# An Improved Mode Cleaner for the 40 m Prototype

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## Abstract

This note contains a proposal to build and test a long mode cleaner, with mirrors independently suspended in a ring cavity configuration. While the mode cleaner will be built and tested at the OTF, it is intended to be used in the 40 m system, and also as a model for LIGO mode cleaners. The choice of parameters should make it possible to achieve a certain target sensitivity, for the 40 m system.

Performance of the ring cavity mode cleaner will be evaluated by using another long cavity, consisting of two suspended mirrors. The two cavities will be built as parts of the same task.

# Contents

# 1 Introduction: Motivation and Purpose

The motivation for replacing the rigid mode cleaner, currently used in the 40 m system, with a longer cavity, having three mirrors, independently suspended, in a ring configuration, can be summarized as follows:

1. Independently suspending the mirrors will do away with:
    - Mechanical resonances in the spacer
    - Mechanical noise possibly associated with the glue joints between mirrors and spacer
2. A long cavity has the following advantages:
    - The RF modulator needed for locking the interferometer arms can be placed ahead of the mode cleaner (MC)
    - For the same finesse, the cavity bandwidth is reduced, thus providing a higher degree of passive filtering for amplitude and frequency fluctuations in the laser light
    - For the same finesse, less frequency noise is generated at the cavity, from input beam jitter
    - For fixed bandwidth, mirror transmission is higher, thus increasing the power handling capability of the cavity. This aspect can be traded against the ones listed above, merely by changing mirror transmission
3. The ring configuration allows to eliminate the Faraday isolator currently placed between the MC and the interferometer proper.

It is felt that all the above will result in decreasing the residual frequency noise and diminish potential, as yet poorly understood noise contributions, associated with the Pockels cell and the Faraday isolator. These, in turn, should make it possible to achieve LIGO level displacement sensitivity, by using LIGO style lay-outs and input power.

Building the long mode cleaner at the OTF, and testing it against another long cavity, is intended to provide the opportunity to measure the MC performance, without interfering with the experimental program of the 40 m prototype. Performance parameters to be measured are:

- Residual frequency noise
- Residual beam jitter
- Beam jitter suppression by the MC
- Coupling of input beam jitter into residual frequency noise
- the relative importance of spurious interferometers
- Other aspects, more difficult to quantify, at this stage, like ease of alignment, overall stability of the servo systems, reliability, etc.

# 2 Assumptions

1. The improved MC will consist of three mirrors, in a ring configuration.
2. The MC will be used either with the current optical configuration of the 40 m prototype, or with the rebuilt 40 m system.
3. The improved MC should make it possible to achieve a sensitivity of $10^{-19}$ m/Hz$^{1/2}$, at some frequency between 100 Hz and 1000 Hz.
4. The open loop gain of the primary cavity servo will remain at its current value of 100 dB, at 1 kHz
5. The upper limits on laser beam angular jitter, at the laser output, are $3.1 \cdot 10^{-8}$ rad/Hz$^{1/2}$, below 500 Hz, and $7.5 \cdot 10^{-11}$ rad/Hz$^{1/2}$, above 2 kHz, with a steep slope connecting these two points. The corresponding figures for lateral displacement are $1.1 \cdot 10^{-7}$ m/Hz$^{1/2}$ and $2.6 \cdot 10^{-10}$ Hz$^{1/2}$, respectively[1].
6. The primary cavity servo should contain no correction elements after the MC.
7. The RF phase modulator necessary for locking the two interferometer arms[2] will be ahead of the MC. The same modulation will be used to lock the MC to the laser.

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[1] derived from measurements by A. Gillespie, with the laser running at 40 A, and no acousto optic modulator in the beam path

[2] or the anlayzer cavity, during testing

8. The modulation index will be optimized for best sensitivity of the 40 m prototype.
9. The input and output MC mirrors have the same transmission $T$ and loss $L$. The third mirror is a high reflector with loss $L$. $L$ can be maintained under 250 ppm for a time span of at least six months[3].
10. 90% of the laser beam power is in the $\mathrm{TEM}_{00}$ mode.
11. Residual frequency noise measured after the current MC is due to the following effects, in order of their perceived importance (see also Fig. 1):
    a) Seismic and acoustic excitation of the MC structure, and, above 1 kHz, mechanical noise intrinsic to epoxy joints[4].
    b) Thermal excitation of the MC quartz spacer, creating frequency noise 3 times lower than the measured one, at 1.2 kHz[5].
    c) Up- and/or down-conversion of noise, due to nonlinearities that are not known or understood, as yet.
    d) Shot noise, 10 times lower than the measured frequency noise, at 1.2 kHz.
12. The beam at the MC input carries 3 W of green light.
13. The MC can sustain at least 1.5 kW of circulating power, without showing any signs of heating effects[6]
14. While at the OTF, the MC will be tested with a prestabilized laser source. It is assumed, though, that, when first used with the 40 m interferometer, the MC will still have to serve as a reference for laser frequency stabilization.

