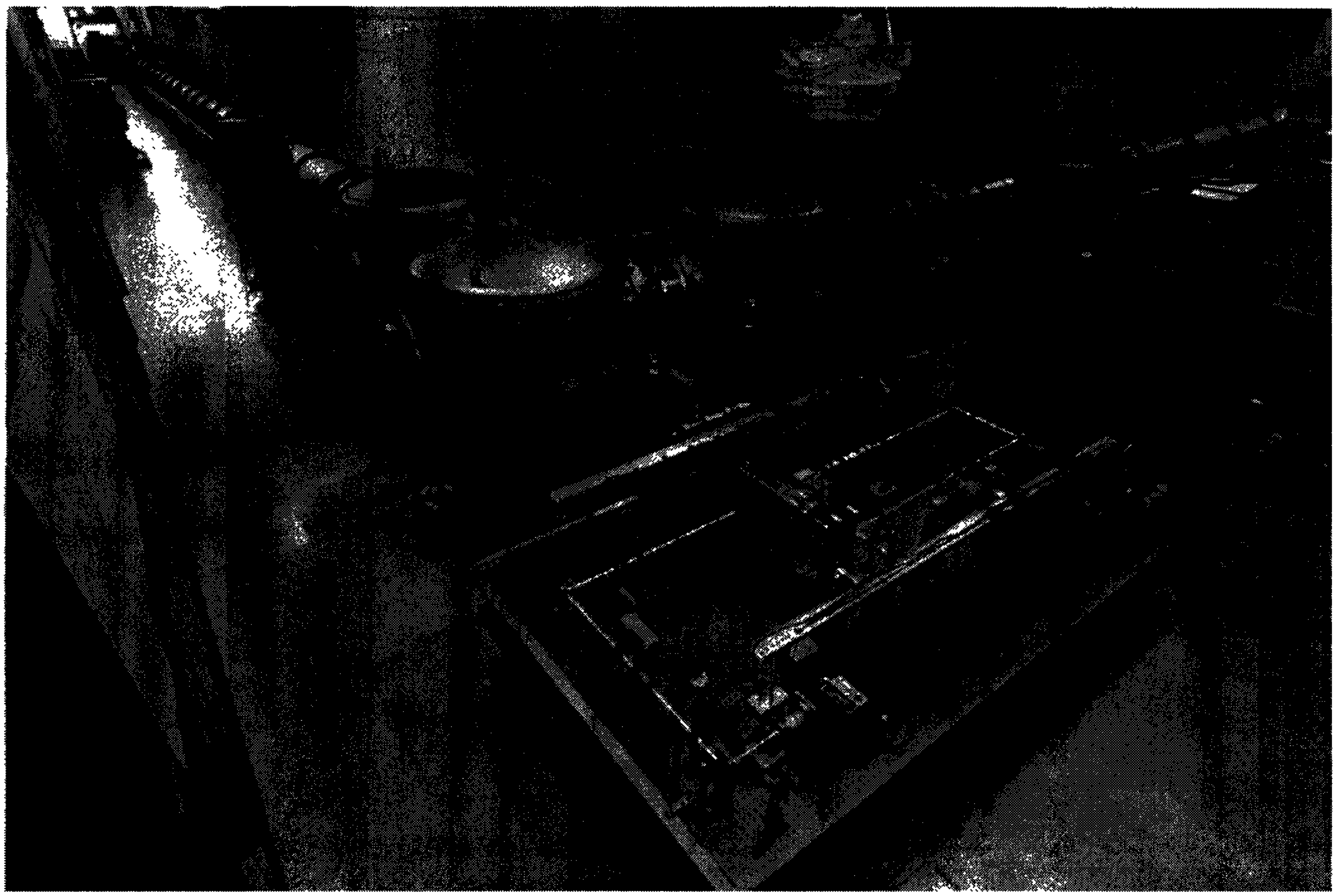
Recent Research on the LIGO 40m Interferometer

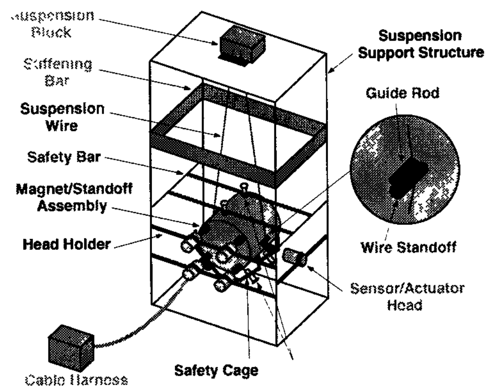


Seiji Kawamura
(LIGO, Caltech)

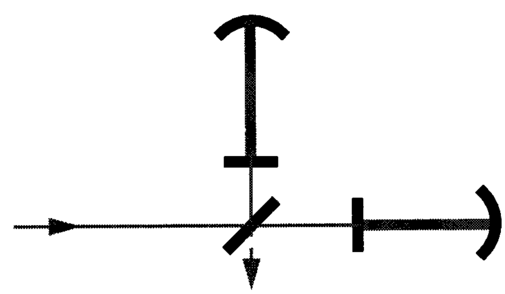
LIGO-G960223-00-D

Recent Developments

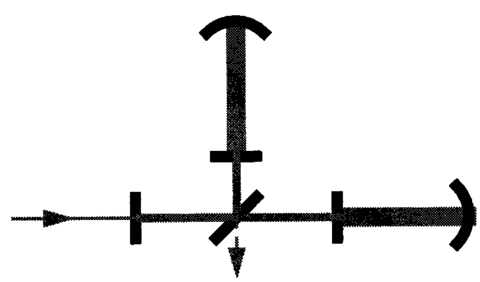
- New Suspension Prototype
  - ››Installed and tested



- Recombination
  - ››Completed



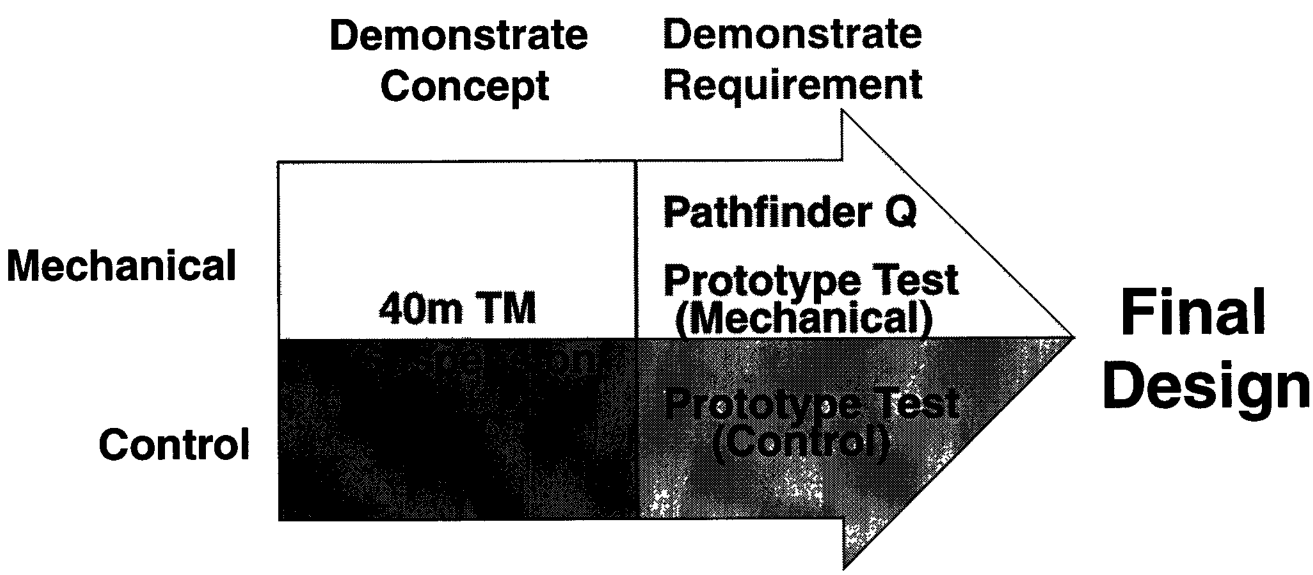
- Recycling
  - ››Started



Significance of 40m TM Suspension Test

LIGO Large Optics Suspension

(Test Mass, Beamsplitter, Recycling Mirror, Folding Mirror)

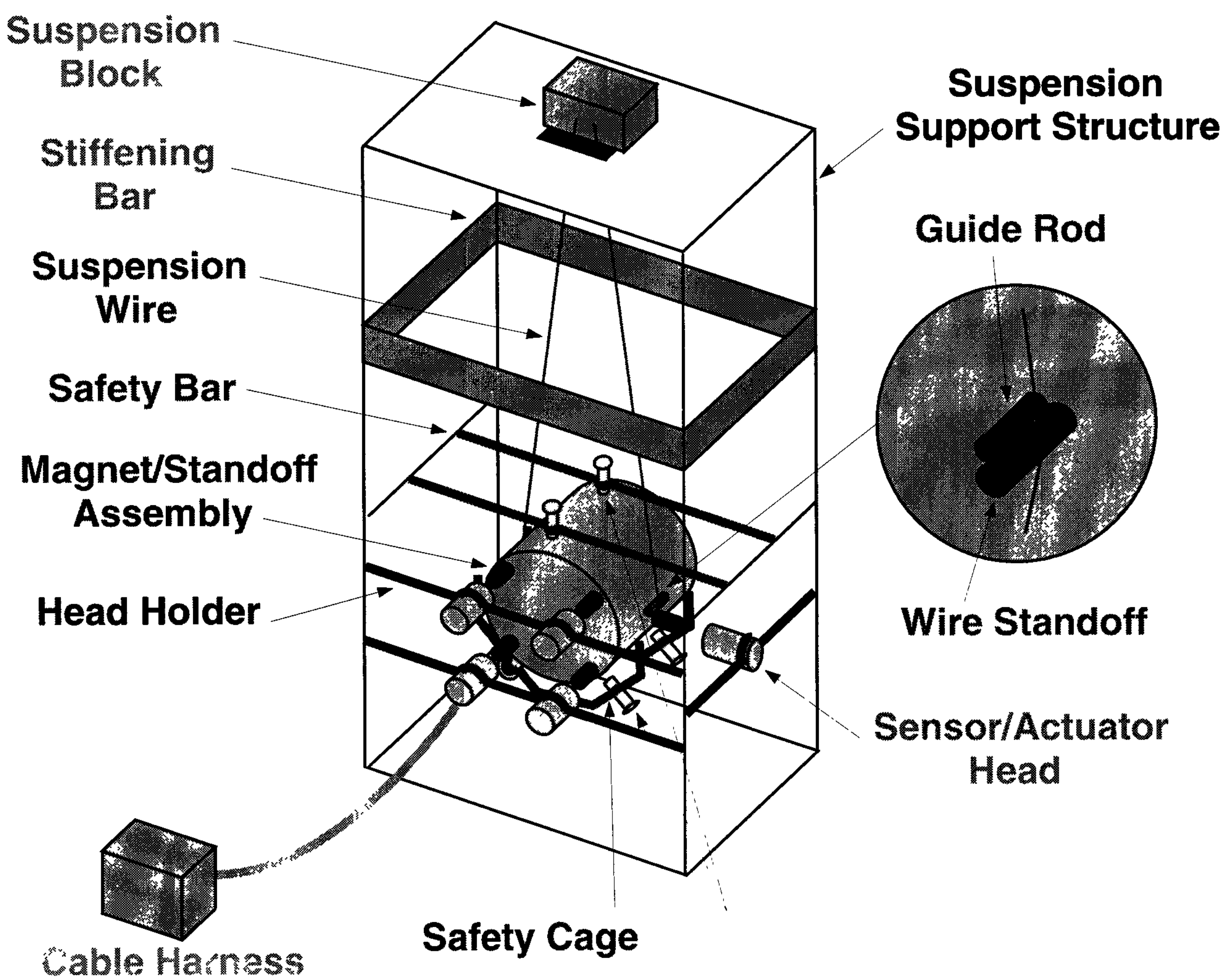


40m Test Mass Suspension

- One prototype was designed, fabricated, installed in the 40m, and characterized.
- New mechanical design worked.
- New control design worked.
- General performance was satisfactory.
- 40m was locked using the LSC (Length Sensing Control) input of the controller.
- 40m sensitivity with the prototype was NOT degraded with and without the LSC input.

