnostics (within LSC Subsystem)

- complete servo loop transfer function measurements
  - ››summing nodes and monitor points
  - ››servo electronic noise and null offsets
  - ››shot noise measurements
- lock acquisition functionality
  - ››test impulses to masses, measure velocity
- photodiode sensitivity and noise
- LSC response to laser light frequency, intensity and pointing modulation
- other (TBD)

LSC Diagnostics (outside subsytem)

- IFO cavity storage time measurements (ring-downs)
- recycling gain and contrast defect
- operation of various configurations: single cavity, recycled Michelson, coupled cavity
- open loop test mass seismic excitation through fringe observation
- SUS and SEI closed loop xfer function
- other (TBD SYS)

Calibration

Strain output shall be calibrated at all times in Detection mode to an accuracy of +/- 1 dB. (TBD SYS).

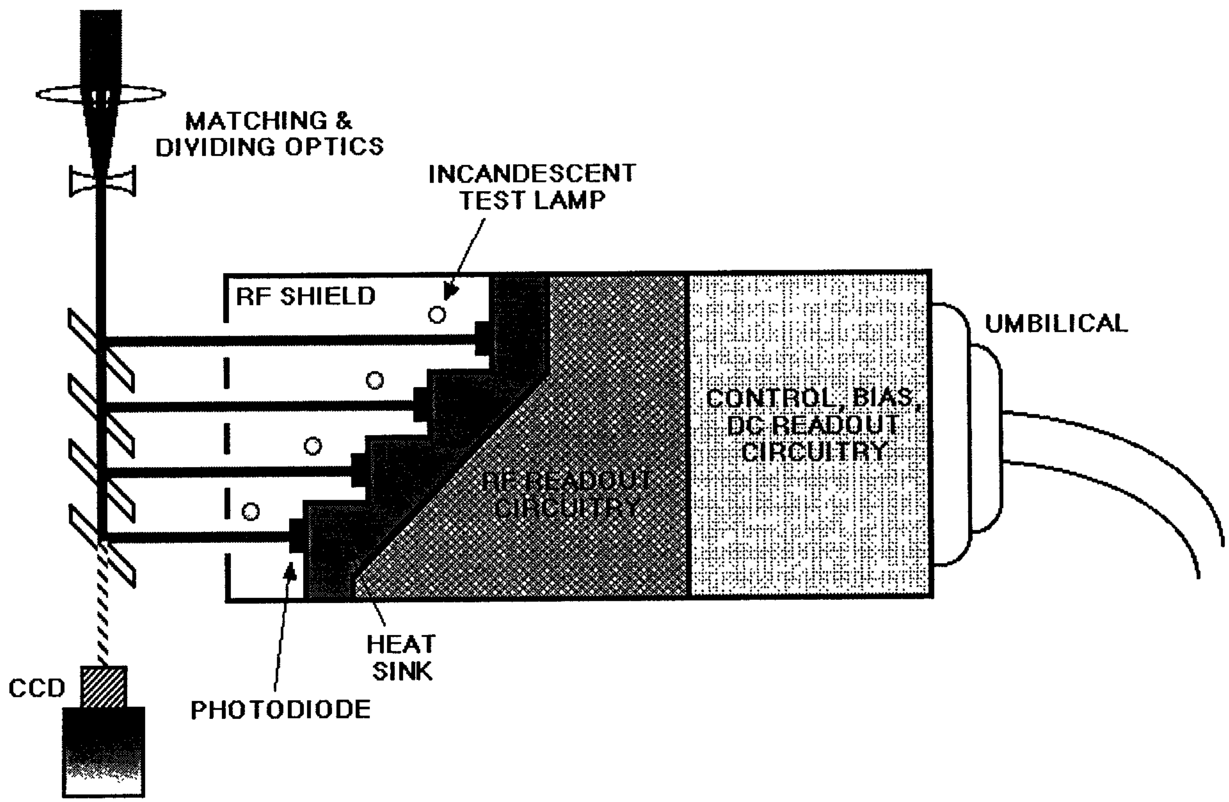
VI. Hardware, Diagnostics, and Calibration Conceptual Design

