New Folder Name Improved Mode Cleaner

BATCH
START

1st Draft

STAPLE
OR
DIVIDER

An Improved Mode Cleaner for the 40 m Prototype

Alex Abramovici

1^{st} draft, 16 October 1990

Abstract

Starting from a target performance for the 40 m prototype and from a number of assumptions concerning various aspects of prototype operation, it is found that a mode cleaner between 16 m and 19 m long is desirable. Its mirrors should have transmission between 2000 p.p.m. and 4000 p.p.m., and should be independently suspended.

1 Assumptions

Terminology: the cavity that we call *mode cleaner* does more than ensure mode purity of the laser beam. Therefore, the term *intermediary optical cavity* (IOC) will be used in what follows, to indicates the position of the cavity between the laser and the interferometer proper.

1. In its first generation, the improved IOC will have a conventional, linear lay-out. Because of their lower level of demonstrated performance and since they are more complicated, ring cavities are not considered in the present preliminary study.
2. The IOC will be used with the current optical configuration of the 40 m prototype. This assumption is quite restrictive, and is made here only in order to keep the process of defining and specifying the IOC reasonably transparent. It should be easy to repeat that process, if and when a different configuration for the 40 m prototype is chosen.
3. The improved IOC should make it possible to achieve a sensitivity of 10^{-19} m/Hz$^{1/2}$, at some frequency between 300 Hz and 1000 Hz.
4. The open loop gain of the primary cavity servo will remain at its current value of 70 dB, at 1 kHz
5. The upper limits on laser beam angular wiggle, 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 IOC.
7. The RF phase modulator necessary for locking the two interferometer arms will be kept between the IOC and the beam splitter[2].

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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] Reasons: a) placing the modulator before the IOC is entirely non-trivial, as MIT experience shows; b) placing the modulator before the IOC would expose it to a non-dewiggled beam, which is potentially dangerous

8. Both IOC mirrors have the same transmission T and loss L. L can be maintained under 200 ppm for a time span of at least six months.
9. RF sidebands needed for locking the laser to the IOC carry 20% of beam power.
10. 90% of the laser beam power is in the TEM_{00} mode.
11. Residual frequency noise measured after the current IOC is due to the following effects, in order of their perceived importance (see also Fig. 1):
    a) Seismic and acoustic excitation of the IOC structure, and, above 1 kHz, mechanical noise intrinsic to epoxy joints[3].
    b) Thermal excitation of the IOC quartz spacer, creating frequency noise 3 times lower than the measured one, at 1.2 kHz[4].
    c) Possible polarization effects associated with the Pockels cells, and up- or down-conversion of noise, due to not yet understood nonlinearities.
    d) Shot noise, 10 times lower than the measured frequency noise, at 1.2 kHz.

2 Intermediary Optical Cavity: Functions and Requirements

2.1 Optical Efficiency

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

2.2 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 of approximately 3000, if the IOC operated at its shot noise limit, as shown in Fig. 1. A desirable safety

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[3] effect documented in Glasgow
[4] estimate by M. E. Zucker

factor of 3, for the IOC shot noise limit, can be achieved by increasing the IOC storage time by a factor of 3, that is by decreasing the ratio T/d three times[5].

In order to achieve shot noise limited IOC performance, the sum of seismic, acoustic and thermal excitations has to be substantially reduced. Suspending each IOC 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[6]. This is possible if the IOC 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 ~ 2 MHz bandwidth of the laser locking (frequency pre-stabilization) servo is a highly desirable feature. Since it is probably necessary that the IOC free spectral range be at least 4 times the servo bandwidth, it would appear that the IOC length should not exceed 18.75 m.

In order to keep the behavior of the laser locking servo simple, the frequency of the RF phase modulation should be away from the free spectral range of the IOC. For a modulation frequency of 12.33 MHz, the IOC length should therefore be different from 12.165 m, e. g. by at least 1 m.

2.3 Beam Dewiggler

1. When a laser is locked to an external resonator, beam wiggle is turned into frequency noise. Comparing the wiggle that corresponds to the target performance of Assumption 3 with the measured wiggle at the laser output (Assumption 5), it results that the required dewiggling factor is about five[7]. An IOC that is a scaled down version of the 40 m cavities[8] and has mirror transmission 2000 p.p.m. attenuates the first higher mode by a factor of 800.

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[5] T: IOC mirror transmission, d: IOC length

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

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

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

2. In order to keep the frequency noise at the IOC 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 wiggle as measured (Assumption 5), the following relation has to hold[9]:

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

where it was assumed that the IOC is a scaled down version of the 40 m cavities.