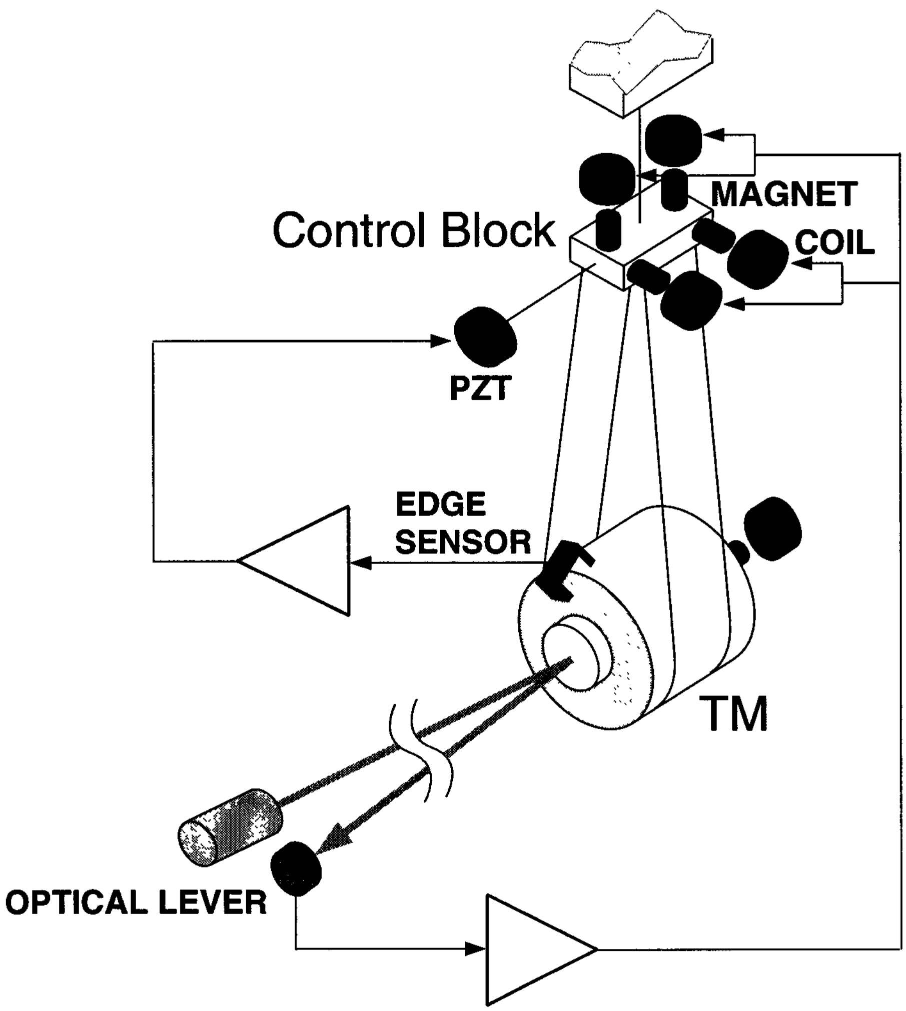
Mechanical System

- Single loop wire
- Modular support structure



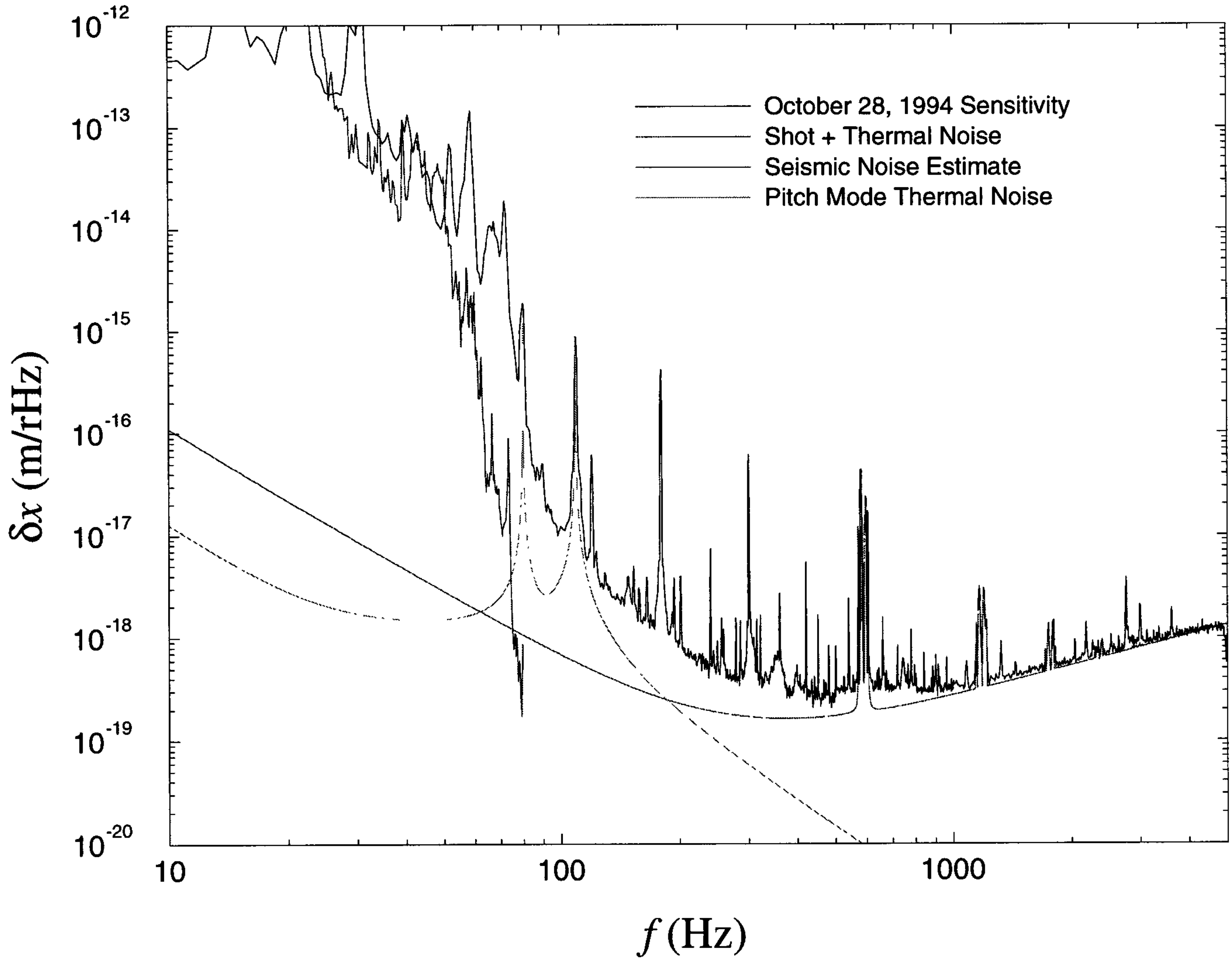
Double Loop Wire Configuration (Old 40m TM Suspension)

- Too complicated mechanical design
- Pitch and yaw mode thermal noise



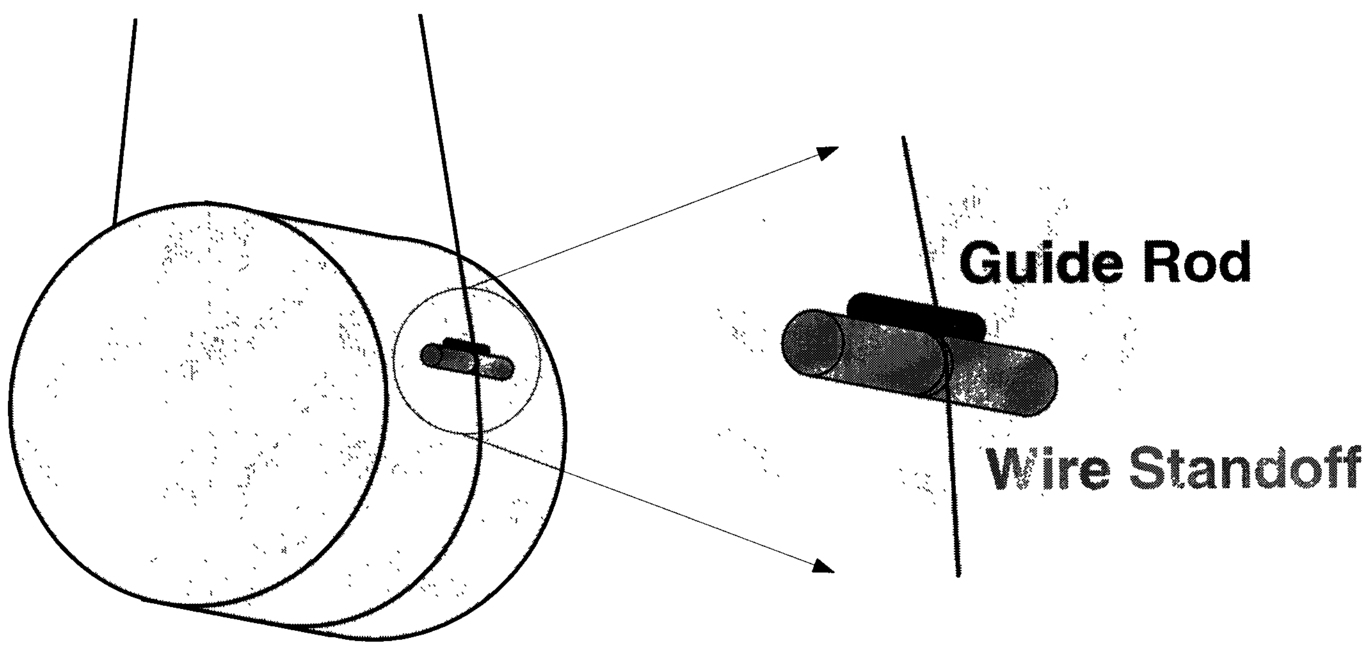
Pitch Mode Thermal Noise

- Measured Q: 2,000 - 3,000

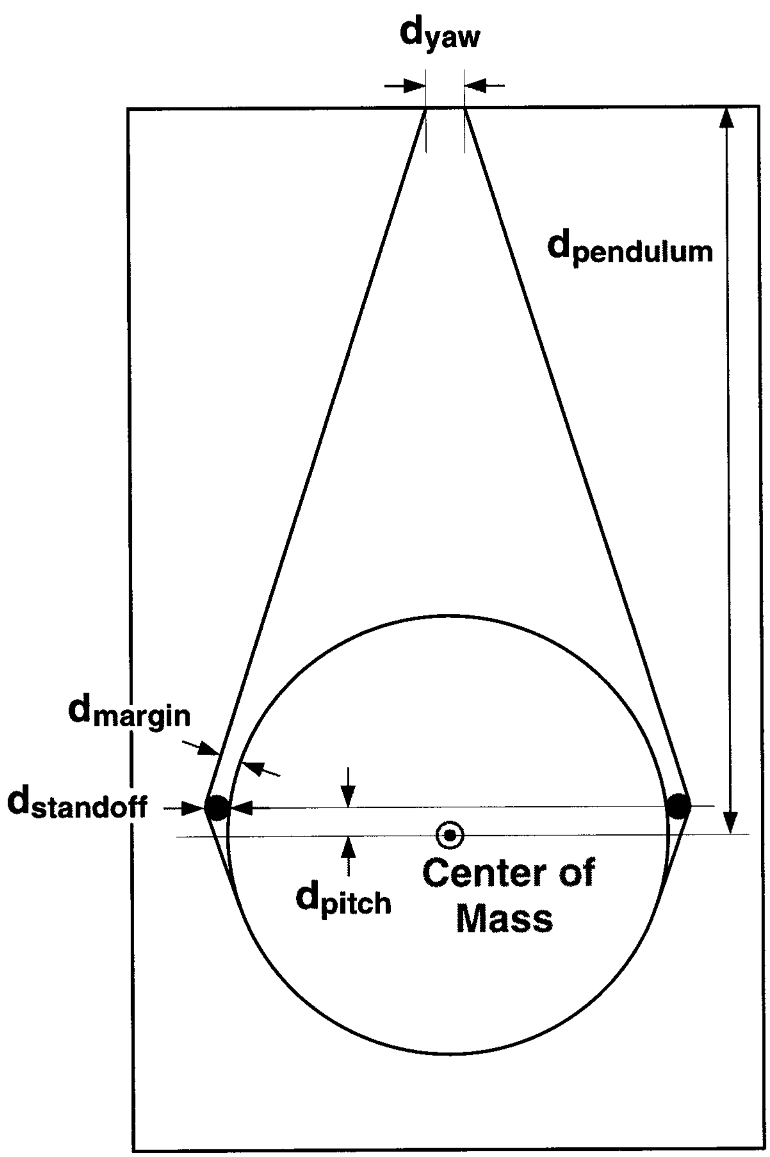


Balancing Test Mass with Single Loop Wire

- Balanced using guide rods and wire standoffs with groove
- Negligible *Q* degradation due to attachments