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[3] 50 p.p.m. initial loss plus 200 p.p.m. due to contamination

[4] effect documented in Glasgow

[5] estimate by M. E. Zucker

[6] as seen in the 40 m lab, with one specific set of mode cleaner mirrors

# 3 An Improved Mode Cleaner: Functions and Requirements

## 3.1 Optical Efficiency

An optical efficiency (throughput) of at least 60% is required, over a time span of at least 6 months.

## 3.2 Frequency Domain Filter

The MC has the important function of attenuating frequency noise in the tens-of-kilohertz range and above, where the frequency stabilization servos have little gain.

MC length is fixed, to 12.165 m, by the requirement that the modulation side bands (12.33 MHz?) be passed through adjacent resonances (Assumption A7). Then, a mirror transmission $T$ =2,000 ppm will bring the circulating power just to the highest level where we know, from lab experience, that the cavity is still free from heating effects (A12,13). The corresponding cavity bandwidth, for $L = 250$ ppm (A9), is 9.3 kHz.

## 3.3 Reference for Laser Frequency Pre-Stabilization

A displacement sensitivity of $10^{-19}$ m/Hz$^{1/2}$ (Assumption 3) corresponds to frequency fluctuation power spectral density $1.4 \cdot 10^{-6}$ Hz/Hz$^{1/2}$. This frequency noise level would be achievable, with the current primary arm servo gain (approximately 100000, at 1 kHz, and higher at lower frequencies) even at the level of frequency noise currently measured after the MC. If the MC operated at its shot noise limit, as shown in Fig. 1, a sufficient safety factor of at least 20 would be available.

In order to achieve shot noise limited MC performance, the sum of seismic, acoustic and thermal excitations has to be substantially reduced. Suspending each MC mirror from an independent isolation stack, similar to those used for the test masses, should go a long way towards that goal.

For a displacement sensitivity of $10^{-19}$ m/Hz$^{1/2}$, at 300 Hz, an eightfold increase of the power reaching the 40 m cavities is necessary[7]. This is possible if the MC optical efficiency requirement of Section 2.1 is met, if the laser power is increased to 5 W and if the acousto-optic modulator is removed.

The current $\sim$ 2 MHz bandwidth of the laser locking (frequency pre-stabilization) servo is an essential feature, as it makes it possible[8] to achieve a 700 kHz bandwidth for the primary cavity servo, which, in turn, results in a 100,000 gain of that servo, at 1 kHz.

## 3.4 Beam Dewiggler

1. When a laser is locked to an external resonator, beam jitter is turned into frequency noise. Comparing the jitter that corresponds to the target performance of A3 with the measured jitter at the laser output (A5), it results that the required dewiggling factor is about five[9]. A MC that is a scaled down version of the 40 m cavities[10] and has mirror transmission 2000 p.p.m. attenuates the first higher mode by a factor of $\sim$ 800.

2. In order to keep the frequency noise at the MC output down to $10^{-3}$ Hz/Hz$^{1/2}$, i. e. three times lower than the shot noise limit shown in Fig. 1, with a laser beam jitter as measured (A5), the following relation has to hold[11]:

$$T \leq 1.15 \cdot 10^{-3} \left(\frac{d}{1\ m}\right)^{\frac{1}{2}} \qquad (1)$$

   where it was assumed that the MC is a scaled down version of the 40 m cavities. For $d$ =12.165 m, that means $T \leq 4{,}000$ ppm, which is amply met by the choice $T = 2{,}000$ ppm, made is Section 3.2.

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[7] R. E. Spero, *Overcoupled Cavities and Sensitivity Formula*, 12 October 1990

[8] by supporting a wide band feed-around servo path

[9] assuming a static higher mode amplitude of 0.3, due to imperfect mode matching or misalignment

[10] i. e. has the same ratios between mirror curvatures and mirror spacing

[11] A. Abramovici, *Do Wiggle Effects Depend on Mode Cleaner Length?*, Eq. 8

## 3.5 Frequency Correction Element

In the current configuration of the 40 m prototype, corrections that keep the light in resonance with the primary cavity are applied by adjusting the MC length (DC - 500 Hz), and by setting off the error point in the laser locking servo (500 Hz - 700 kHz).

It is reasonable to require that, as a frequency correction element, the mode cleaner dominated the primary cavity servo from DC to 1.5 kHz, the high frequency limit being determined by the lowest mechanical resonances of the mirrors[12].

## 3.6 Pointing Reference

Due to its design, the current MC provides an almost drift free pointing for the beam entering the interferometer. A MC with independently suspended mirrors will no longer have this feature, which will have to be provided by a separate, specifically designed, subsystem.

# 4 Mirror Isolation, Suspension and Control

## 4.1 Isolation and Suspension (Fig. 2)

1. The mirror will be suspended from a single loop of wire, attached to a suspension block.
2. The suspension block will rest on a platform supported by four damped rods (Newport?).
3. The support structure will sit atop an isolation stack, consisting of three layers of aluminum/rubber.