2.4 Frequency Domain Filter

The IOC has the important function of attenuating frequency noise in the tens-of-kilohertz range and above, where the frequency stabilization servos have little gain. The most prominent feature in the frequency noise spectrum, above 10 kHz, is a broad peak, centered at 15 kHz, due to line spikes. A cavity with bandwidth of 10 kHz would attenuate this peak by a factor of three[10].

2.5 Frequency Correction Element

In the current configuration of the 40 m prototype, the frequency corrections that keep the light in resonance with the primary cavity are applied driving a test mass (DC - 100 Hz), by adjusting the IOC length (100 Hz - 1 kHz), and by applying appropriate voltages to the slow (1 kHz - 10 kHz) and fast (10 kHz - 300 kHz) Pockels cells. It has been found that the Pockels cells are a source of noise. The need for Pockels cells can be obviated as follows:

1. Extending the bandwidth where the IOC length corrections dominate the primary cavity servo to 10 kHz. At present, the useful bandwidth for IOC length corrections is limited to 1 kHz by the resonances of the fused silica spacer, with the lowest one located at 2.7 kHz. Independently suspending the IOC mirrors would

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

[10] Our best sensitivity of $3 \cdot 10^{-18}$ m/Hz$^{1/2}$ was measured with an IOC having a bandwidth of 240 kHz. However, at that time, the laser locking servo was quite different, e. g. a Pockels cell was inside the laser resonator, so that there may have been better suppression of the line spike induced noise at 15 kHz.

eliminate this problem. For a useful servo bandwidth of 10 kHz, the first longitudinal resonance of the mirrors has to be at least ~ 80 kHz[11], which sets a limit of 3 cm to the thickness of IOC mirrors made of fused silica. Furthermore, the mirror diameter should be as small as practically possible, e. g. 7.5 cm, and the points where force is applied should be on the antinode of the lowest bending mode.

2. Using a feed-around path for corrections above 10 kHz.

With appropriate care in design, the servo outlined above should be able to function from DC, thus making it unnecessary to drive a test mass in the primary arm in order to keep the arm in resonance. Then, there will be no correction element physically placed after the IOC (Assumption 6).

2.6 Pointing Reference

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

3 Characteristics of Improved IOC

1. The various constraints on T and d are shown in Fig. 2. Using the Assumptions from Section 1 and the considerations from Section 2, it results that T can be chosen between 2000 p.p.m. and 4000 p.p.m., and d should be between 13 m and 18.75 m. The small hatched area in Fig. 2, below 11 m, has been conservatively discarded.
2. IOC mirrors will be independently suspended, from seismic isolation stacks like those used for the test masses.
3. IOC mirror thickness and diameter should be 3 cm and 7.5 cm, respectively.
4. The axial position of the IOC mirrors will be controlled with coils and magnets. The magnets will be placed on the antinodal line of the lowest bending mode.