Suspension Configuration



$f_{pendulum}$ = 0.84 Hz

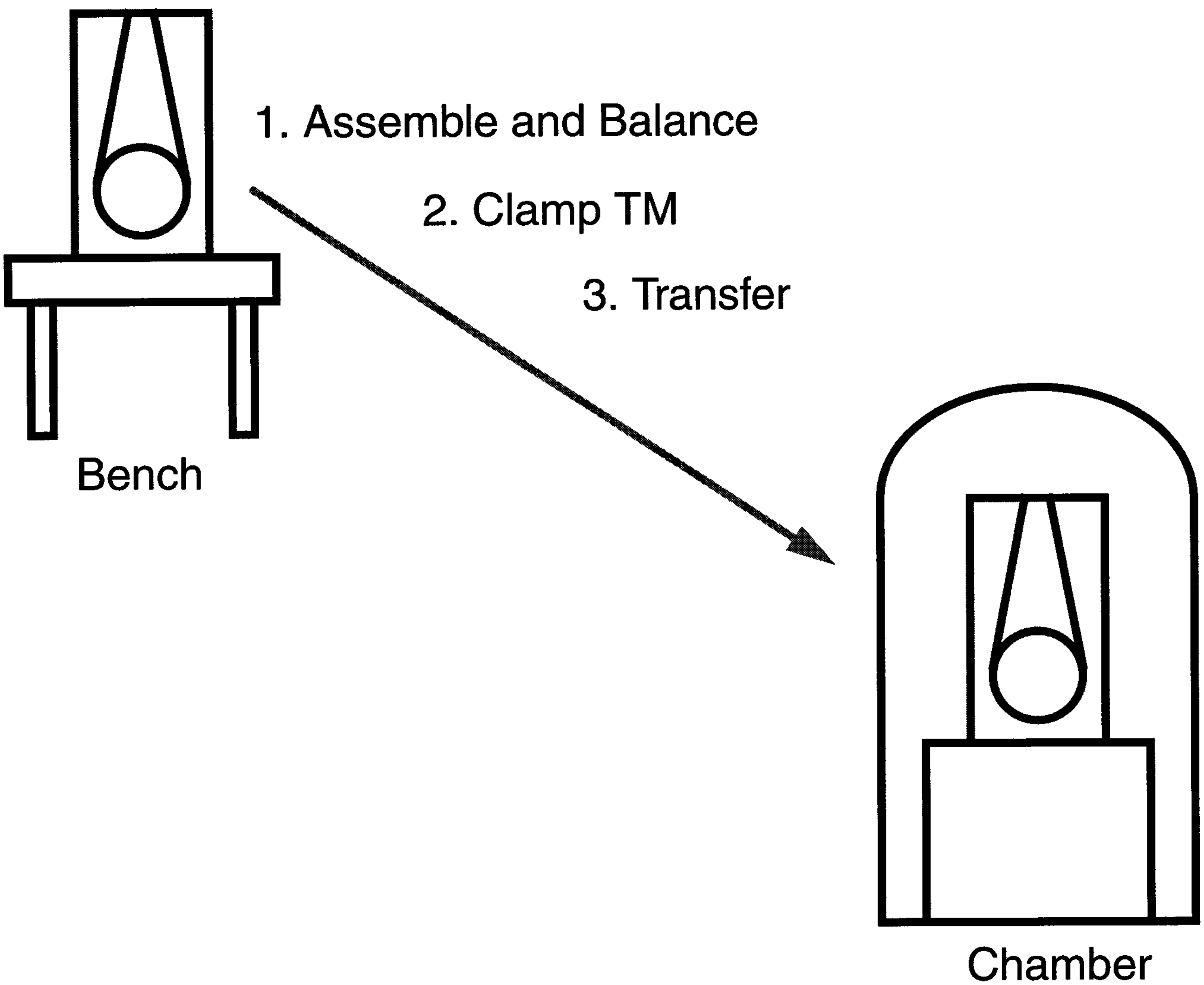
f_{pitch} = 0.50 Hz

f_{yaw} = 0.60 Hz

f_{violin} = 548 Hz

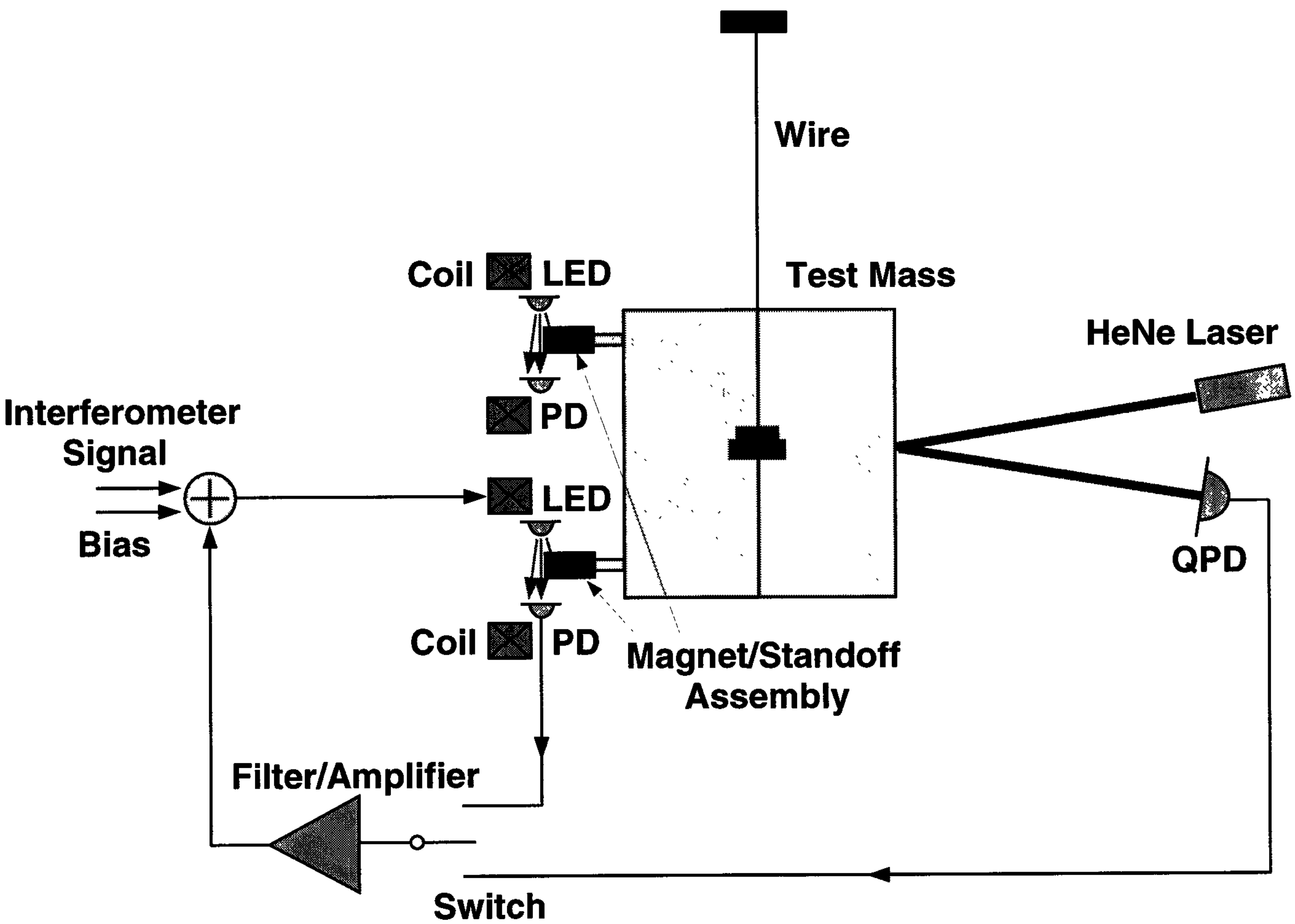
$f_{vertical}$ = 11.1 Hz

Assembly on Bench, Then Transfer into Chamber



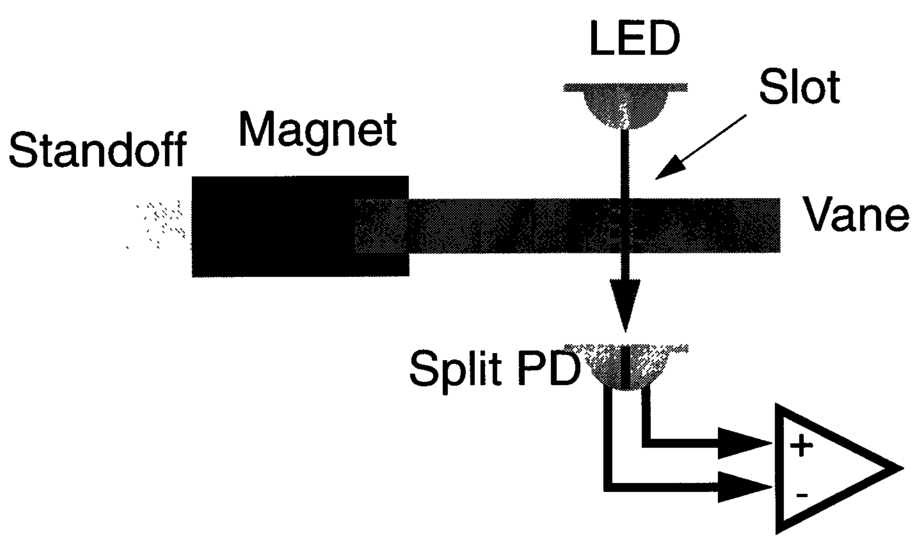
Control System

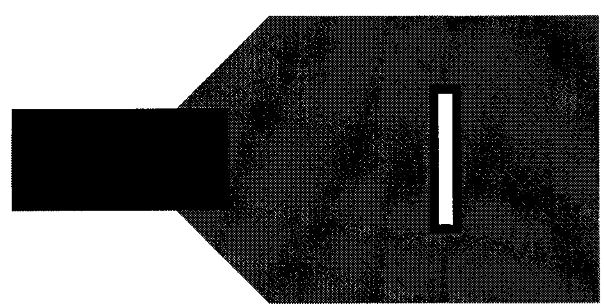
- Simple edge sensor
- Current-source type driver



Slot Sensor with Vane (Old BS Suspension)

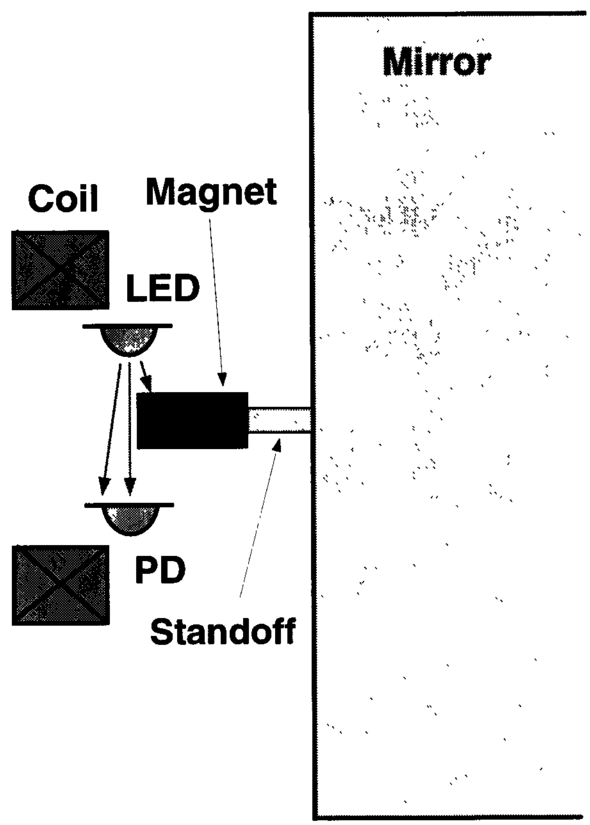
- Resonant frequency ~1 kHz due to the big vane
- Q degraded due to the big vane
- Complicated electronics





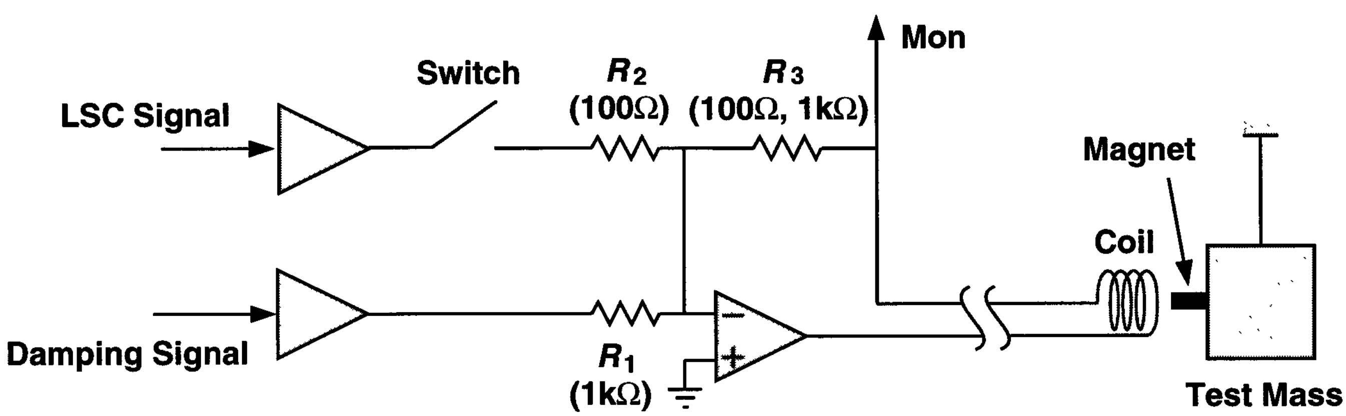
Edge Sensor without Vane

- Resonant frequency ~8 kHz
- Reasonable *Q*
- Simple electronics



Current-Source Type Driver

- No pick-up current into the coil
- Monitor signal free from pick-up.
- No eddy current dragging.
- Switchable between the acquisition mode and operation mode without gain change



