New Folder Name LIGO Input Optics

BATCH START

Version 1 - March 1991

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LIGO-T910030 00-D

LIGO Input Optics: Conceptual Design

Alex Abramovici

Part A, version 1, 9 March 1991

1 Introduction

This document is a brief conceptual outline of the optics ahead of the LIGO interferometer proper. The optics is broken down as follows:

- Prestabilized laser
- Mode cleaner
- Optics 1, between the prestabilized laser and the mode cleaner
- Optics 2, between the mode cleaner and the interferometer

For each of the above items, whenever applicable, the following aspects are covered:

1. Requirements/assumptions
2. Description
3. Control systems
4. Parameters
5. Performance

6. Trade-offs

Optical isolation requirements and the mode cleaner geometry (linear versus ring cavities) are not addressed here. They are being covered under **Part B**, by Fred J. Raab. For the sake of defining the parameters, linear cavities are considered in what follows.

As conceptual design work on other interferometer subsystems becomes available, it is likely that the lay-outs and many of the parameters defined here will have to be readjusted. One notable case is that of the servo that locks the frequency of the light to the interferometer, or vice-versa. Since the topology of the interferometer control system is not yet defined, the approach taken here is that the servo systems relating to the input optics are self contained. This serves the purpose of defining some of the relevant parameters, for the time being.

Some of the assumptions and requirements are on anything but firm grounds. Topics, the investigation of which seems most urgent, are listed.

2 Prestabilized Laser

2.1 Requirements/assumptions

1. The light delivered to the input optical chain will have its frequency stabilized to a level, comparable to what is measured in the 40 m system, after the mode cleaner: at least down to 10^{-2} Hz/Hz$^{1/2}$, in a frequency range TBD.

2. The optical power at the output of the prestabilized laser subsystem will be at least 3.5 W.

3. Optical power fluctuations will be kept down to a level TBD, in a frequency range TBD, by use of a power stabilization servo.

4. The frequency prestabilization servo will have VCO inputs for both fast signals (up to hundreds of kilohertz) and slow signals (kilohertz), for further frequency stabilization using signals from the mode cleaner and/or the interferometer. The VCO inputs will also be used to phase lock different lasers.

5. No laser mode hopping is allowed.
6. Component apertures of 5 mm should be sufficient.

2.2 Description

The optical and control lay-out of the prestabilized laser subsystem is shown in Fig. 1. It strongly resembles the arrangement currently used in the 40 m lab, with the following notable differences:

- The rigid reference cavity will not be used as a mode cleaner. Approximately 0.5 W of green light will be diverted to the reference cavity path.
- A fiber[1] is provided for spatially filtering the beam, so that geometrical beam fluctuations will not be converted into frequency noise.

A similar lay-out is likely to be used for prestabilization of the new Spectra Physics laser, soon to take place in the OTF.

The laser will be rebuilt as where the lasers currently used in the 40 m lab, with increased emphasis on thermal stability.

Al optical components will be in air, bolted to an optical table.

2.3 Control systems

Frequency prestabilization is done with a wide band servo system that uses slow and a fast piezo mirrors in the laser and phase correcting Pockels cells as correcting transducers.

Power stabilization is carried out by using an acousto-optic modulator (AOM). An input is provided for signals derived further downstream in the optical chain.

2.4 Parameters

1. Optical components will have clear aperture of 5 mm.

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[1] the fiber can be inserted in the reference cavity path, because the optical power there is less than 0.5 W, and the optical efficiency in that path is not critical

2. All components that are not at Brewster angle will be provided with narrowband AR coatings (V-coatings).

2.5 Performance

With the laser delivering 5 W of raw power, and taking into account the power diverted to the reference cavity, and also the power reduction that makes the use of the AOM possible, the prestabilized laser should perform as follows:

1. 3.5 W of green light should be available at the output of the prestabilized laser subsystem.
2. The frequency noise, at that point, should be less than 10^{-2} Hz/Hz$^{1/2}$, in a frequency range TBD.
3. Power fluctuations are reduced to a level TBD, within a frequency range TBD.
4. Laser mode hopping will not occur.

3 Optics 1

3.1 Requirements/assumptions

1. 3 W of green light will be available at the mode cleaner input.
2. At least 95% of power in the beam will be mode matched to the mode cleaner.
3. A degree of optical isolation TBD will be provided between the output of the prestabilized laser subsystem and the input of the mode cleaner.
4. Component apertures of 5 mm should be sufficient.

3.2 Description

The optics in this part of the system (Fig. 2) is meant to:

- mode match the beam to the mode cleaner
- provide the necessary optical isolation between the prestabilized laser and the mode cleaner, by using Faraday isolator(s)
- impress RF phase modulation on the beam, by using Pockels cells

Some beam steering capability is needed, in order to correctly oint the beam towards the mode cleaner. Steering mirrors are not shown in Fig. 2, for simplicity. The steering mirrors, design TBD, have to be provided with remote control, and possibly with servo control.

3.3 Parameters

1. Optical components will have clear aperture of 5 mm.
2. All components that are not at Brewster angle will be provided with narrowband AR coatings (V-coatings).

4 Mode Cleaner

4.1 Requirements/assumptions

1. LIGO interferometer target performance and parameters are as in Fig. III-2. p. 18 of the December 1989 Proposal, Vol. 1.
2. Geometric fluctuations of the laser beam impinging on the mode cleaner are as in Fig. 3.
3. Geometric laser beam fluctuations have to be reduced to a level, compatible with LIGO target performance.
4. At the mode cleaner output, the frequency noise has to be reduced to a point where the gain available in the 4 km system servo(s) is sufficient to further reduce frequency noise to a level, compatible with LIGO target performance. This sets requirements on:

- Mode cleaner shot noise limit.
- Available gain/bandwidth in the servo that locks the frequency of the light to a mode cleaner resonance.