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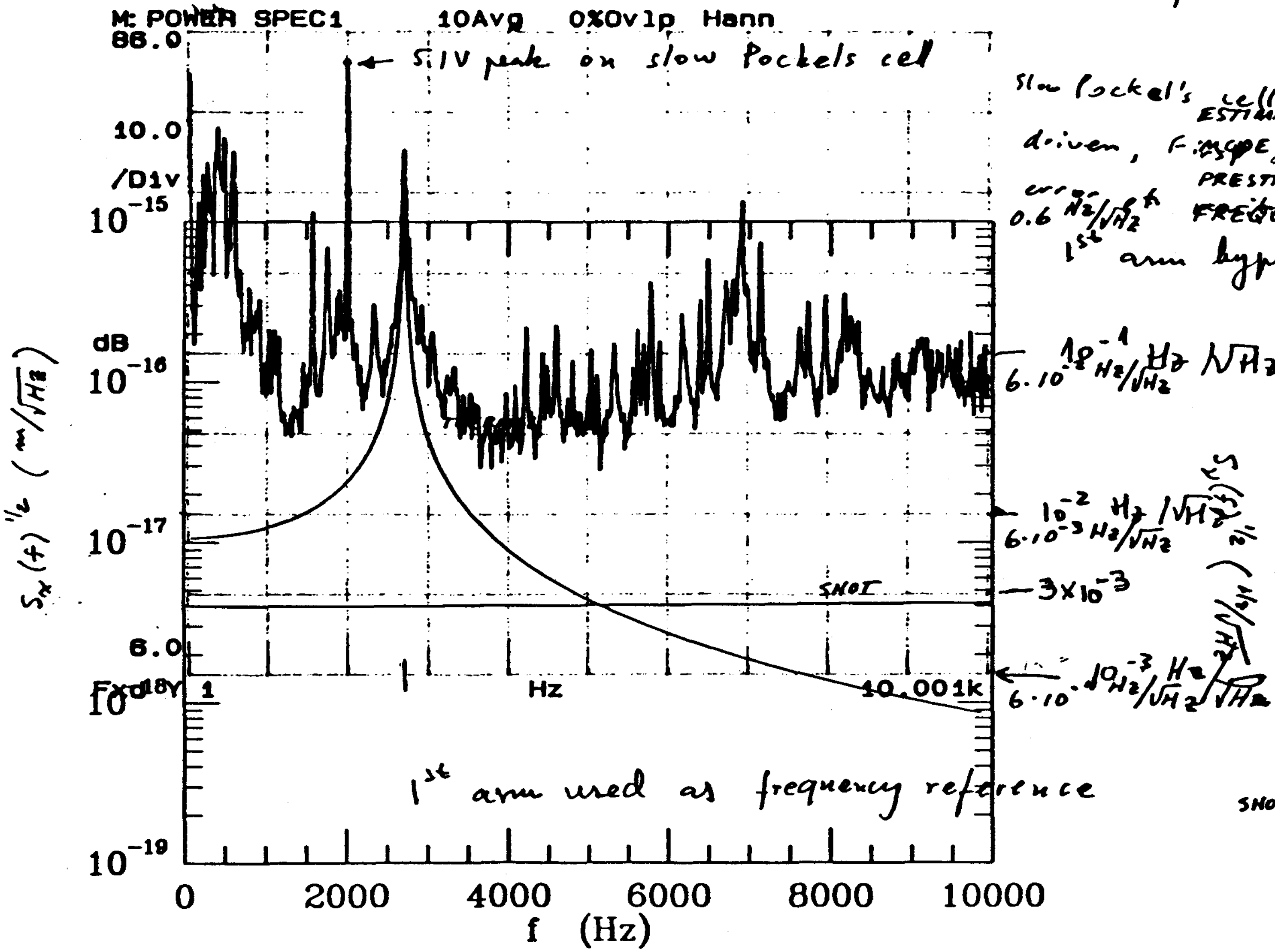
[11] extrapolated from known test mass behavior

9/11 p. 3

Laser loop amp set to H
Modulation amp attenuation: −18 dB
M.C. Bypass on
Mode Cleaner contrast: 60 → 8/10/90 mV
Mode Cleaner PD DC light level: 70 mV



1st arm used as frequency reference

Slow Pockel's cell (Amit) driven, F: error of 0.6 Hz/$\sqrt{Hz}$
1st arm bypass: off.

ESTIMATED NOISE IN 1m MODE CLEANER LENGTH (OR arm PRESTABILIZED LASER FREQUENCY)

