LASERS AND INPUT OPTICS

LIGO MODE CLEANER

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LIGO-G930038-00-D

Mode Cleaner

Highly stable, high throughput resonant cavity. Provides:

- Active frequency stabilization $\nu < 4$ kHz
- Passive frequency stabilization $\nu > 4$ kHz
- Passive spatial stabilization all ν

REQUIRED NOISE SUPPRESSION OF PRESTABILIZED LASER (at 100 Hz)

Noise type	Initial interferometer	Advanced interferometer
Frequency noise	$1.7 \cdot 10^6$	$9 \cdot 10^7$
Intensity noise	50	2500
Beam jitter	75	3750

Spatial Variation from higher order (N>1) modes

Resonator Gaussian beam modes:

$$E(x,y,z)_{mn} = U_{mn} \times \phi_{mn}$$

$$U_{mn} = \frac{1}{w(z)} H_m\left(\frac{x}{w}\right) H_n\left(\frac{y}{w}\right) e^{-(r/w)^2}$$ Spatial Mode

$$\phi_{mn} = e^{i\left(kz-(m+n+1)\tan^{-1} z/z_0\right)} \; e^{ikr^2/2R(z)}$$ Phase

$$U_0 = e^{-(x/w)^2}$$

$$U_1 = \frac{2x}{w} e^{-(x/w)^2}$$

$$U_2 = \left(4\frac{x^2}{w^2} - 1\right) e^{-(x/w)^2}$$

lateral displacement of aligned (TEM 00) beam by amount ***a*****:**

$$U = e^{-(x/w)^2} \longrightarrow e^{-((x-a)/w)^2}$$

$$\sim e^{-(x/w)^2} \left(1 + \frac{2xa}{w^2}\right)$$

$$\sim U_0 + (a/w) U_1$$

tilt of beam through angle α**:** $U \sim U_0 + i\pi\frac{\alpha w}{\lambda} U_1$

change of beam width Δ**w/w:** $U \sim U_0 + 2(\Delta w/w) U_2$

$\Longrightarrow$Spatial variation characterized by ϵ, the higher order mode amplitude:

$$U = U_0 + \sum_n \epsilon_n U_n$$

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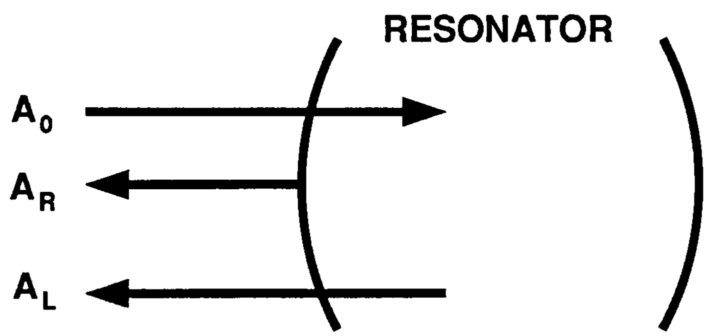
Frequency Noise From Mode Contamination



$$A_L = A_0 \frac{T\sqrt{R}}{1-Re^{i\phi}}$$

Signal S at photodiode: $S = \left|\left(A_R + A_L\right)\right|^2$

$$= \frac{T\sqrt{R}\sin\phi_0}{1+R^2-2R\cos\phi_0}$$

= 0 at cavity resonance

Mode contamination

$$S' = \frac{T\sqrt{R}sin\phi_0}{1+R^2-2R\cos\phi_0} + \epsilon_n(f)\frac{2\,\epsilon_s\,T\sqrt{R}sin\phi_n}{1+R^2-2R\cos\phi_n}$$

where $\phi_n = \frac{4\pi d\nu}{c} + 2\,(n+1)\,\cos^{-1}\sqrt{1-\frac{d}{r}}$

$\epsilon_s \sim 0.3$ (static misalignment)

for $S' = 0, \quad \nu_0 \longrightarrow \nu_0 + \nu(f)$

$$\nu(f) = \frac{(1-R)^2 c}{4\pi d}\ \epsilon_n(f)\frac{2\,\epsilon_s\sin\phi_n}{1+R^2-2R\cos\phi_n}$$

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Frequency Noise (cont.)

$$\nu_e(f) = \frac{(1-R)^2 c}{4\pi d} \; \epsilon(f) \frac{2\,\epsilon_s \sin\phi_n}{1+R^2-2R\cos\phi_n}$$

LIGO initial interferometer: d=4 km, r=6 km, 1–R = 0.985

$\nu(f) < 6 \cdot 10^{-7} Hz/\sqrt{Hz}$: Frequency noise requirement

$\Longrightarrow \epsilon(f) < 2 \cdot 10^{-6}/\sqrt{Hz}$: High order mode amplitude requirement