- Photodetectors
- RF Modulation and Demodulation
- Diagnostic Capabilities
- Calibration

Photodetector Concept: Features

- InGaAs (Q.E. @ 1060 nm, max. I_{DC} , low bias/heat)
- Multiple diodes (4-8) with dividing optics
- Range switchable transimpedances (low Z for Acq. mode)
- Fast crowbar transient protection on reverse bias
- Mechanical shutter (diagnostics, long-term protection)
- RF test in, integral 'shot noise' lamp tester
- Dual package: Head (remote box) + Support/Interface (bin)

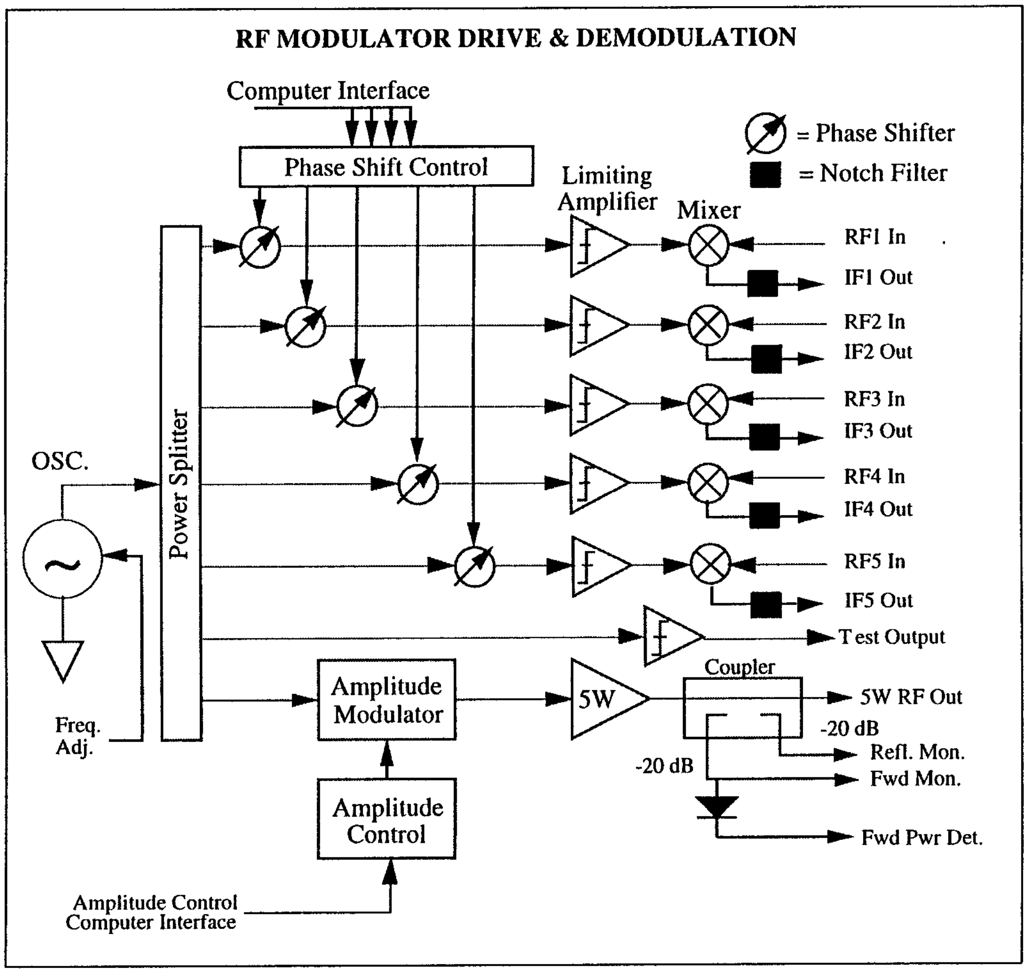
Photodetector Concept (cont'd)