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

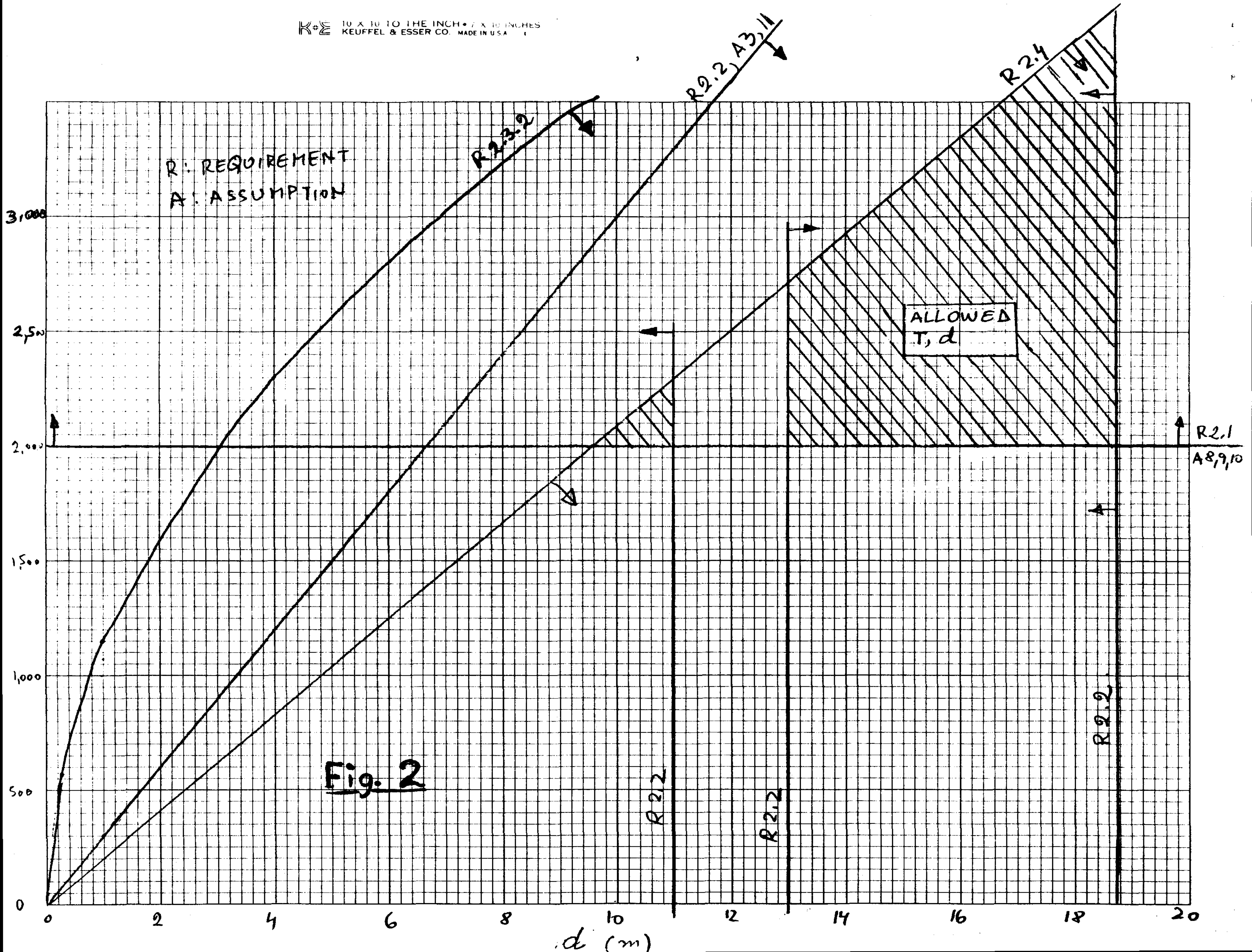

R: REQUIREMENT
A: ASSUMPTION
R2.3.2
R2.2, A3, 11
R2.4
ALLOWED
T, d
R2.1
A8,9,10
R2.2
R2.2
R2.2
0
500
1,000
1,500
2,000
2,500
3,000
0
2
4
6
8
10
12
14
16
18
20
d (m)

Fig. 2

BATCH
START

2nd Draft

STAPLE
OR
DIVIDER

An Improved Mode Cleaner for the 40 m Prototype

Alex Abramovici

2^{nd} version, 23 January 1991

Abstract

Starting from a target performance for the 40 m prototype and from a number of assumptions concerning various aspects of prototype operation, it is found desirable that mode cleaner length be at least 13 m. Mirror transmission should be higher than 2600 p.p.m., but less than 210 p.p.m. for each meter of length. The mirrors should be independently suspended.

A preliminary listing of analysis, design and construction tasks, associated with installation of a long mode cleaner, is given.

It is recommended that design and building of selected subsystems be started immediately.

Note: This version is based on the 1st draft of 16 October 1990, on the many comments I received, and on the findings in the lab since the first draft was circulated.

1 Assumptions

1. In its first generation, the improved mode cleaner (MC) will have a conventional, linear lay-out. Because of their lower level of demonstrated performance and since they are more complicated, ring cavities are not considered in the present study.
2. The MC will be used with the current optical configuration of the 40 m prototype. This assumption is quite restrictive, and is made here only in order to keep the process of defining and specifying the MC reasonably transparent. It should be easy to repeat that process, if and when a different configuration for the 40 m prototype is chosen.
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 wiggle, 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 will be kept between the MC and the beam splitter[2].
8. Both MC mirrors have the same transmission T and loss L. L can be maintained under 250 ppm for a time span of at least six months[3].

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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] Reasons: a) placing the modulator before the MC is entirely non-trivial, as MIT experience shows; b) placing the modulator before the MC would expose it to a non-dewiggled beam, which is potentially dangerous. Yet another mode cleaner, between the laser and the RF modulator, would take care of this, however an additional MC does not form the object of this study.