## 4.2 Control and Damping (Fig. 3)

1. Mirror control and damping will be carried out with four OSEM assemblies. The magnets will be arranged in a square pattern. This arrangement allows to separate the two tilts and can be

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[12] the lowest compressional resonance is at 50.5 kHz, and the lowest bending resonance is at 19 kHz, for the 3" diameter, 0.5" thick substrates that we have in stock

made insensitive to fluctuating magnetic fields and magnetic field gradients.

2. Placing the magnets at some distance from the edge of the mirror decouples the servo, to some extent, from the first bending resonance. This should allow a unity gain frequency of approximately 1.5 kHz, for the position servo.
3. The position and the pointing servos, and the 1 Hz damping arrangement will share the coils and the final stages of the electronics that drive the coils. The final stages will be provided with multiple inputs, in a summing configuration, and will have flat transfer functions (DC-10 kHz).
4. The error signals for global pointing control will be generated with global optical levers of the conventional kind.
5. The pointing servos will have unity gain frequency of approximately 10 Hz.
6. The error signals for local pointing control and for damping the pendulum motion will be generated by the OSEM's.
7. Damping will be made effective only around 1 Hz, the pendulum frequency of the mirror suspension.

# 5 Optical Lay-out (Fig. 4)

1. The mode cleaner consists of three mirrors: two are flat, and have $T = 2,000$ ppm, at $45^o$ incidence, and one is a curved (17 m) high reflector, placed 12 m away from the flat ones. The perimeter of the triangle is 12.165 m long, in order to pass the 12.33 MHz modulation side bands.
2. The analyzer cavity is 10 m long, so that it uses the conventional reflection locking scheme.
3. As shown in Fig. 4, the servo that locks the light to the mode cleaner uses a photodetector placed ahead of the mode cleaner. One could use a photodetector that is placed after the mode cleaner, as well, as indicated with dotted lines.
4. The beam jitter monitors are provided for assessing the effectiveness of the mode cleaner in suppressing beam jitter.

5. The residual frequency noise will be measured at the output of the analyzer cavity photodiode, by comparing the noise with a known level of FM, impressed onto the beam with a Pockels cell.

## 6 Vacuum System (Figs. 5,6)

For simplicity, only selected components are shown in Fig. 5.

The vacuum system consists of 5 standard 18" tanks, connected with adequately sized sections of 8" pipe. 4 of the tanks will house the suspended mirrors, while one tank is reserved for optics that are placed between the two cavities. A shown in Fig. 6, the tanks housing suspended components will be covered with squat bell jars. The optics between the two cavities will be placed on a stack, but will not be suspended, thus the tank housing it can be covered with a flat lid.

The long tube sections will be connected to the tanks via pivotted bellows.

The system will be evacuated with a small turbomolecular pump, backed by a rotary roughing pump.

## 7 Summary of Parameters and Performance

A tentative selection of parameters for the mode cleaner, the analyzer cavities, and the servo systems, is given in Table 1. The corresponding estimated performance indicators are summarized in Table 2.

## 8 Implementation

The following critical path items have been identified so far:

(a) The modulation frequency has been tentatively chosen at 12.33 MHz. It determines the mode cleaner length. The particular value one will eventually use should be selected with the size of the lab in mind, so that easy access to the various parts of the system is guaranteed.

(b) Vacuum system procurement is incomplete, at this point. The vacuum pipes and the bellows are potential long lead items. Leak hunting and fixing is another possible delaying factor.

(c) Electronics for the pointing systems and for damping will be based on existing designs, however a substantial amount of redesign is required. The sheer quantity of electronics involved is also of concern.

The frequency servos will use existing designs, with some modifications, consisting mainly of changing time constants.

Based on past experience, it is believed that the mirrors can be coated in a timely fashion, using substrates that we have in stock.

**Recommendation:** Ther conceptual outline of the long mode cleaner evaluation set-up, as described in this document, should be refined at the fastest possible pace, to a point where it can be subjected to a design review.

Table 1: Tentative parameters for mode cleaner, analyzer cavity, and servos

| | Parameter | Value |
|---|---|---|
| 1 | MC length | 12.165 m |
| 2 | I/O mirror transmission | 2,000 ppm |
| 3 | Mirror diameter/thickness | 3"/0.5" |
| 4 | Mirror curvatures | Flat/17 m |
| 5 | Analyzer cavity length | 10 m |
| 6 | I/O mirror transmission | 2,000 ppm |
| 7 | Mirror diameter/thickness | 3"/0.5" |
| 8 | Mirror curvature | 17 m |
| 9 | Modulation frequency | 12.33 MHz |
| 10 | Modulation index | TBD |
| 11 | Detuning of sidebands from resonance | TBD |
| 12 | MC servo bandwidth | 500 kHz |
| 13 | Analyzer servo bandwidth | 1.5 kHz |
| 14 | Pointing servo bandwidth | 10 Hz |
| 15 | Mirror damping effective at | Pendulum frequency |