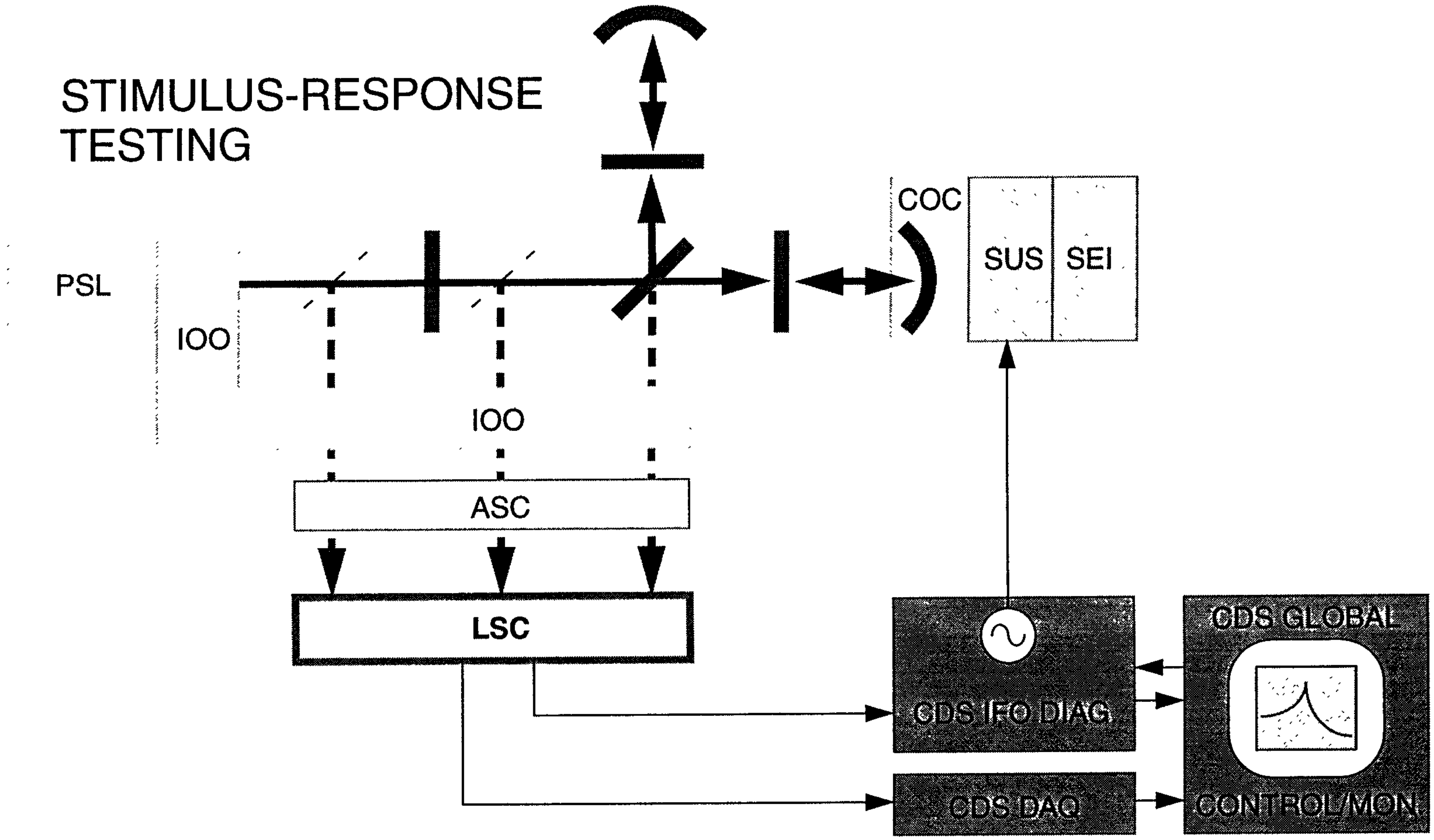
RF Modulation and Demodulation Concept

- Low-noise TCXO primary oscillator
- Low-noise RF power amplifier
- Tunable over TBD range (possibly by oven temp.)
- 'Standard' double-balanced mixers
- Delayline or varicap phase shifters, digital cal. lookup