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

9. RF sidebands needed for locking the laser to the MC carry 20% of beam power.
10. 90% of the laser beam power is in the 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.

2 An Improved Mode Cleaner: Functions and Requirements

2.1 Optical Efficiency

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

2.2 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. Thus, the ratio $T/d = 1000$ ppm/m, which the current mode cleaner has, is adequate[6].

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[4] effect documented in Glasgow

[5] estimate by M. E. Zucker

[6] T: MC mirror transmission, d: MC length

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. Therefore, the free spectral range of the MC should not be smaller than 2 MHz, that is, MC length should not exceed 75 m. Keeping the MC confined to the building automatically answers this requirement.

In order to keep the behavior of the laser locking servo simple, the frequency of the RF phase modulation should be away from the free spectral range of the MC. For a modulation frequency of 12.33 MHz, the MC length should therefore be different from 12.165 m, e. g. by at least 1 m.

2.3 Beam Dewiggler

1. When a laser is locked to an external resonator, beam wiggle is turned into frequency noise. Comparing the wiggle that corresponds to the target performance of Assumption 3 with the measured wiggle at the laser output (Assumption 5), 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 800.

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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

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 wiggle as measured (Assumption 5), the following relation has to hold[11]:

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

where it was assumed that the MC is a scaled down version of the 40 m cavities.

2.4 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. The most prominent feature in the frequency noise spectrum, above 10 kHz, is a broad peak, centered at 15 kHz, due to high order multiples of the line frequency. A cavity with bandwidth of 10 kHz would attenuate this peak by a factor of three[12], while the current MC does not provide any attenuation at 15 kHz. While there is no evidence, at this time, that high frequency frequency noise dominates the measured displacement noise spectrum at any frequency below 5 kHz, it seems prudent to require that at least an attenuation of 3 be provided at 15 kHz.

2.5 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 driving a test mass (DC - 100 Hz), by adjusting the MC length (100 Hz - 500 Hz), and by setting off the error point in the laser locking servo (500 Hz - 700 kHz). At frequencies where a correction signal is applied to the test mass, frequency noise is not reduced by the servo. Thus, there will be no frequency correction at all bellow 100 Hz, and we measured that frequency noise reduction corresponds to the primary cavity loop gain only above 500 - 700 Hz. We have,

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

[12] the cavity acts like a low pass filter, with corner frequency equal to half the cavity bandwidth

indeed, found that, when no correction signal is applied to the test mass, displacement noise is reduced by up to a factor of 2, between 300 Hz and 700 Hz.

While it has proved possible to operate the primary cavity with no correction signal to the test mass, this mode of operation is likely to be marginal, for a rigid mode cleaner the length of which is adjusted with piezos. A mode cleaner with independently suspended mirrors would certainly do the job, though, as we know from our experience with the 40 m arms.

It is reasonable to require that, as a frequency correction element, the mode cleaner dominated the primary cavity servo from DC to 10 kHz.

2.6 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.

2.7 Some Characteristics of the Improved MC

1. The various constraints on T and d are shown in Fig. 2. Using the Assumptions from Section 1 and the considerations from Section 2, it results that T should be higher than 2600 p.p.m., but less than 210 p.p.m. for each meter of MC length. The length d itself should be in excess of 13 m.
2. MC mirrors will be independently suspended, from seismic isolation stacks like those used for the test masses.
3. MC mirror thickness and diameter of 3 cm and 7.5 cm, respectively, should make it possible to control mode cleaner length up to a frequency of 10 kHz, by pushing one of the suspended mirrors, while complying with the constraints imposed by servo stability.
4. The axial position of the MC mirrors will be controlled with coils and magnets. The magnets will be placed on the nodal line of the lowest axially symmetric membrane mode, in order to comply with servo stability requirements.

3 Implementation Aspects

Abreviations: A: analysis is required, D: design is required, C: fabrication/construction are required, LLT: particularly long lead time

3.1 MC mirror Spacing

A

The distance *d* between MC mirrors has to be chosen before analysis and definition of other optical parameters can be attacked. Defining *d* will require a considerable amount of thinking, as it is related to deep questions, like what the modulation frequencies should be, and also to less critical issues, like the location of the point where light is injected into the system.