Table 2: Estimated mode cleaner performance

| | Performance indicator | Level |
|---|---|---|
| 1 | Shot noise limited frequency noise | TBD |
| 2 | Bandwidth | ~ 10 kHz |
| 3 | Beam jitter suppression factor | ~ 800 |
| 4 | Input power, before onset of heating effects | 3.3 W |
| 5 | Transmission | 64% |

9/11 p. 3

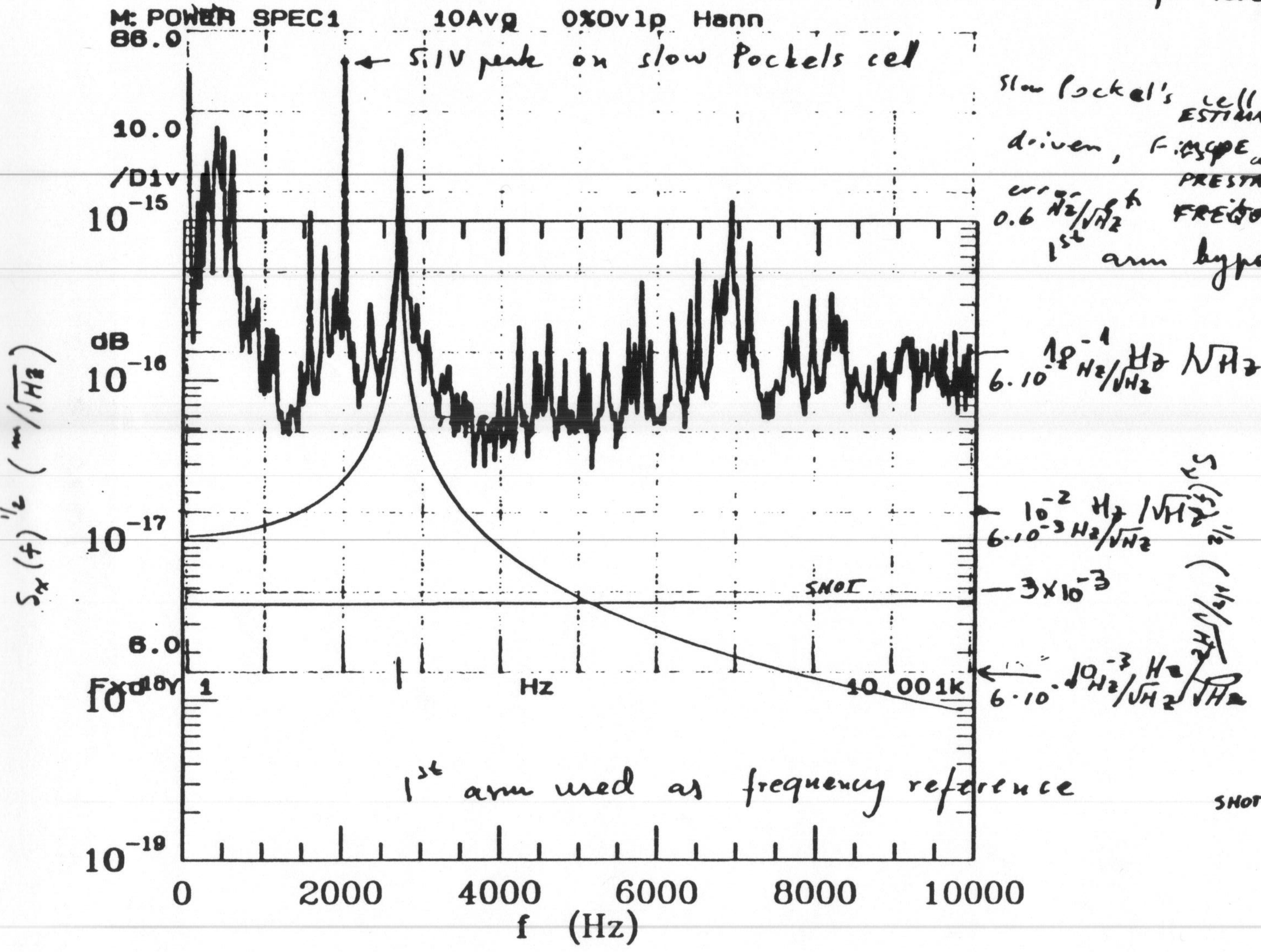
Laser loop amp set to H

Modulation amp attenuation: −18 dB

M.C. Bypass on

Mode Cleaner contrast: 6078/10/90 mEy

Mode Cleaner PD OC light level: 70 mV



Slow Pockel's cell (Amit) driven, F-P arm error 0.6 Hz/√Hz

ESTIMATED NOISE IN 1m MODE CLEANER LENGTH (OR PRESTABIL/250 LASER FREQUENCY)

1st arm bypass: off.