Extrapolation to the LIGO

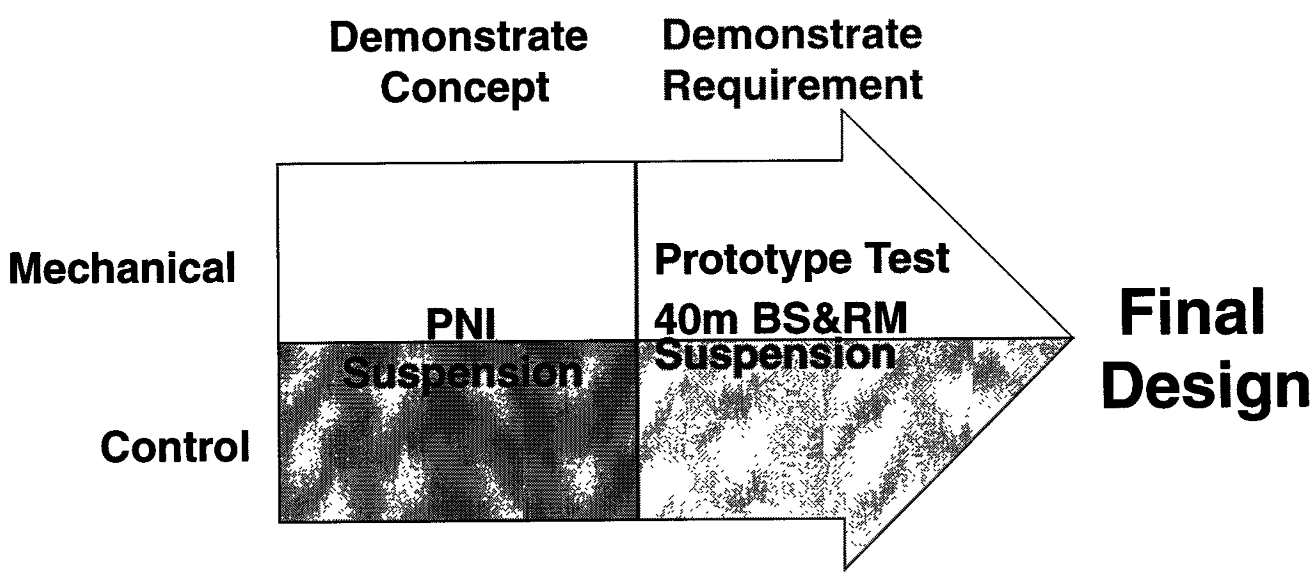
Large Optics Suspension

Items	40m TM Suspension or Pathfinder Q measurement	Extrapolated to LIGO	LIGO Requirements
Residual Q when damped	< 3	< 3	< 3
Internal Mode Loss	3×10^{-7}	3×10^{-7}	$< 4 \times 10^{-7}$
Pendulum Mode Loss	2×10^{-5} (Violin Mode)	7×10^{-6}	$< 7 \times 10^{-6}$
Actuator Range (f < 0.15 Hz)	44 μmpp	8 μmpp	> 80 μmpp
Driver Noise (at 40 Hz)	$6 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$	$9 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$	$< 5 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$
Sensor Noise (at 40 Hz)	$4 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$	$4 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$	(Option) $< 5 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$

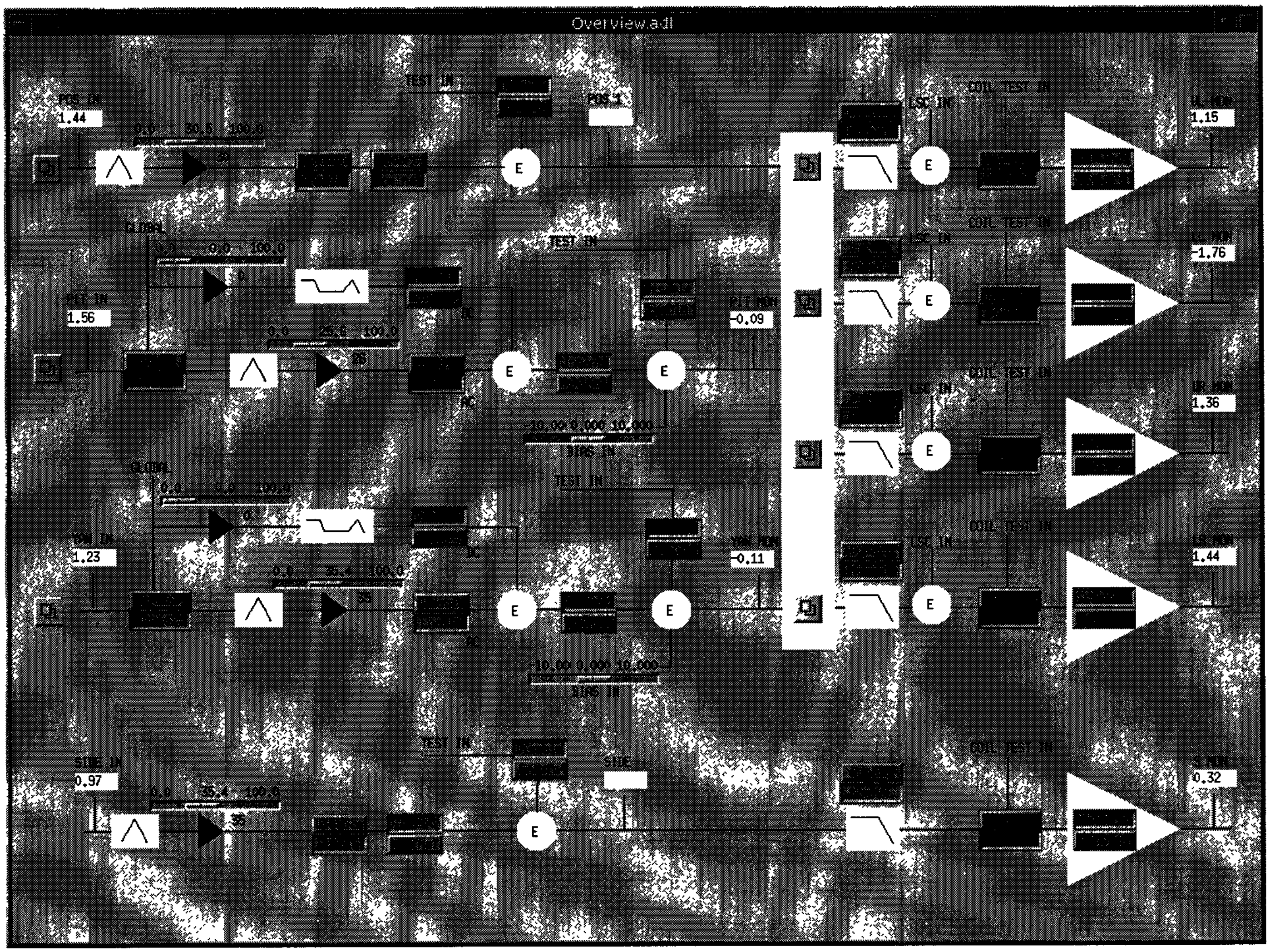
Next...
40m BS&RM Suspension

LIGO Small Optics Suspension

(Mode Cleaner Mirror, Steering Mirror)