3.2 Mirrors

A, D, C, LLT

1. **Transmission**
   Once *d* has been chosen, a preliminary range for *T* can be red off Fig. 2. The ultimate choice for *T* will depend, most likely, on system considerations. For example, MC bandwidth has to be such as to ensure sufficient dynamic range for the feed-around path of the primary cavity servo. That, in turn, is determined by the frequency band over which the corrections can be applied by adjusting MC length.
2. **Curvature**
   For given *d*, mirror curvatures determine the relative amount of suppression of higher transverse modes. However, since one does not really know which modes need to be rejected[13], mode suppression requirement can be turned, at best, into a very weak criterion for mirror curvature selection. Therefore, curvature choice will be based on lower level considerations, such as:

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[13] the higher mode content varies as the pointing of the laser drifts, as the temperature of optics changes with laser power, etc.

- The requirement to do modematching with lenses that are as weak as possible, both into the MC and between the MC and the 40 m cavities.
- The need to pass the beam through limited apertures, e. g. Pockels cells.
- The requirement that mirror pointing be made insensitive to pointing fluctuations of the He-Ne laser beams used as optical levers.
- Flexibility in the choice of mirror spacing

3. **Size, shape**
   Mirror size and shape will be determined mainly by servo considerations. For example, the mirrors have to be big enough to accomodate coils and magnets used for the pointing and axial position control, and at the same time provide ample clearance for the main green beam and for the optical levers.

   For given diameter, choice of thickness is driven by the frequencies of the acoustic modes, which are constrained by servo requirements.

3.3 Mirror Orientation and Axial Position Control

A, D, C

1. **Reference beams and sensors**
   It is possible to use global optical levers and OSEMs for sensing changes in pointing of MC mirrors. While it is desirable, and likely, that available components and designs be used, the actual configuration will have to be tailored with the specific requirements (TBD) of a mode cleaner in mind.
2. **Orientation transducers**
   Coil/magnet transducers, as currently used for controlling beam splitter pointing, are probably adequate for controlling the pointing of MC mirrors. The magnet pattern may have to be changed, in order to avoid cross coupling between the two pointing degrees of freedom, and also with axial mirror motion.
3. **Axial motion transducers**
   Since it seems to be very hard to decouple angular from axial

motion, when only three magnets are used (as in the case of the beam splitter in the 40 m system), it may be necessary to provide a separate set of magnets and coils for axial motion. The actual pattern for these magnets has yet to be determined.

4. **Electronics**
   All electronics for the pointing and axial motion servoes will have to be built. Existing designs are probably usable, possibly with minor modifications.

3.4 Mirror Suspensions

C

Single loops of wire will be used to suspend the mirrors from seismic isolation stacks identical to those used for the test masses and the beam splitter.

3.5 Green Beam Pointing Control

D, C

A small amount of green light will be picked off before the MC, and led down one of the 40 m arms to a position sensitive detector. The resulting signal will be used to correct for drift in green beam pointing.

3.6 Vacuum System

C

The vacuum system that will house the long mode cleaner will consist of two 18" tanks of standard design, with flat bottoms, sitting on optical tables. Each tank will contain one of the mirrors and auxiliary equipment. The tanks will be connected with an appropriate length of 8" stainless steel pipe. This vacuum system will be directly connected to the 40 m vacuum system. An 8" gate valve, provided with an optical window, will allow to separate the two systems, though, in order to make maintenance and changes easier. A small pumping station, including a turbo molecular pump, will be dedicated to the MC vacuum system.

3.7 Comments, Recommendations

Comments:

1. At the present time, substantial progress in the 40 m lab is possible, and expected to take place, with the 1 m rigid mode cleaner. Therefore, even if the hardware for a long mode cleaner were available, there would be little incentive to shut down the lab now, and proceed with MC installation.
2. The mode cleaner parameters that are most likely to change, as a result of findings in the lab, are mirror transmission and spacing.
3. As the preceding subsections show, installing a long mode cleaner that uses independently suspended mirrors involves a substantial amount of analysis, design and construction. It would take approximately 6 months to obtain the mirrors, and probably at least as much to have the rest of the hardware ready.
4. If research in the 40 m lab maintains its present momentum, we might expect a development that will render a long mode cleaner desirable, possibly as soon as 2-3 months from now.
5. A long mode cleaner as outlined in this study is probably similar, in many respects, to a LIGO MC.

Recommendations:

1. Identify items that are unlikely to change as a result of research in the lab. Start at once with their detailed analysis and design and order them as soon as possible.
2. LIGO requirements should be kept in mind, at least to some extent.
3. Select a mirror curvature compatible with the widest possible range of mirror spacings[14], decide on mirror diameter and thickness and order substrates with the least possible delay.