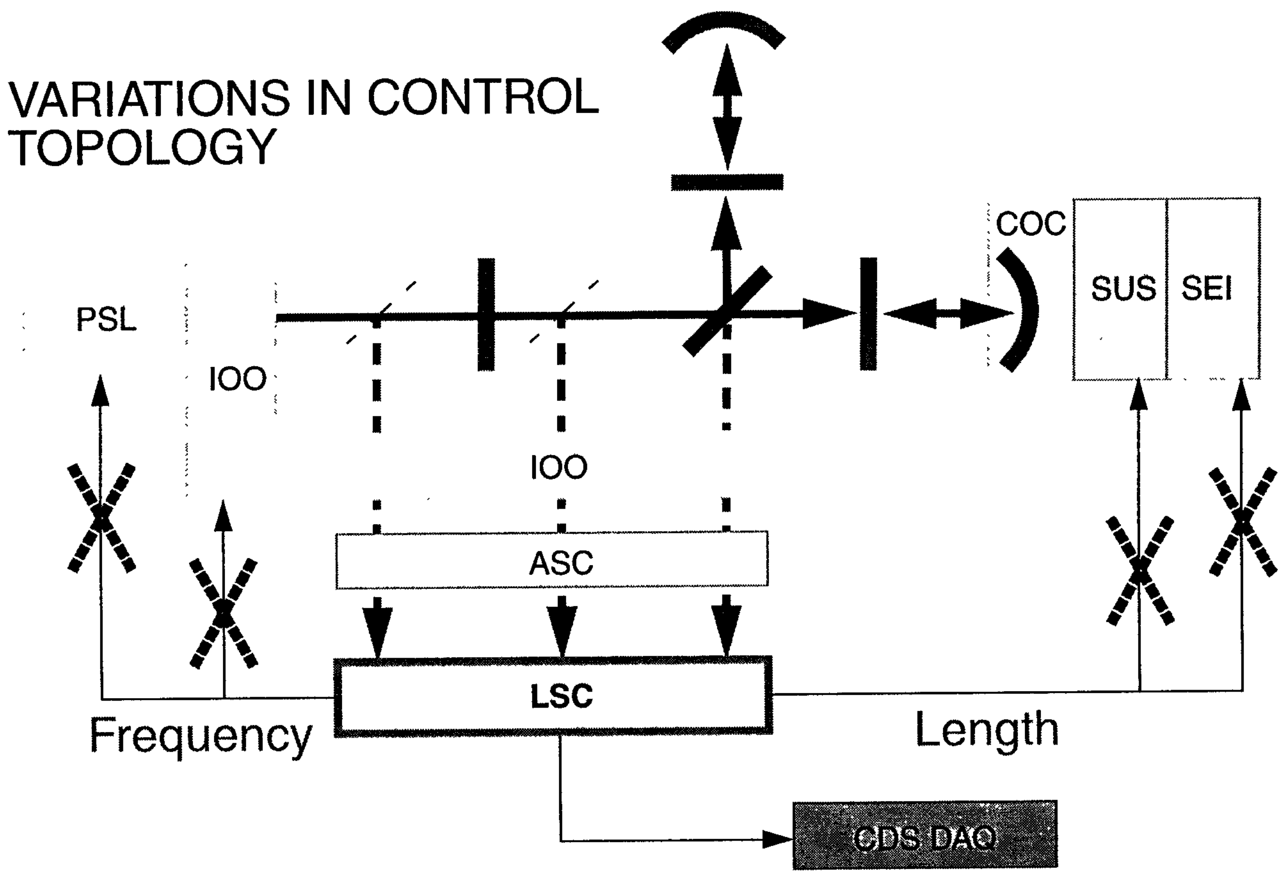
RF Modulation and Demodulation Concept (cont'd)