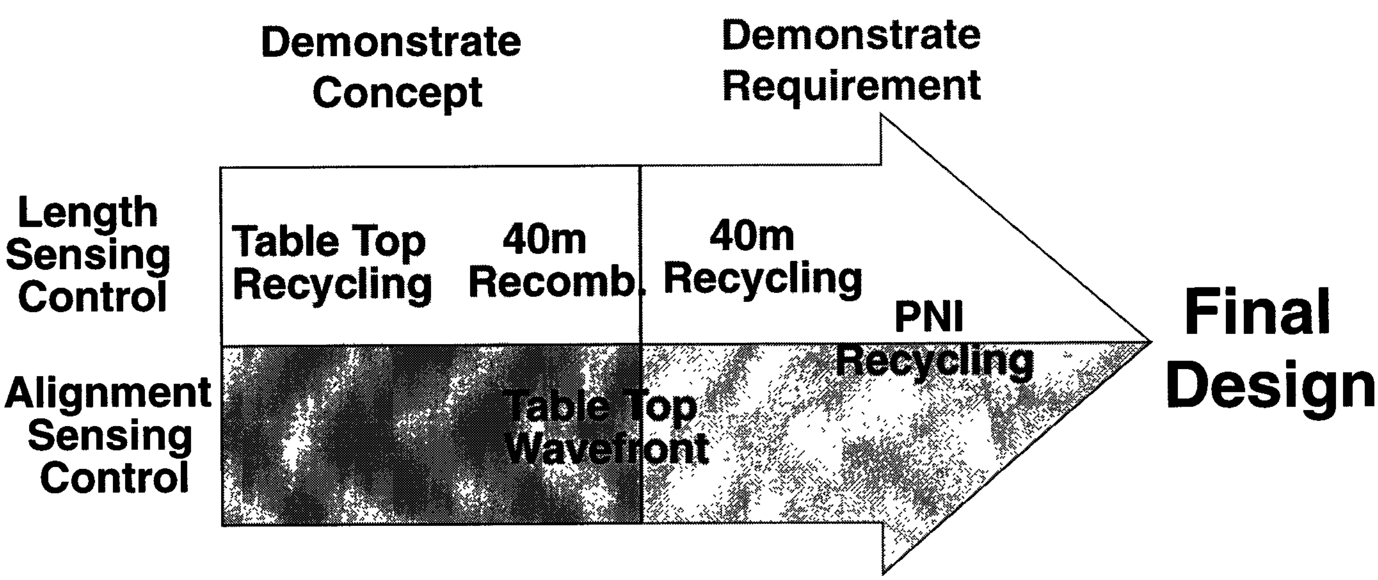


VME Based Control System



Significance of Recombination at 40m

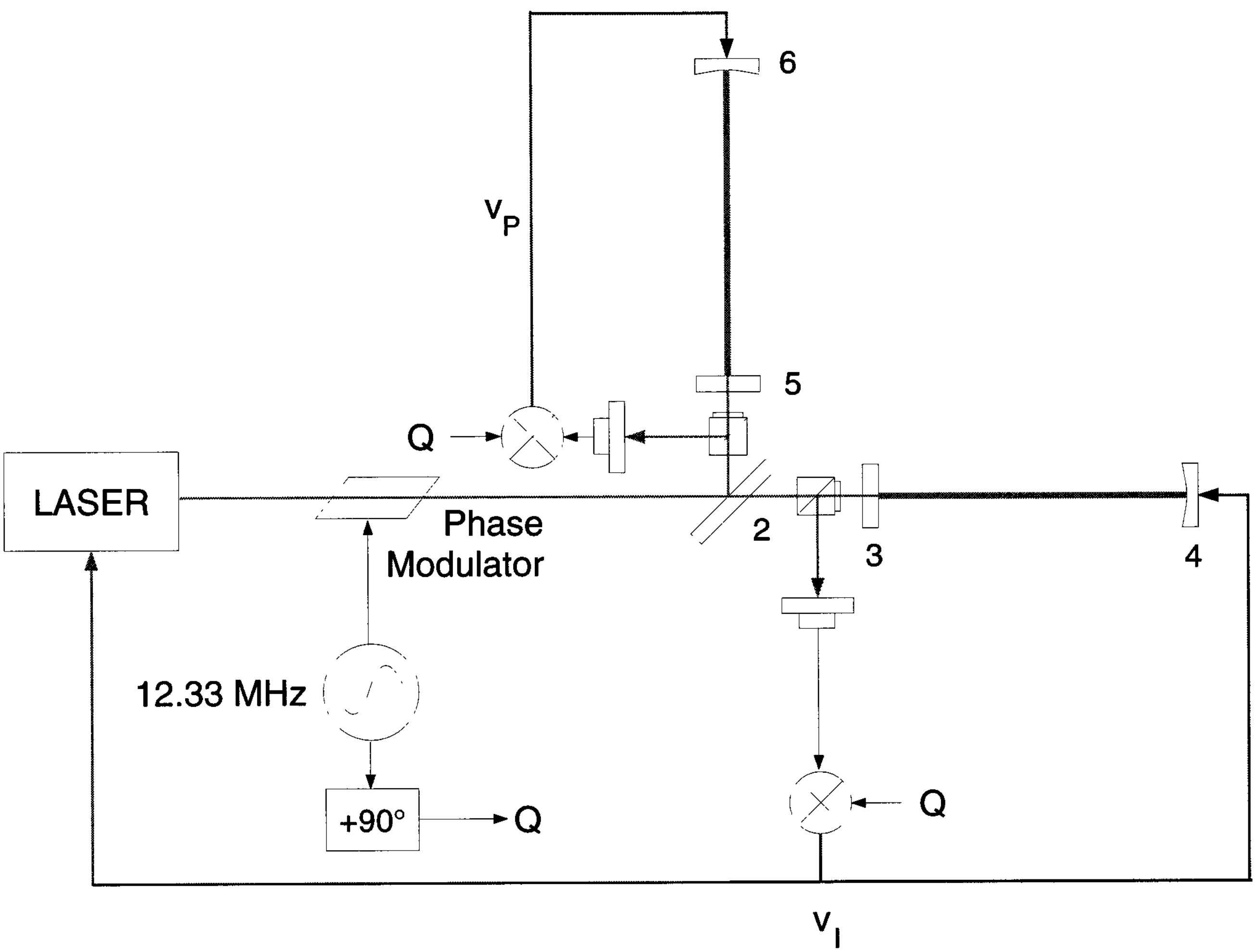
LIGO Interferometer Sensing/Control



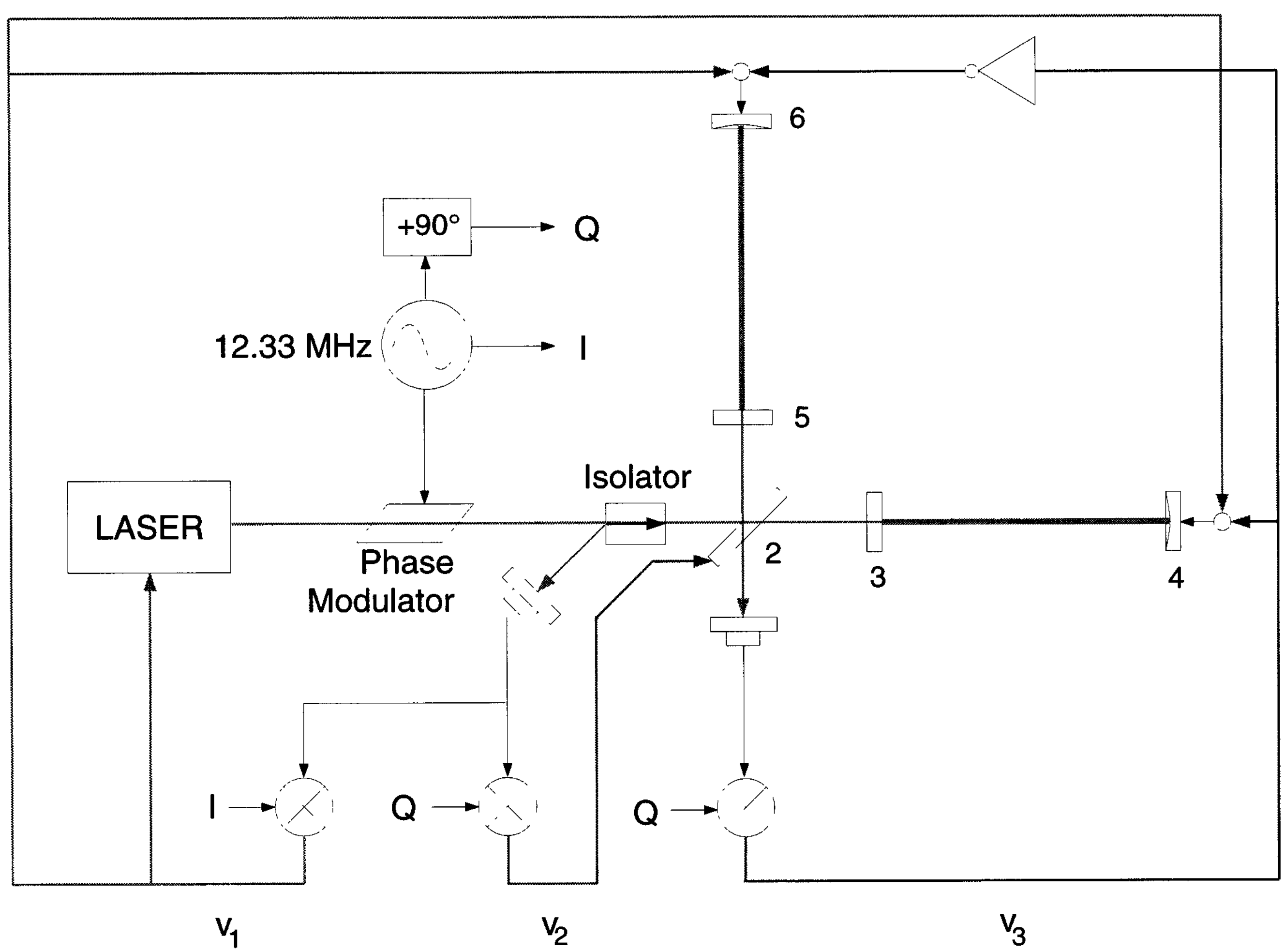
Recombination at 40m

- First demonstration of an optical topology in a suspended interferometer which is extensible to the initial LIGO interferometer.
- Many sources of noise were successfully controlled as predicted.
- Valuable experience was gained in lock acquisition.

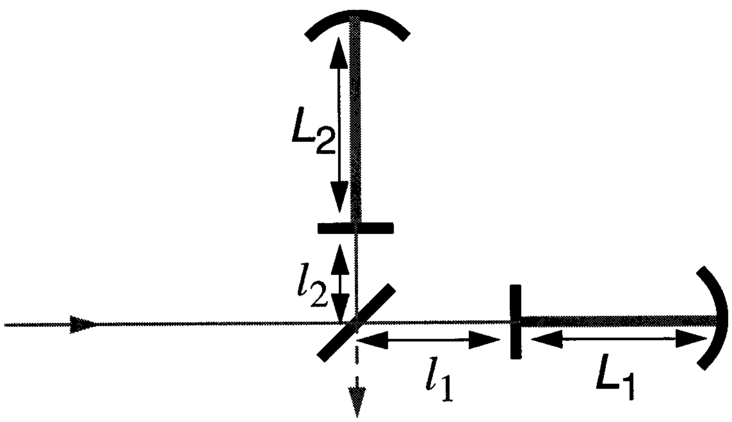
Fabry-Perot Interferometer



Fabry-Perot Recombined Servo Topology



Matrix of Discriminants



$$\Phi_+ = \frac{4\pi}{\lambda}(L_1 + L_2 - \Delta_+^{DC})$$

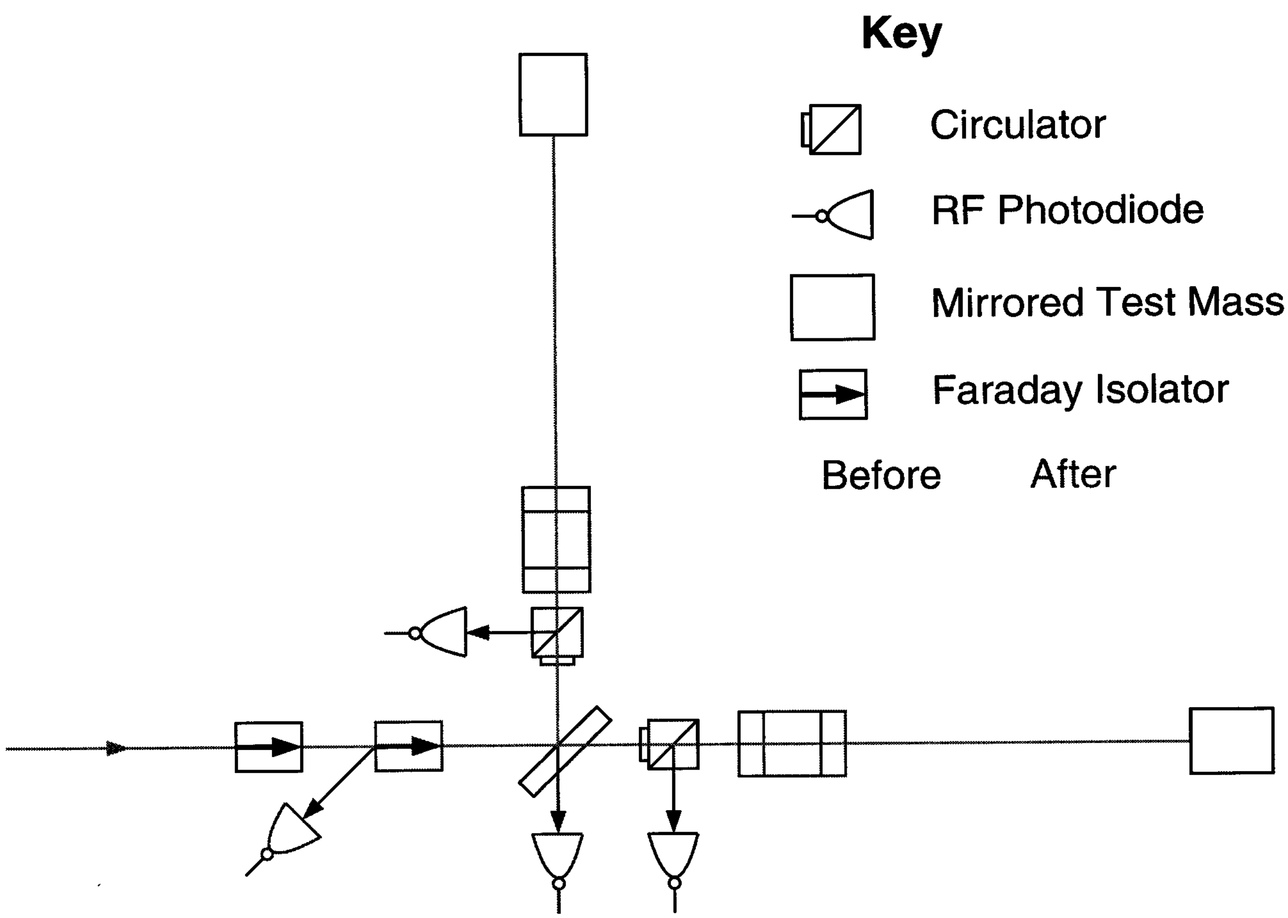
$$\phi_- = \frac{4\pi}{\lambda}(l_1 - l_2 - \delta_-^{DC})$$

$$\Phi_- = \frac{4\pi}{\lambda}(L_1 - L_2 - \Delta_-^{DC})$$

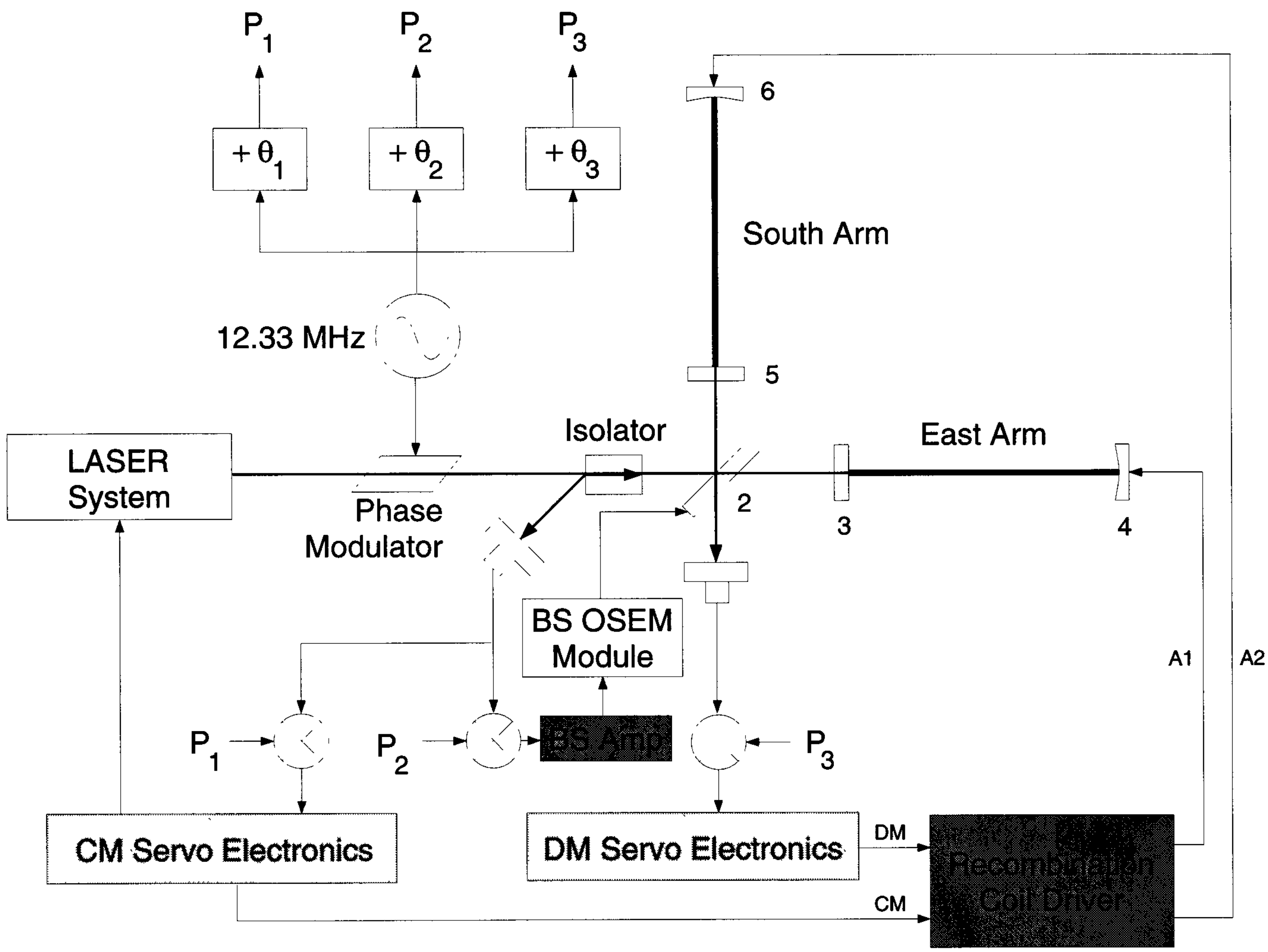
	$\partial \mathbf{v}_1$	$\partial \mathbf{v}_2$	$\partial \mathbf{v}_3$
$\partial\Phi_+$	-7.8	0	-2.2×10^{-1}
$\partial\phi_-$	2.3×10^{-4}	1.9×10^{-4}	-1.9×10^{-4}
$\partial\Phi_-$	2.5	1.6×10^{-8}	1.0

››Normalized so that $\partial v_3/\partial\Phi_- = 1$.