Given: $\epsilon(f) \sim 1.5 \cdot 10^{-4}/\sqrt{Hz}$ from Prestabilized laser,
S (suppression factor) must be > 75

Mode Suppression

$$S_n = \frac{I_T}{I_{IN}} = 1 - \left(\frac{1-e^{i\phi_n}}{1-Re^{i\phi_n}}\right)R$$

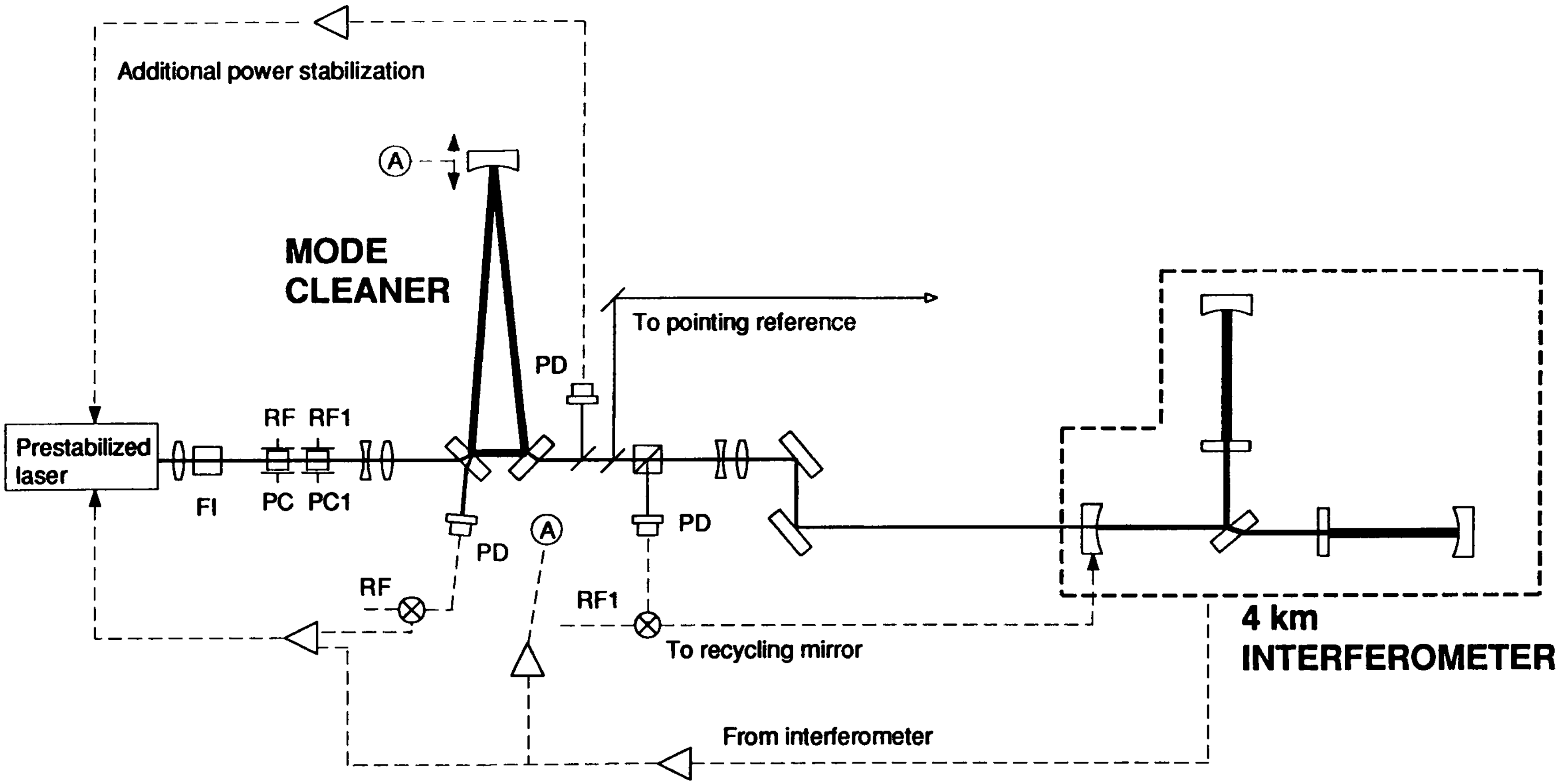
$$= \frac{1}{1+\frac{4R\sin^2\frac{\phi_n}{2}}{(1-R)^2}}$$

Mode Cleaner: 1–R = 0.2 %, d=12.2 m, r=17 m

$\Longrightarrow \; S_1 = 106, \; S_2 = 122$

Additional suppression factor of ~ 10 expected from recycling cavity.