Diagnostic Capabilities

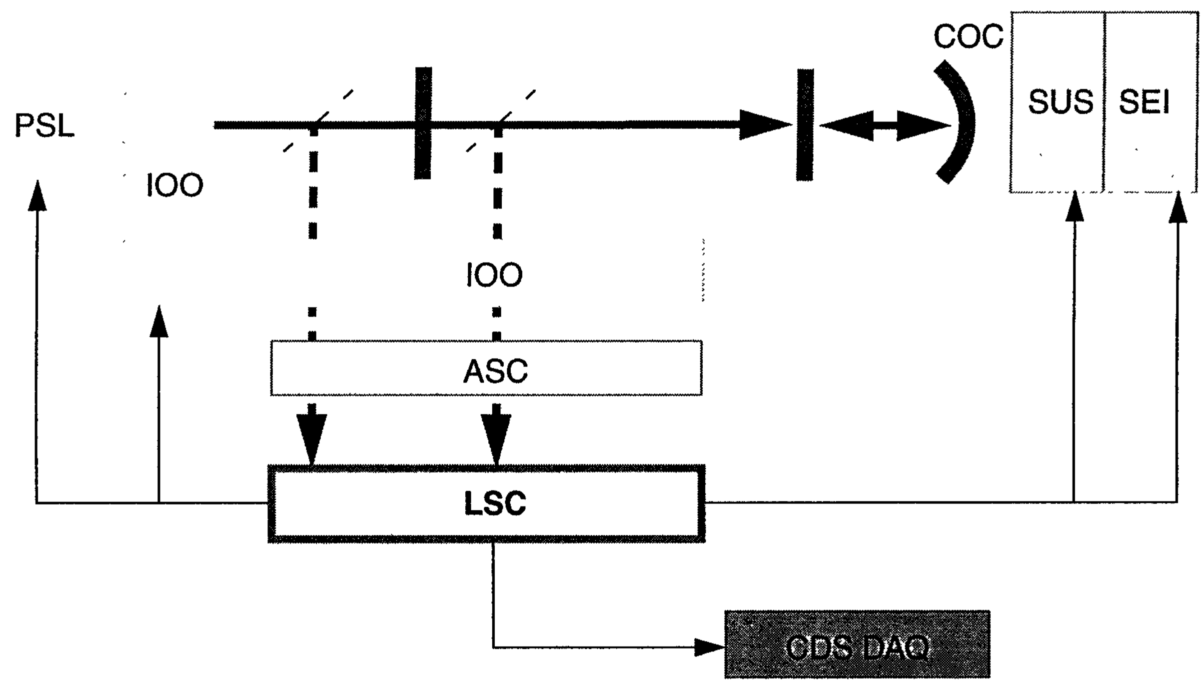


Diagnostic Capabilities (cont'd)



Diagnostic Capabilities (cont'd)

VARIATIONS IN
OPTICAL TOPOLOGY



Calibration

- Absolute:
  - ››Direct component measurements: TM SUS actuator F/I, M, I/V_{mon}
  - ››In situ: $I_{\lambda/2}(f)$
- vs. Frequency:
  - ››Periodic frequency response calibrations
  - ››Normalize loop gains
- vs. Time:
  - ››Continuous sinusoidal test calibration(s)
  - ››Log known influence parameters (circ. power, RF level, temperature, ??)

Calibration (cont'd)

- Crosschecks (at commissioning and/or at intervals):
  - ››Independent laser interferometer
  - ››Direct shot noise calculation
  - ››Residual gas index noise
  - ››Pulsed, modulated light source momentum transfer
  - ››Gravity gradient rotor...

VII. Key Preliminary Design Issues

- Dynamic Reserve/SNR
- Photodetectors
- Signal Transmission
- Digital or Analog?
- Lock Acquisition
- Additional Nonresonant Modulation

Dynamic Reserve/SNR

For a signal y, let $R_y \equiv \dfrac{y_{p-p}}{\min\,[\tilde{y}(f)]}$. Then:

- $R_{i3} \approx \dfrac{60\ \text{mA}}{3 \times 10^{-10}\ \text{A Hz}^{-1/2}} \approx 2 \times 10^{8}\ \ \text{Hz}^{1/2}$ (detection mode only...)
- $R_{L_-} \approx \dfrac{3 \times 10^{-5}\ \text{m}}{3 \times 10^{-20}\ \text{m Hz}^{-1/2}} \approx 10^{15}\ \ \text{Hz}^{1/2}$
- $R_{\ddot{L}_-} \approx \dfrac{3 \times 10^{-4}\ \ \text{m s}^{-2}}{3 \times 10^{-15}\ \text{m s}^{-2}\ \text{Hz}^{-1/2}} \approx 10^{11}\ \ \text{Hz}^{1/2}$