Modifications for Recombination



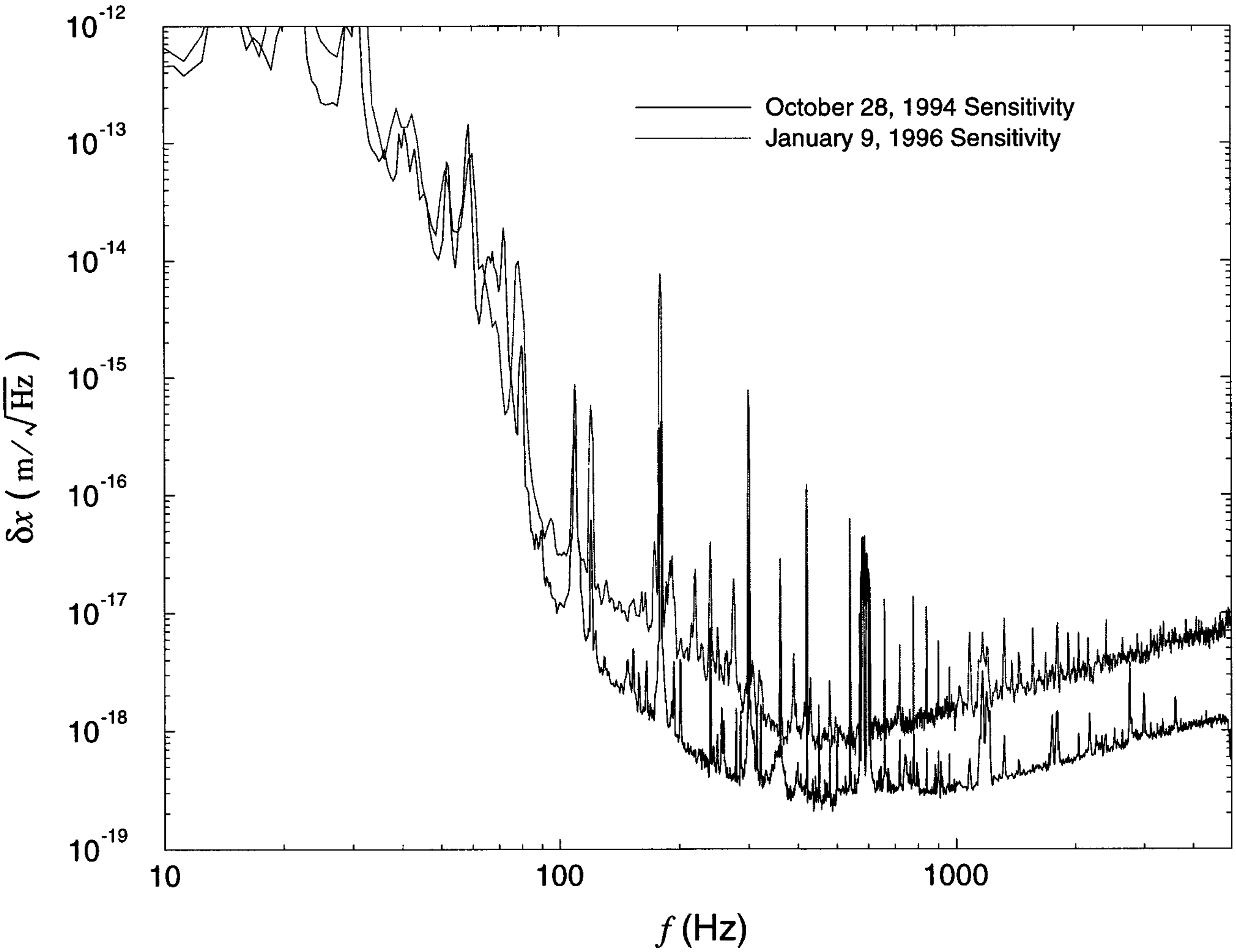
Control System



Interferometer Parameters

Quantity	Symbol	Value
Mirror (power) transmissions	T_2	0.45
	T_3	280 ppm
	T_5	300 ppm
	T_4, T_6	12 ppm
Loss in each mirror	L_3, L_4	110 ppm
	L_5, L_6	56 ppm
Asymmetry	δ	50.8 cm
Modulation frequency	f_{mod}	12.33 MHz
Modulation index	Γ	0.7 - 1.49
Contrast defect	$1 - C$	0.03

Recombination Sensitivity Comparison



Shot Noise Sensitivity Limits

- Differential mode displacement equivalent to shot noise in the differential mode signal:

$$\overline{S_{\Delta_-}}(f)^{1/2} = \frac{\sqrt{3E_+{}^2 + E_{DC}{}^2}}{2k|E_2|E_+} \frac{(1 - r_3 r_4)^2}{T_3 r_4} \sqrt{1 + \left(\frac{2\pi f}{\omega_c}\right)^2}$$

- Apparent differential mode motion due to shot noise in the common mode signal:

$$\left(\frac{S_{\Phi_+ \to \Phi_-}(0)}{S_{\Phi_-}(0)}\right)^{1/2} \approx \left(\frac{P_S}{P_A}\right)^{1/2} \left(\frac{\eta_A}{\eta_S}\right)^{1/2} \frac{\partial v_3/\partial \Phi_+}{\partial v_1/\partial \Phi_+} \sim 0.1$$

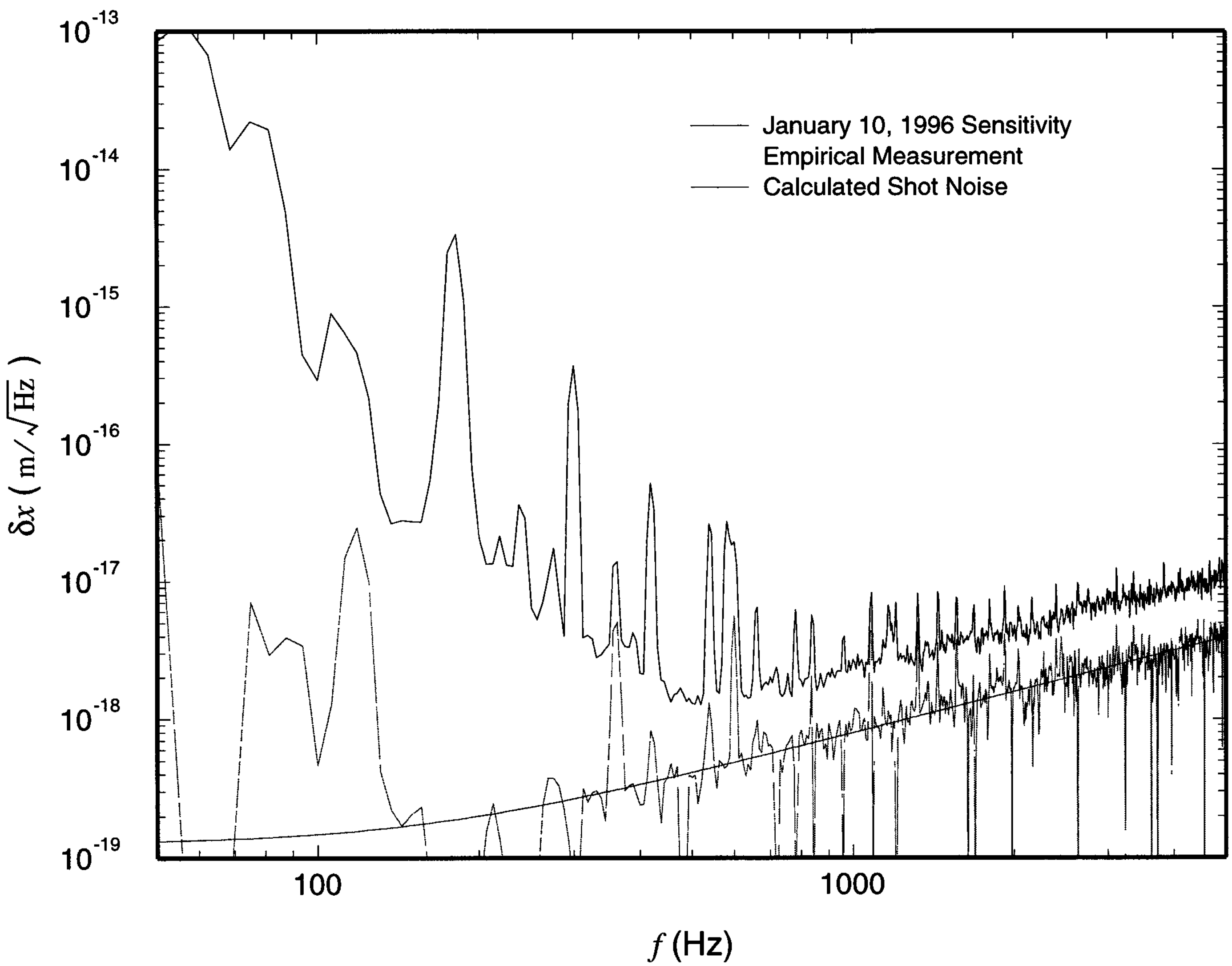
››Not a problem at any frequency.

- Apparent differential mode motion due to shot noise in the beam splitter signal:

$$\left(\frac{S_{\phi_- \to \Phi_-}(0)}{S_{\Phi_-}(0)}\right)^{1/2} \approx \left(\frac{P_S}{P_A}\right)^{1/2} \left(\frac{\eta_A}{\eta_S}\right)^{1/2} \frac{\partial v_3/\partial \phi_-}{\partial v_2/\partial \phi_-} \sim 3$$

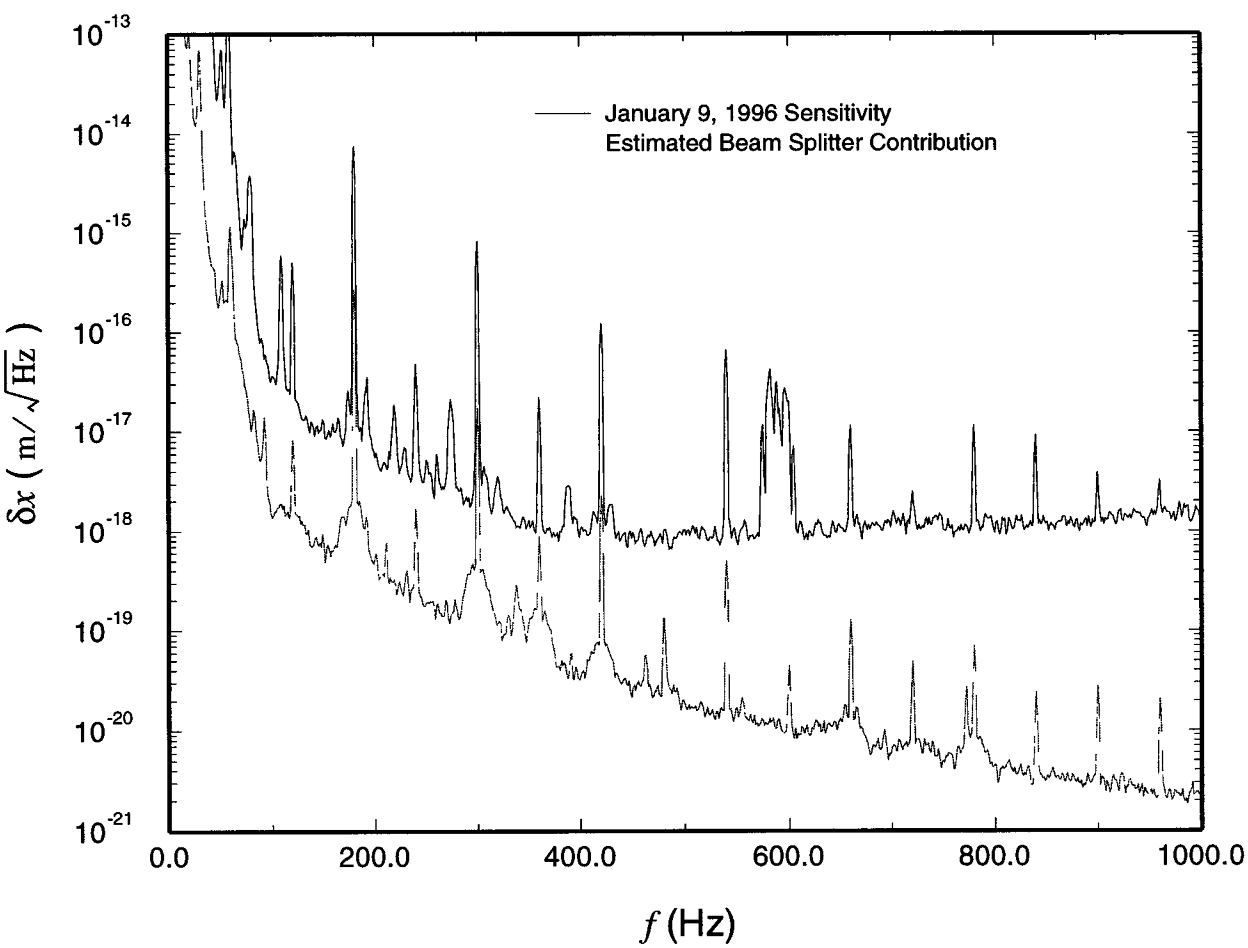
››Potential problem. Requires tailoring of beam splitter servo.