SHOT NOISE: $\eta P = 10$ mW

$V = 50\%$

$m = 0.2$

$T = 1200$ ppm

$\tau_c = 2.7\ \mu s$

THERMAL NOISE: $m_c \simeq 100$ g

$Q \simeq 300$

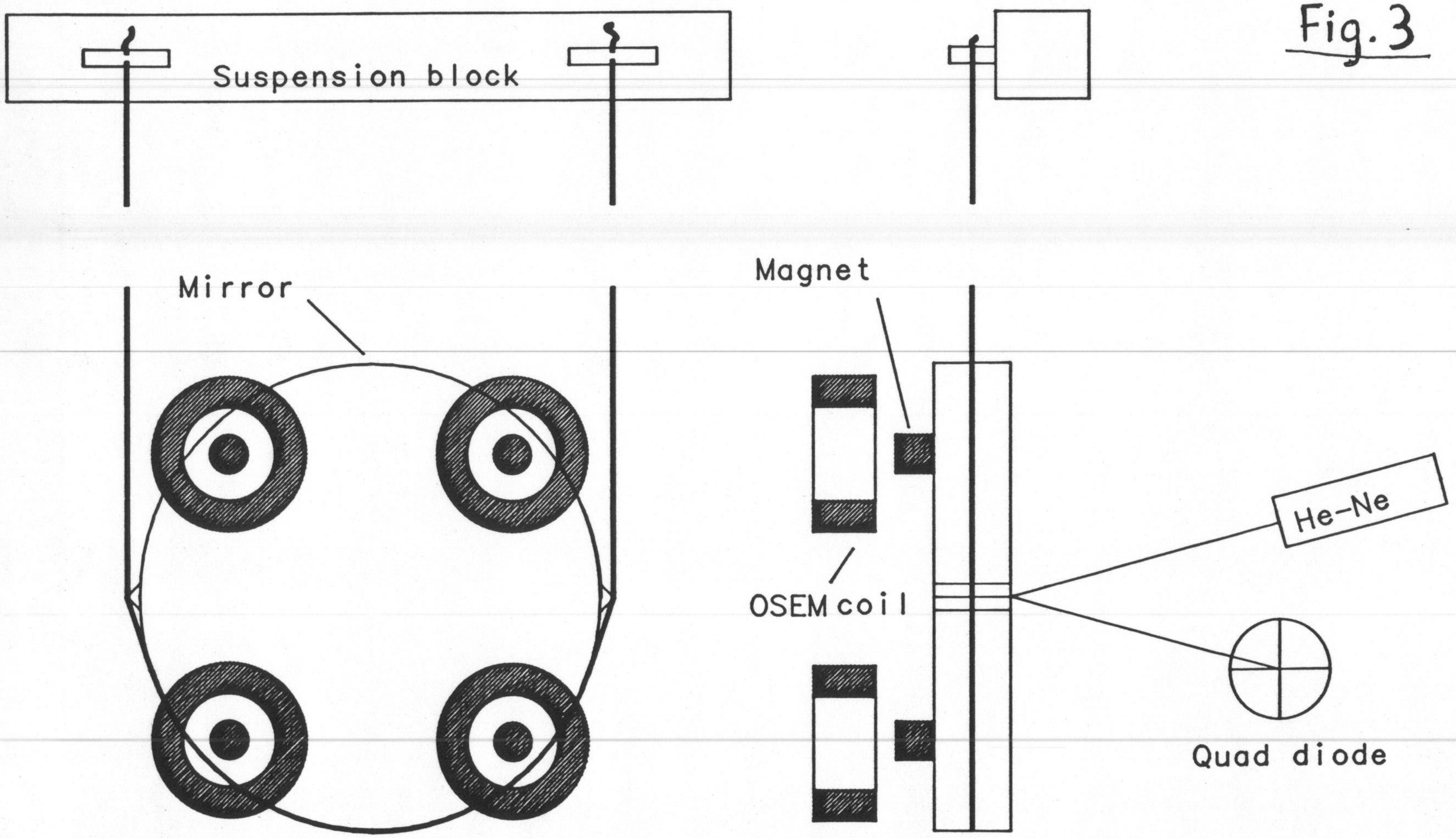
$\omega_0 = 2\pi \times 2.7$ kHz