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[14] maximum range extends from 13 m to 40 m

4. Reassess the need for a long mode cleaner at approximately two months intervals.
5. When need arises, determine mirror transmission and spacing, order coatings.

Obviously, decisions on any of the above aspects should be contingent upon other activities, in progress or planned.

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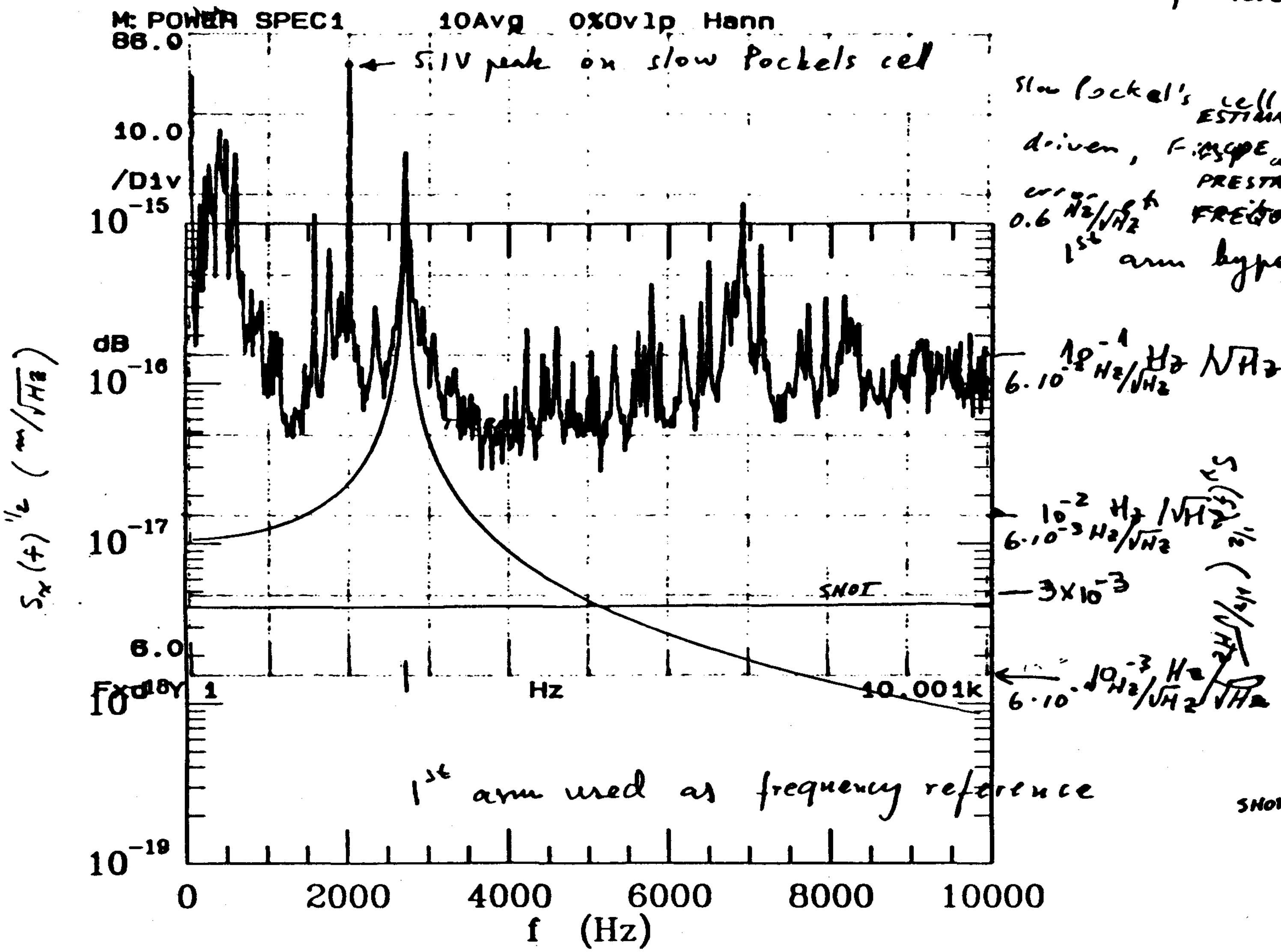
Laser loop amp set to H