Shot Noise Estimate

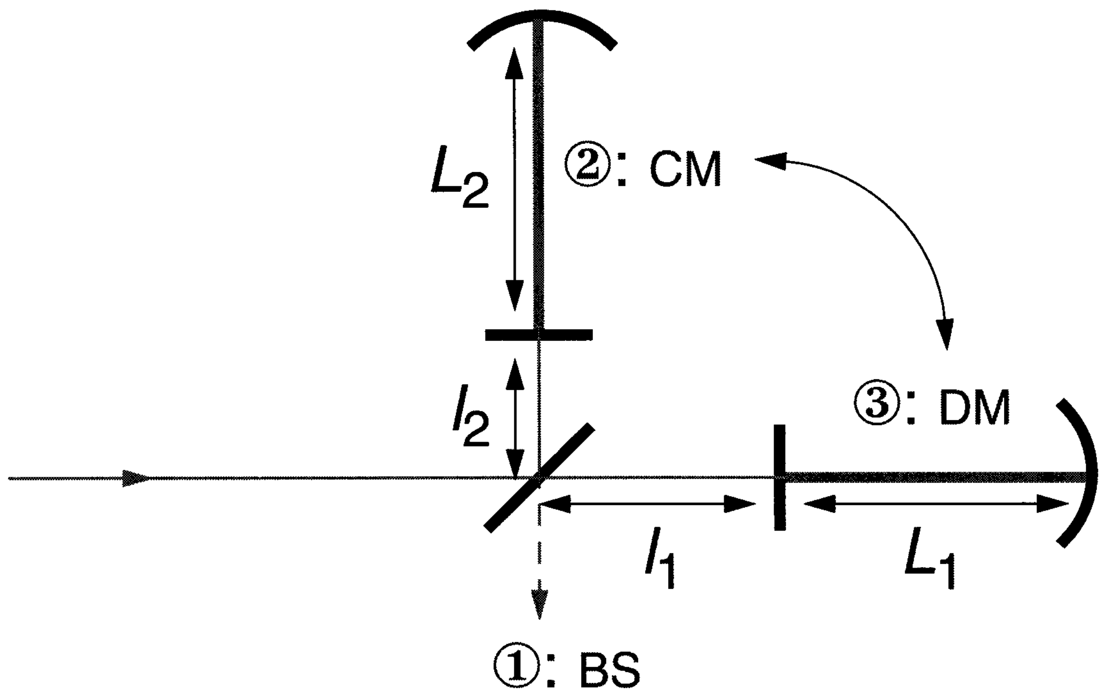


Beam Splitter Motion

- BS motion directly couples.



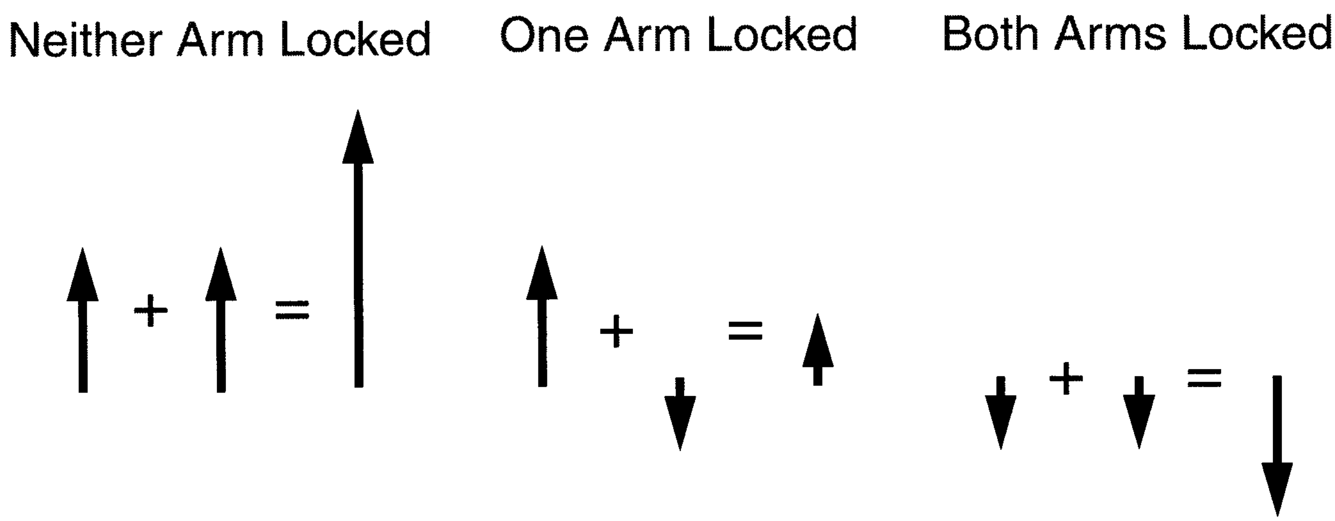
Lock Acquisition Sequence



- Common mode and beam splitter servos NOT disrupted by movement of the out of lock arm.

Beam Splitter Sign Reversal

- The beam splitter error signal can reverse sign in going from one arm and the beam splitter in lock to the entire interferometer in lock.



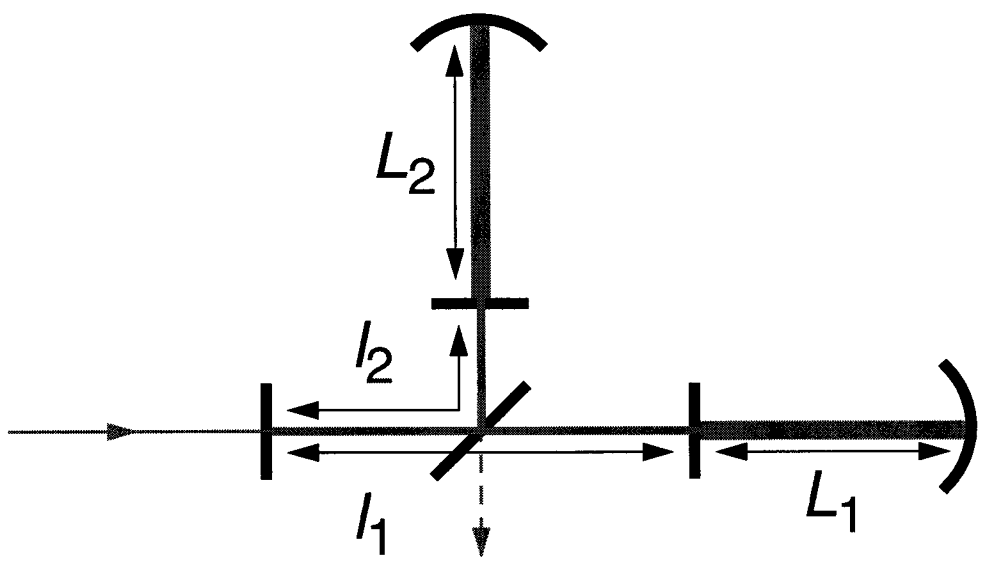
- Three methods to correct this:
  - ››Poor mode matching into arm cavities (Initial case)
  - ››Reverse sign of feedback signal when both arms in lock
  - ››Increase modulation depth (Used for most measurements)

Allowable RMS Deviations

Phase	Distance, m	Explanation
$\Phi_+ < 1.6\times10^{-4}$	$\Delta_+ < 7\times10^{-12}$	arm cavity power
$\phi_- < 8.9\times10^{-2}$	$\delta_- < 4\times10^{-9}$	maintain dark fringe
$\Phi_- < 2.9\times10^{-6}$	$\Delta_- < 1\times10^{-13}$	maintain dark fringe

- Seismic motion of the suspended optical components must be suppressed to this level by the servos.
- The first and second arm servos in the Fabry-Perot configuration met the requirements for the common and differential mode and were used with little modification for recombination.
- The beam splitter servo was designed for recombination to meet the above requirement.

Recycled Interferometer



- Degrees of Freedom:
  - ››Common mode arm length = $L_1 + L_2$
  - ››Differential arm length (GW signal) = $L_1 - L_2$
  - ››Recycling cavity length = $l_1 + l_2$
  - ››Michelson near-mirror difference = $l_1 - l_2$

Steps Required to Achieve Recycling

- Change vertex masses for ones of higher transmission

  ››completed; currently in shakedown phase following this change

- Reconfigure vacuum envelope with installation of side chamber and reconfigure optical layout including replacement of present beamsplitter with SOS prototype