Fig. 1 FREQUENCY NOISE AFTER MODE CLEANER

# MIRROR SUSPENSION AND CONTROL

AA, 7 May 1991

Fig. 3



# LAY-OUT FOR MODE CLEANER TEST SET-UP

AA, 10 May 1991

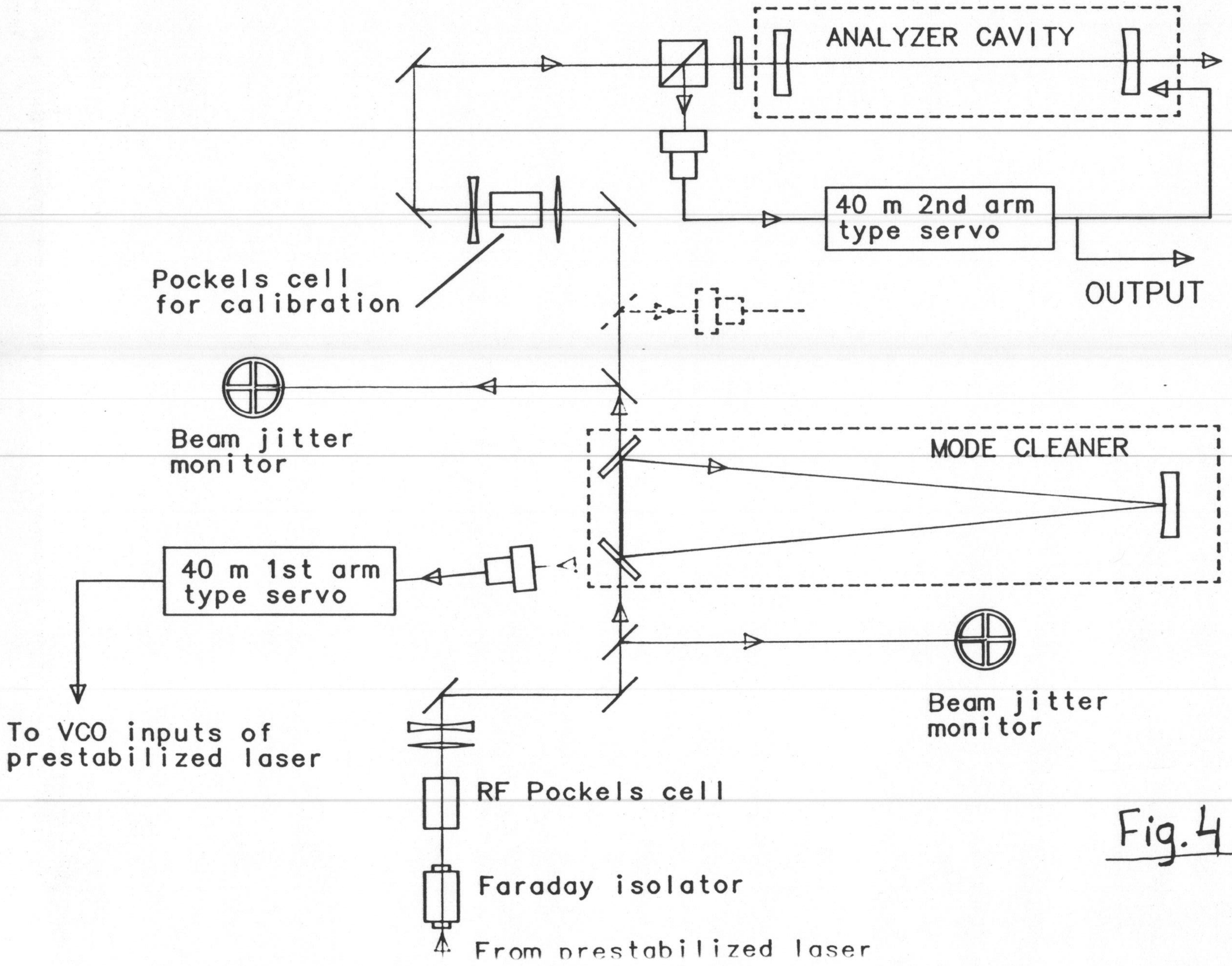