Modulation amp attenuation: −18 dB

M.C. Bypass on

Mode Cleaner contrast: 60% 9/10/90 MEJ

Mode Cleaner PD DC light level: 70 mV



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

ESTIMATED NOISE IN 1m ~~MODE~~ arm CLEANER LENGTH (OR PRESTABIL/260 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

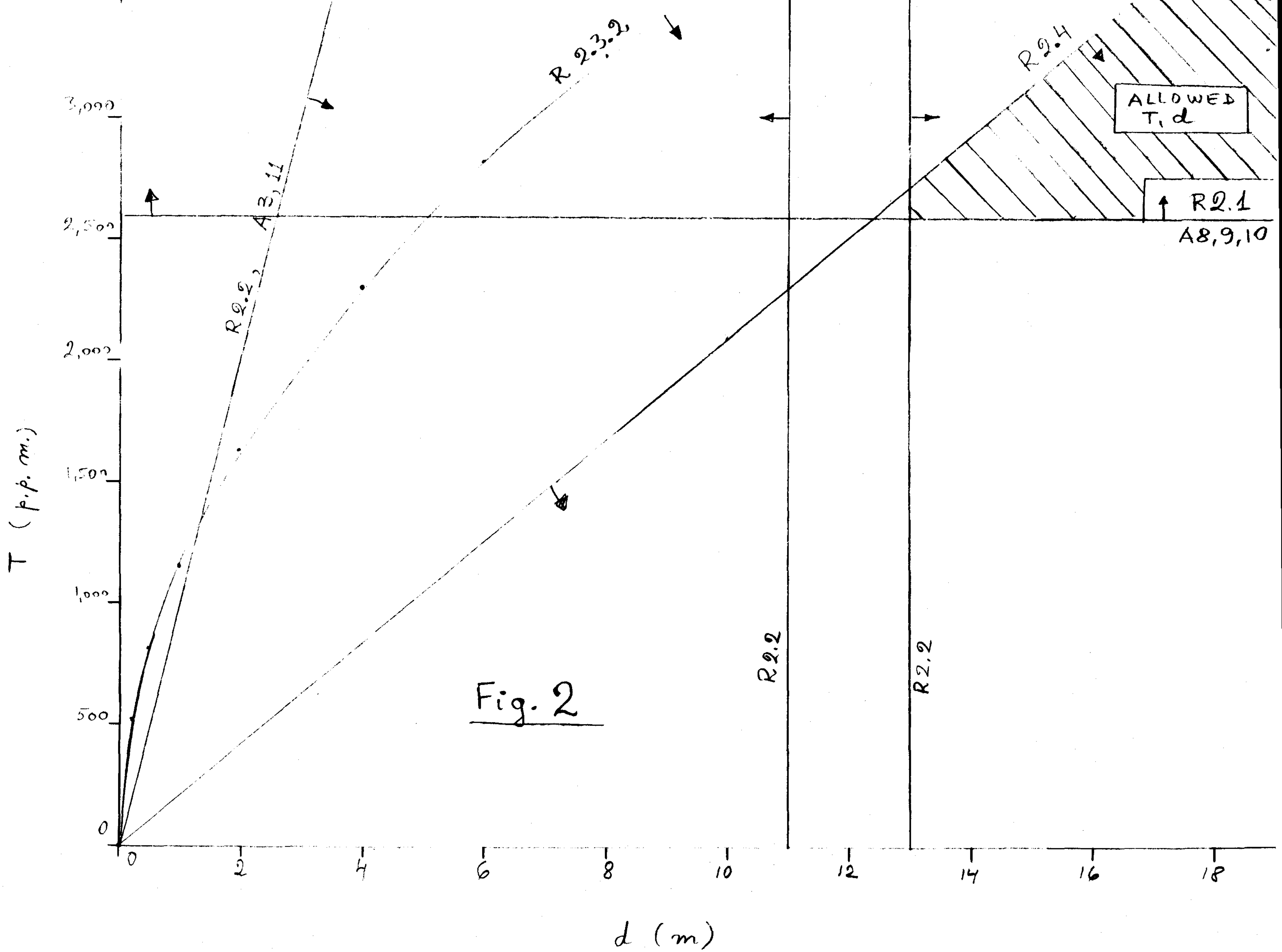

T (p.p.m.)
3,000
2,500
2,000
1,500
1,000
500
0
R2.2
A3,11
R23.2
R2.4
ALLOWED T, d
R2.1
A8,9,10
R2.2
R2.2
0
2
4
6
8
10
12
14
16
18
d (m)

Fig. 2