  ››task scheduled to start mid-November

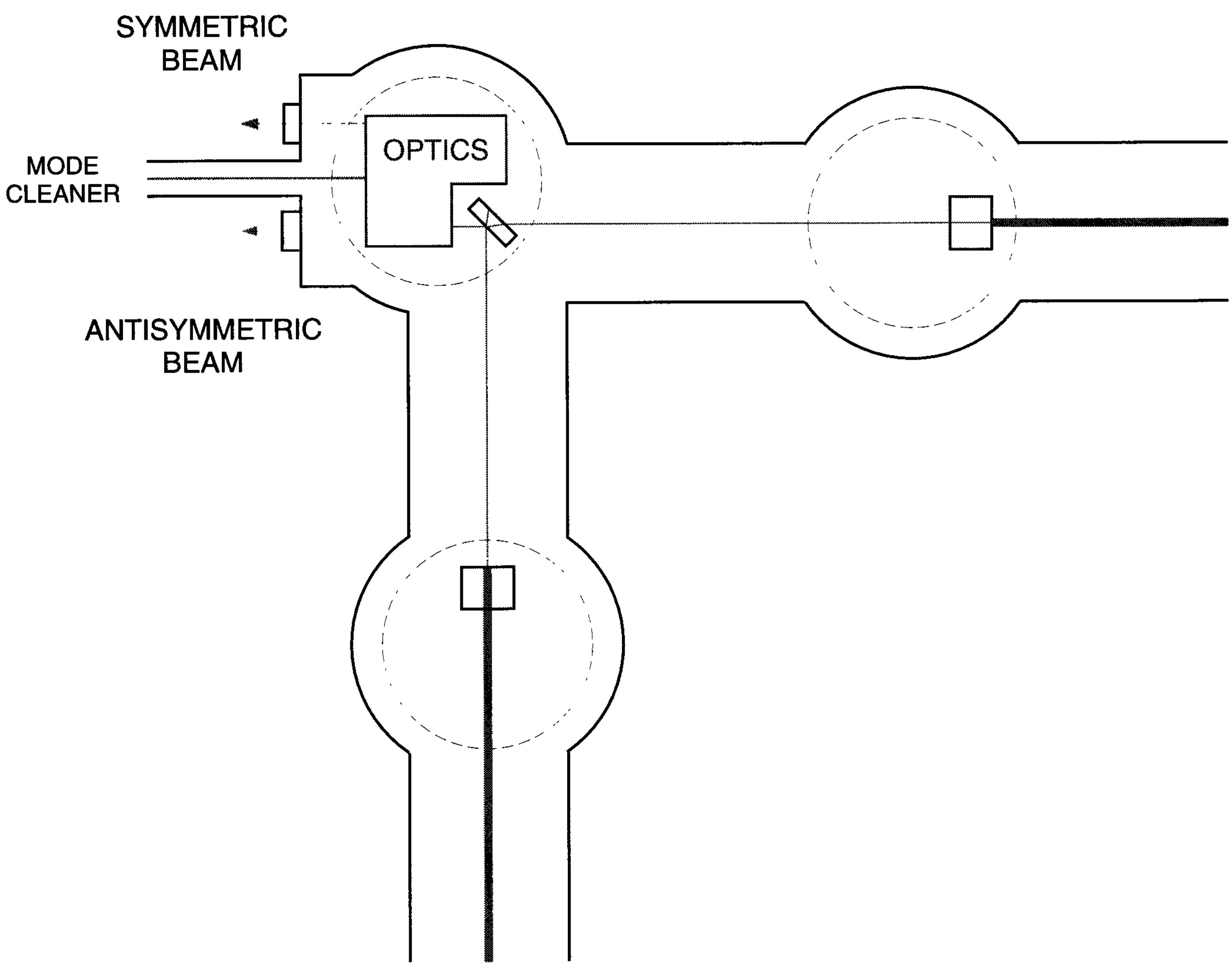
- Change modulation frequency

  ››new reference source built to LIGO specifications

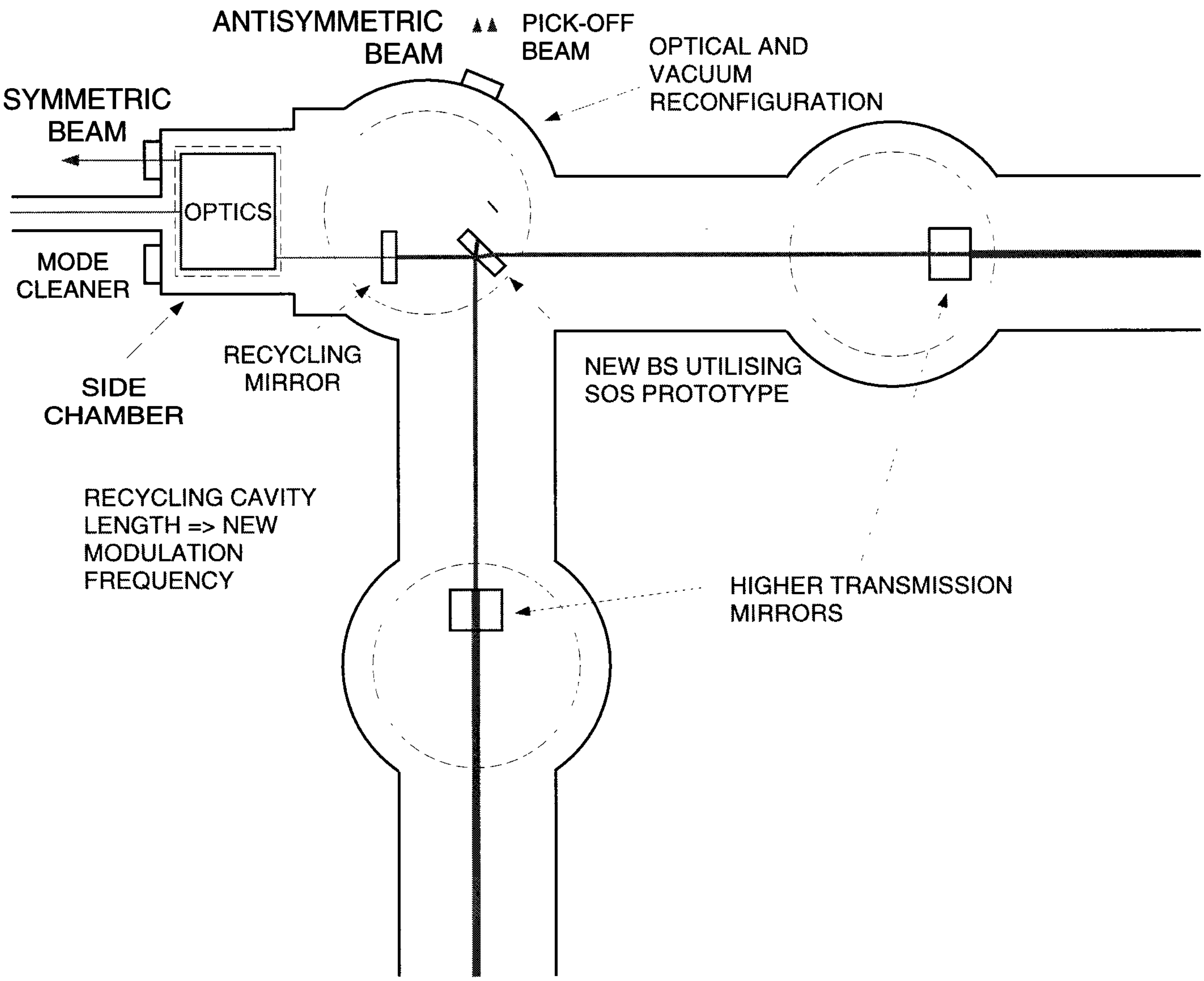
- Install recycling mirror

  ››scheduled for end of March

Optical Configuration (Recombination)

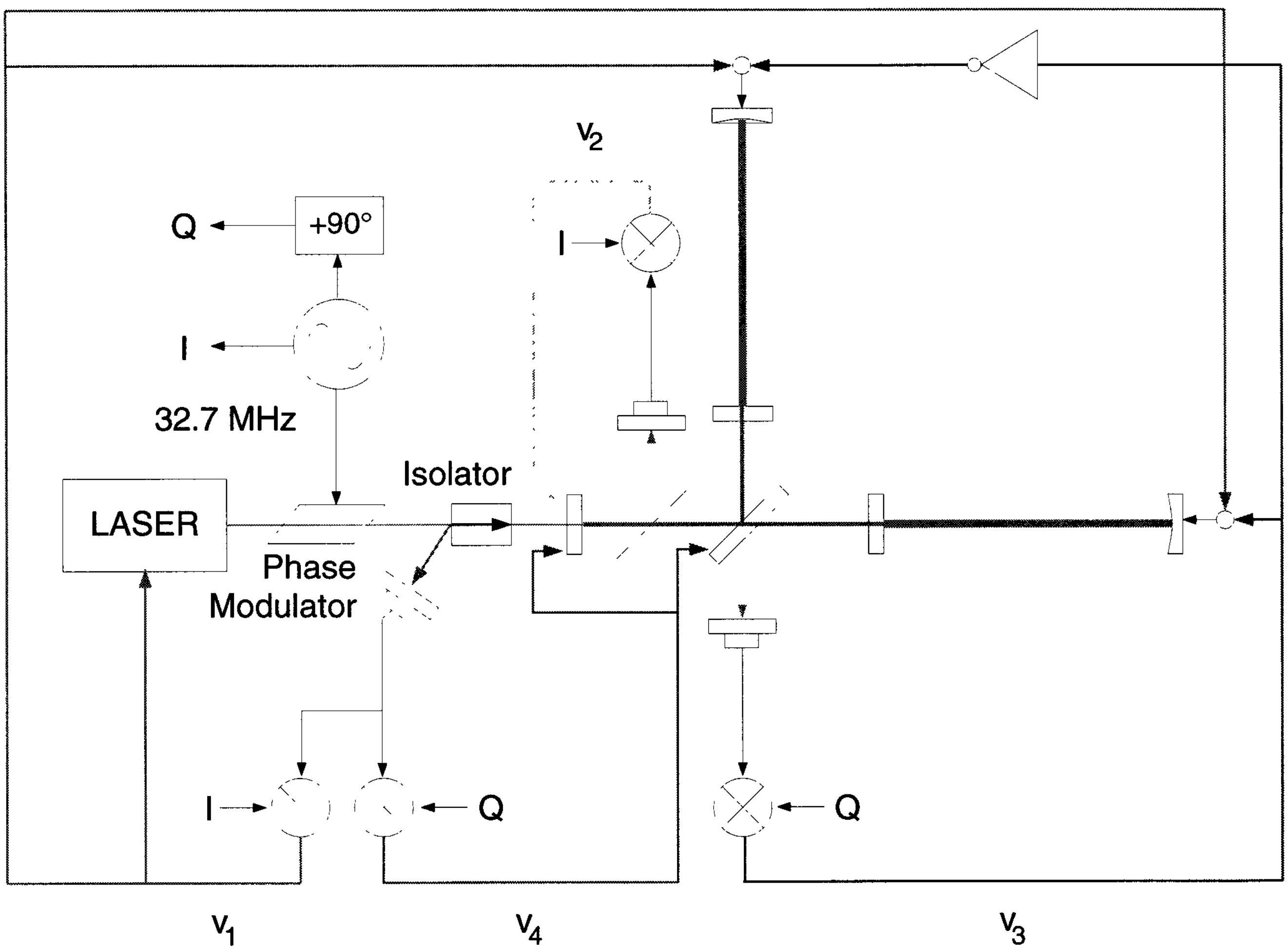


Optical Configuration (Recycling)

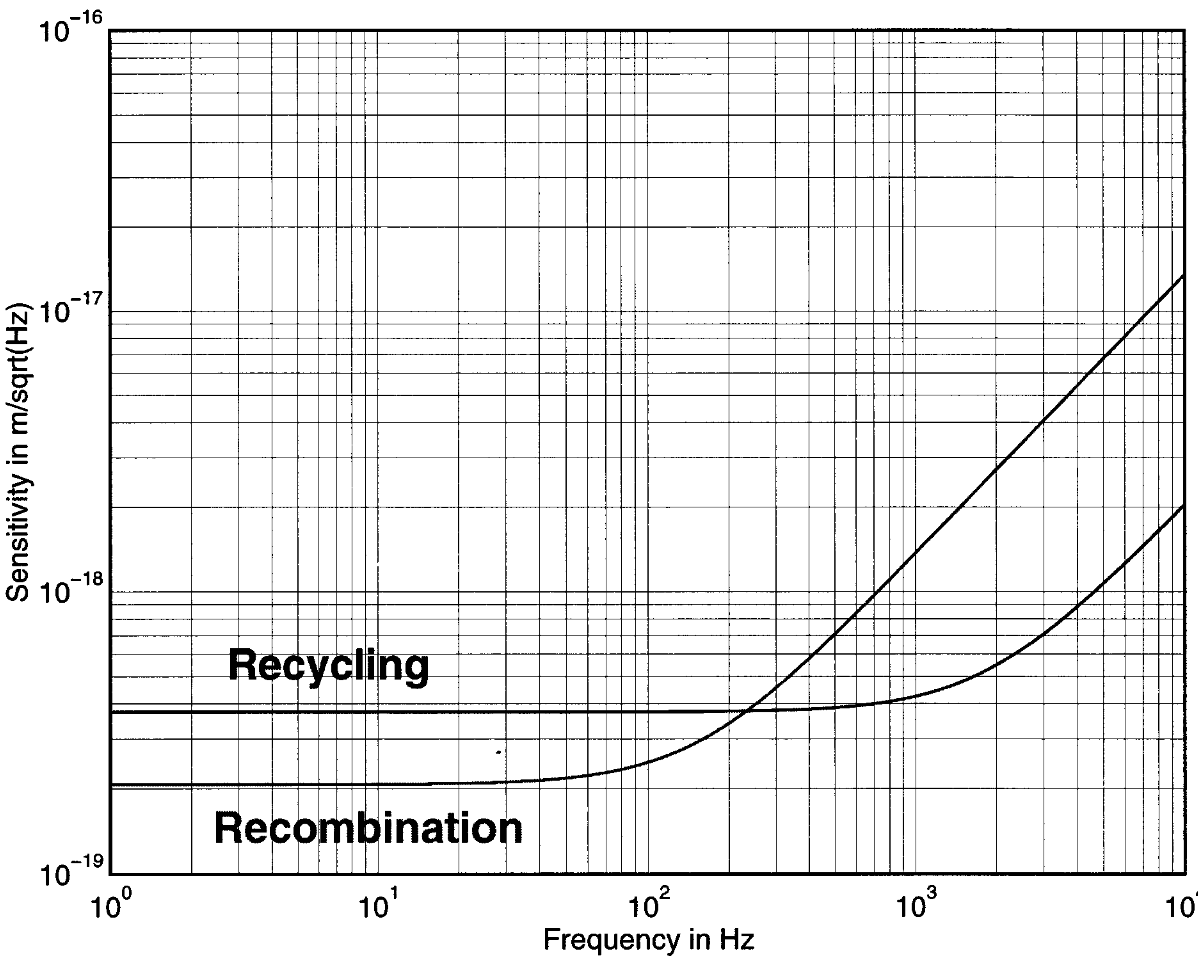


Control System (Recycling)

Optical and Servo Topology for the Recycled 40-m Interferometer



Predicted Shot Noise Sensitivity



Conclusion

- New 40m TM suspension prototype successfully tested
- LIGO small optics suspension prototype is ready to try for the 40m BS
- First demonstration of an optical topology in a suspended interferometer which is extensible to the initial LIGO interferometers
- Recycling with the initial LIGO configuration started in the 40m