LIGO INTERFEROMETER OPTICS



FI: Faraday isolator, PC, PC1: Pockels cells, RF, RF1: RF modulation frequencies, PD: photodetector

Mode Cleaner Design Parameters

Input and Output Mirror Transmission

Maximum stored power = 1500 W

Output power = Stored power × transmission

3 W = 1500 W × T

T = 2000 ppm

Length, Bandwidth

FSR = $\frac{c}{2L}$ = 12.3 MHz.

L = 12.2 m

$$B = \frac{c}{2\pi L}\frac{1-R}{\sqrt{R}} \sim 8\,kHz$$

Throughput

$$\eta = M\;\frac{T^2}{(L+T)^2}$$

with L=50 ppm, T=2000 ppm, M=0.95 (mode matching):

η = 0.9

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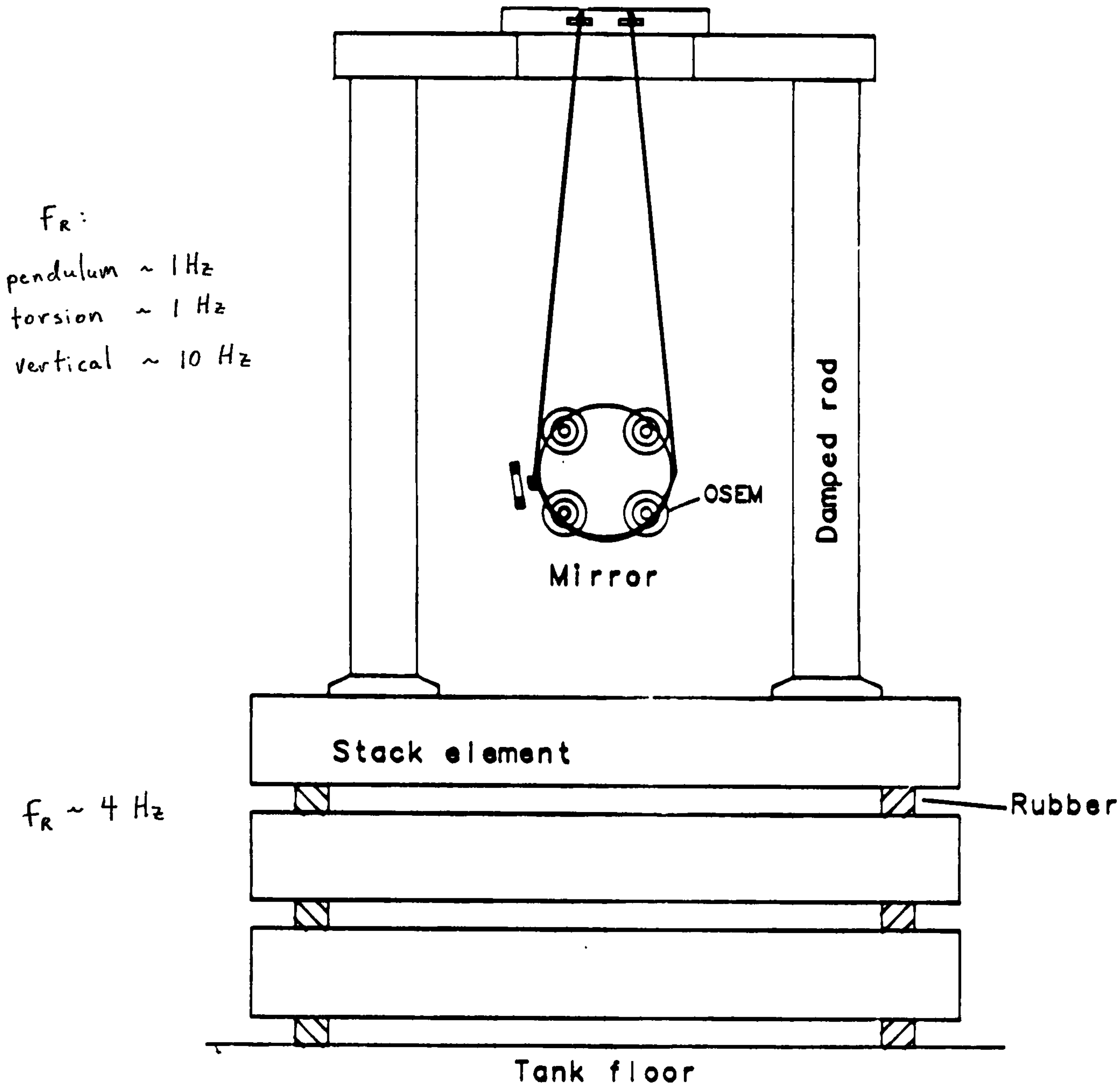
SEISMIC ISOLATION



Seismic Isolation

Seismic vibration amplitude: $A(f) \sim 10^{-11}\, m\, /\sqrt{Hz}$

stack attenuation:

$>10^4$ @ 100 Hz horizontal, vertical displacement

mirror suspension attenuation:

10^4 pendulum and torsional motion

10^2 vertical motion

Predicted Noise from Mirror Motion

Pendulum mode ⟶ frequency noise

$$L(f) = 10^{-11}\, 10^{-4}\, 10^{-4} = 10^{-19}\, m/\sqrt{Hz}$$

$$\nu(f) = \frac{L(f)}{L}\,\nu = 5 \cdot 10^{-6}\, Hz/\sqrt{Hz}$$

Vertical mode ⟶ beam displacement

$$y(f) = 10^{-11}\, 10^{-4}\, 10^{-2} = 10^{-17}\, m/\sqrt{Hz}$$

$$\epsilon_1(f) = \frac{y(f)}{w} \sim 10^{-14}/\sqrt{Hz}$$

Torsional mode ⟶ beam tilt

$$\epsilon_1 < 10^{-15}/\sqrt{Hz}$$

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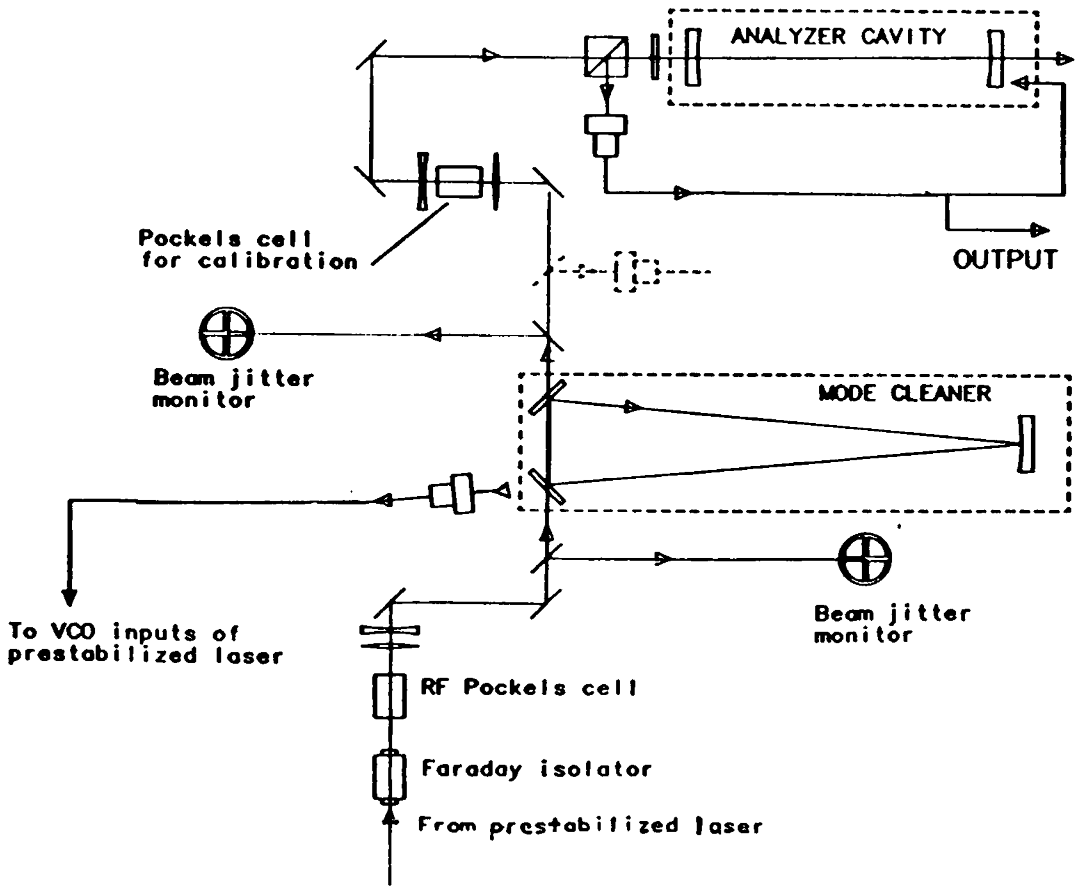
LAY-OUT FOR MODE CLEANER TEST SET-UP



Planned Tests

- Higher mode suppression measured with quad diode at mode cleaner input and output
  - displaced beam
  - tilted beam
- Conversion of spatial variation to frequency noise: $\epsilon(f) \longrightarrow \nu(f)$
- use at 40 m prototype

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Mode Cleaner Present Status

- Assembled Components
  - Prestabilized laser
  - Seismic isolation stacks
  - Mirrors and suspensions
  - Vacuum system
- Tested Components
  - Mirror control actuators
  - Frequency servo electronics

Development for Advanced Interferometer

Additional mode suppression of 50
Comparable stored power

$\Longrightarrow$ 2 mode cleaners in series