Fig. 4

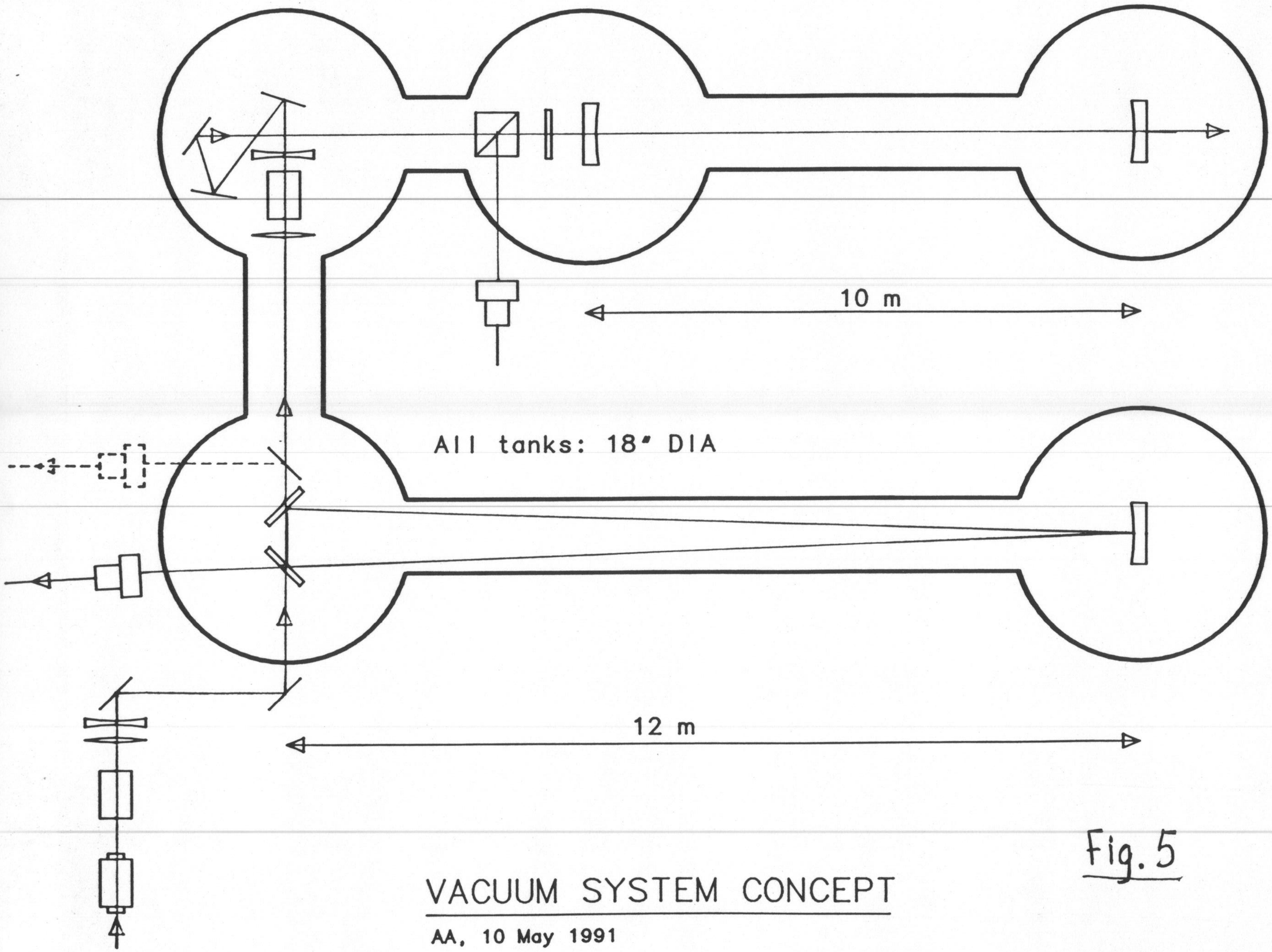


Fig. 5

VACUUM SYSTEM CONCEPT

AA, 10 May 1991

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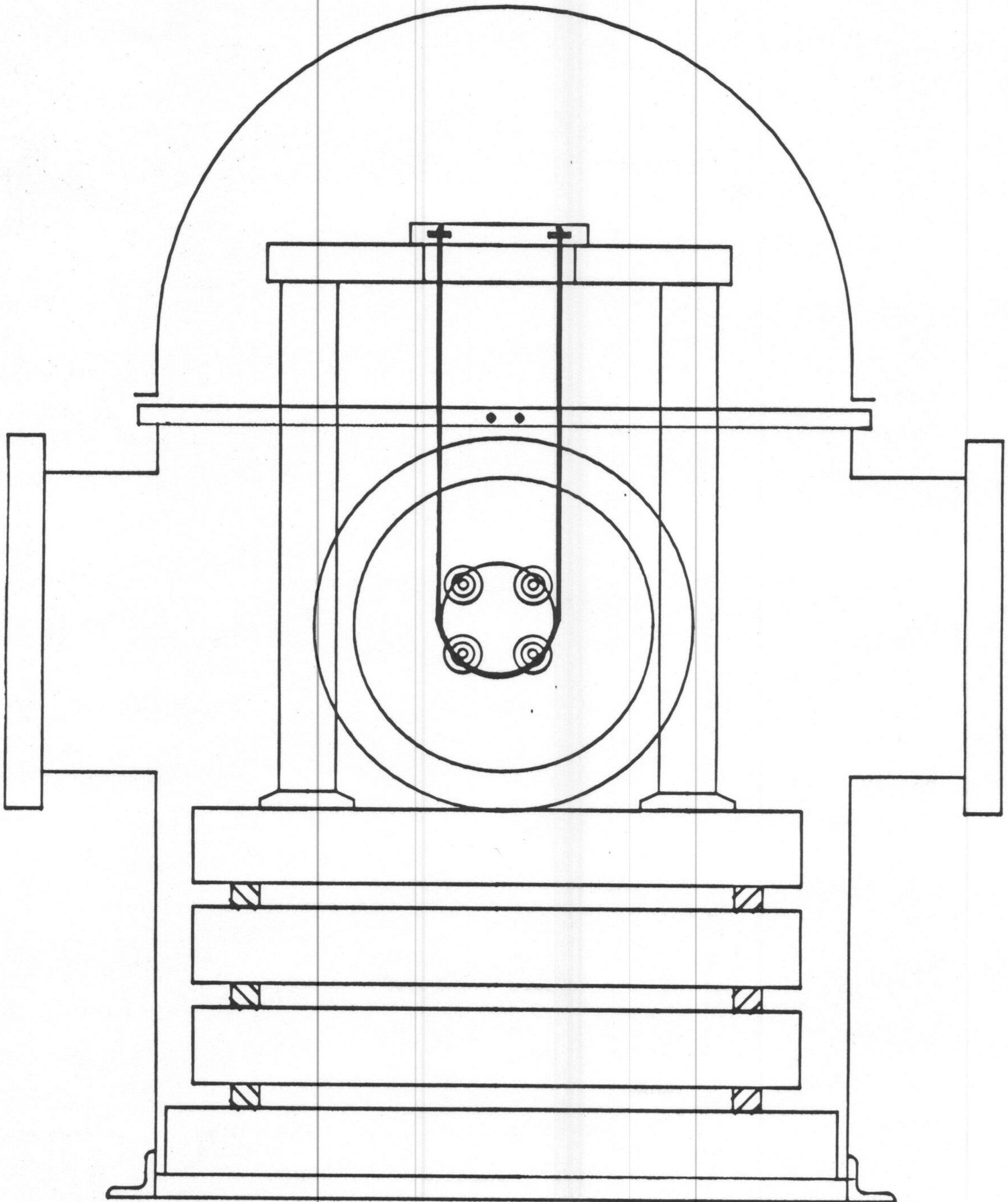