Dynamic Reserve/SNR (cont'd)

For comparison:

- quantized (digital) data stream D_k:

$$R_D = 2^N \sqrt{12 f_s} \approx 3 \times 10^7 \ \ \mathrm{Hz}^{1/2}$$ for N = 16 bits, f_s = 20 kHz

- really good analog opamp (e.g. AD797):

$$R_V \approx \frac{20 \ \mathrm{V}}{10^{-9} \ \mathrm{V\,Hz}^{-1/2}} \approx 2 \times 10^{10} \ \ \mathrm{Hz}^{1/2}$$

- conclusion: electronics implementation NOT TRIVIAL

Dynamic Reserve/SNR (cont'd)

- Approaches:
  - ››better filtration (make signals "whiter" than acceleration)
  - ››nested feedback filter implementations
  - ››high power supply voltages
  - ››digital controls...
- Constraint:
  - ››Optomechanical gain is high; $\frac{\partial i_3}{\partial L_-} \times \frac{\partial L_-}{\partial i_{coil}} \sim 1$ at 140 Hz, so
  - ››Electronic gain required is LOW; low-noise implementation is tough

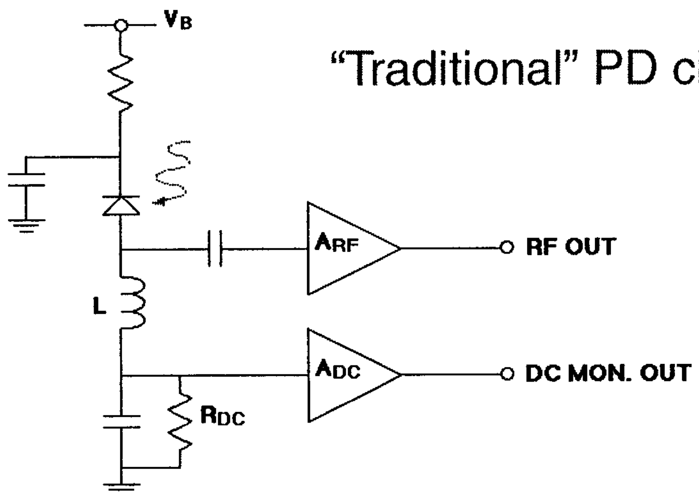
Photodetector Issues

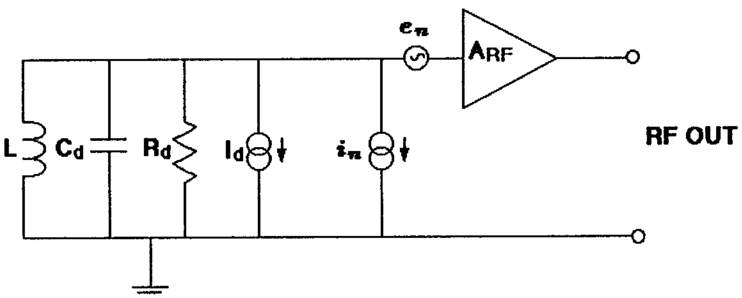
- RF response & circuit design
- Quantum efficiency
- Power handling capability
- Device consistency
- Spatial uniformity
- Linearity

Photodetector Issues (cont'd)

example: RF diode dissipation and Johnson noise

"Traditional" PD circuit & RF equivalent:





- noise < 1/10 x SRD, so $i_{shot}R_d > 10\ N^{1/2}(4kTR_d)^{1/2}$, thus $R_d > 75\ \Omega$[1] or $Q > 6$ ($Q_{Si} < 10$, Q_{InGaAs}= ??)