Fig. 6

# SEISMIC ISOLATION

AA, 6 May 1991

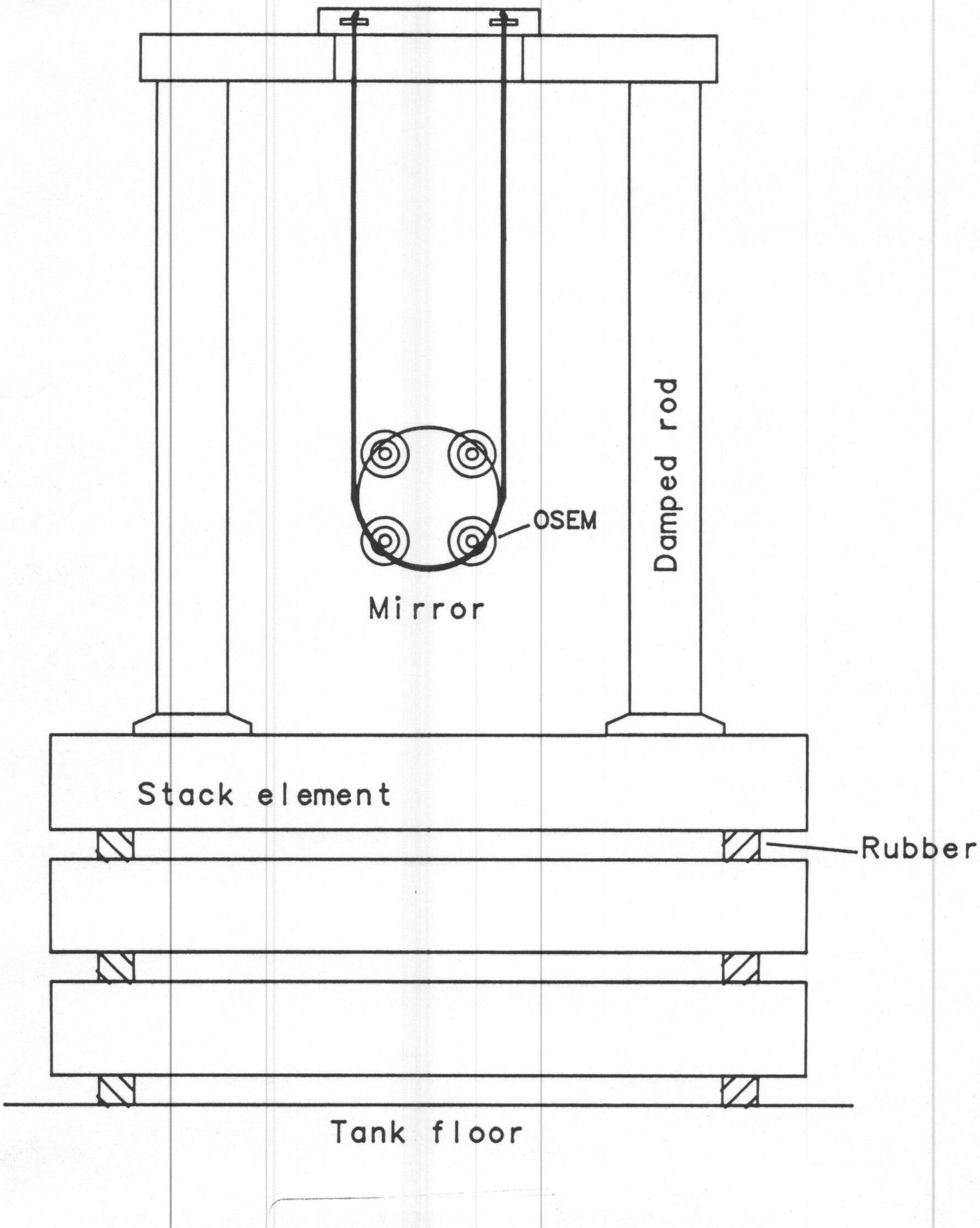

Fig.2