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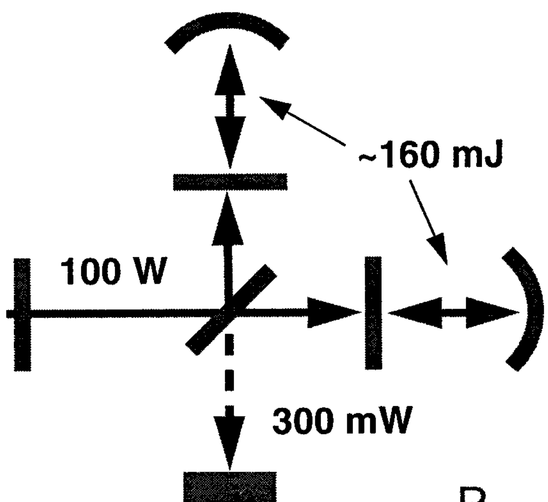
1. InGaAs, 3 mm dia. has C_d ~300 pF$^{(TBR)}$; $\omega_{RF} \sim 2\pi \times 40$ MHz => $|\omega_{RF}C_d|^{-1} \sim 13\ \Omega$; assumes N = 4 diodes (~70 mA DC per diode), i_{shot} = 300 pA/Hz$^{1/2}$, and NO amplifier noise ($i_n = e_n = 0$)

Photodetector Issues (cont'd)

Unlocking power transient:

BEFORE



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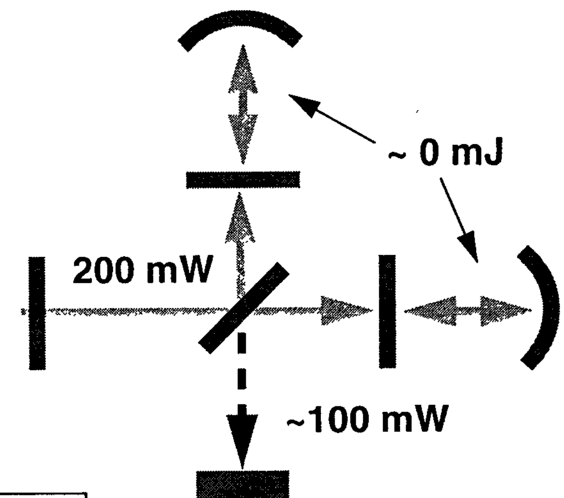

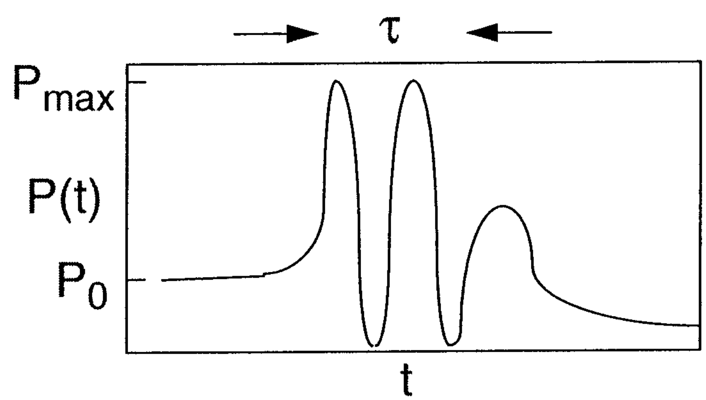

Signal Transmission

(a.k.a. "What? No RG-58 ?!?")

- Problem:
  - ››Feedback signals to ETM's must travel 2 or 4 km without degradation
  - ››No coaxial cable along facility arms (only fiberoptics)
  - ››High dynamic range, SNR, and speed required
- Approaches:
  - ››Special-purpose fiberoptic link (e.g. hybrid analog/digital, FM, ...?)
  - ››Reduced ETM feedback bandwidth
  - ››Digital transmission (ADC, DAC problems?)

Digital or Analog?

- Digital is greatly preferred...
  - ››Better control over loop filter characteristics
  - ››Improved design update cycle (will NOT be perfect the first time)
  - ››Accommodates multiple control modes w/out duplicate hardware
- Significant obstacles;
  - ››Digitization noise & linearity @ ADC (always SOME analog stuff...)
  - ››Output quantization noise & linearity @ DAC (even more analog stuff...)
  - ››Signal processing rate & bandwidth
- CDS group evaluating state of the art; direction to be proposed and reviewed at IFO PDR/CDS DRR.