5. The dominant feature in the raw laser frequency noise spectrum, at higher frequencies, is a broad peak centered at 15-20 kHz, associated with multiples of the line frequency. Since there is little gain in the frequency servos, at those frequencies, the mode cleaner should provide passive filtering, such that the peak is attenuated by at least a factor of 3.

6. At least one set of RF modulation sidebands, required for the servos in the interferometer, should be passed by mode cleaner resonances, adjacent to the one the carrier frequency is locked to.

7. Mode cleaner mirror curvatures should be such as to minimize geometric beam fluctuations induced by mirror wobbling, excited by seismic noise.

8. No significant thermal effects are allowed to occur at the mode cleaner mirrors.

9. 3 W of green light reach the mode cleaner input mirror. 95% of that is mode matched.

10. Mirror loss will be less than 50 ppm/mirror.

4.2 Description

For the purpose of this write-up, the mode cleaner should be visualized as a cavity consisting of two mirrors, suspended from wires, much like in the main cavities used in the 40 m system[2]. The top ends of the wires will be attached to structures supported by seismic isolation stacks. The design of the suspensions and of the stacks are addressed by a separate conceptual design team.

The mode cleaner and all subsequent optics will be housed in vacuum.

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[2] the issue of whether the mode cleaner should be a linear cavity or a ring cavity is not yet settled, and, as mentioned before, is being separately addressed

4.3 Control systems

Frequency control is carried out by to distinct, but interacting control systems:

- One system keeps the mode cleaner in resonance with the light comming from the prestabilized laser. This sytem uses RF1 as modulation frequency (Fig. 2), and is a medium fast, reasonably high gain servo. The correction signals are applied to the VCO inputs of the prestabilized laser.
- Another sytem shown in Fig. 2 uses RF2 as modulation frequency. This system is shown only as a place holder, illustrating the need to make the mode cleaner resonance track some frequency defined by the interferometer, or vice-versa. The actual philosophy and topology for this control system are being addressed by another conceptual design team.

Power stabilization: an additional path for power stabilization is carried in Fig. 2 as a place holder, for the case additional power stabilization will be found necessary.

Pointing control of mode cleaner mirrors will be done with optical levers and voice coil transducers at the suspension points[3], unless new work comes up with a better or more convenient way.

Axial position control and damping of mode cleaner mirrors will be done with OSEM's.

4.4 Parameters

Essential parameters of the mode cleaner and mode cleaner locking servo are given in Table 1. Some of the possible trade-offs are listed below, in Section 4.6.

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[3] method currently used in the 40 m system

Table 1: Essential mode cleaner parameters

	Parameter	Value	Dominant requirement
1	Bandwidth	10 kHz	Passive filtering, 4.1.5
2	Storage time	16 μs	Line 1
3	Mirror transmission	2,000 ppm	Power handling, 4.1.8
4	Length	10 m	Lines 2,3
5	Mirror curvature	15 m	Minimize induced wiggle, 4.1.7
6	Beam radius w_0	1.1 mm	Lines 4,5
7	Mirror size, shape	TBD	Suspension, servo
8	Mirror material	Fused silica	
9	Gain at 5 kHz	>100	4.1.4, 2.1.1
10	Servo bandwidth	100 kHz	Line 9
11	Modulation at RF1	1%	4.1.4

4.5 Performance

The performance of the mode cleaner outlined above, can be characterized as follows:

1. The geometric fluctuations of the input beam will be suppressed to a point where shot noise limited performance of the 4 km arms is possible, at a level consistent with the target performance[4]
2. The shot noise limit of the mode cleaner itself is at a level from where the target performance of the interferometer can be achieved, given the gain available in the 4 km arms servos.
3. The sensitivity of the mode cleaner to geometric fluctuations of the input beam is low enough, so that its own shot noise limit can be reached.
4. 3 W at the mode cleaner input will cause no visible mirror heating effects.

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[4] The amplitude of many higher order modes is suppressed by a factor of more than 200. This would allow the target performance to be reached even without the benefit of the mode cleaning provided by the recycling cavity.

5. The power of the beam delivered at the mode cleaner output will be at least 2.5 W.

4.6 Trade-offs, Comments

The requirements listed in Section 4.1 can be met in more than one way. Here are some possible trade-offs:

1. By increasing the modulation index for RF1, at the expense of reducing the power at the mode cleaner output, the shot noise limit for frequency stabilization by the mode cleaner can be improved by a factor of about then, to $\sim 10^{-5}$ Hz/Hz$^{1/2}$.
2. The actual length of the mode cleaner will be determined from the requirement that RF2 (TBD) be passed by an adjacent resonance. Increasing the length, for example, makes the following trade-offs possible:
   - Increasing mirror transmission by the same factor keeps the shot noise limit, the bandwidth unchanged, increases the power handling capability, but reduces the spatial filtering and increases the sensitivity of the mode cleaner to input beam wiggle.
   - Keeping transmission constant reduces bandwidth, improves the shot noise limit within the bandwidth, and decreases the sensitivity of the mode cleaner to input beam wiggle. The spatial filtering capability is unchanged, if the ratio between length and mirror curvature is kept constant.
   - Increasing the length leads to a wider beam.
3. Mirror size and shape determines the location of mechanical resonances, which in turn affects the servos that rely on pushing the mirrors directly, e. g. with coil/magnet arrangements.

5 Optics 2

5.1 Requirements/assumptions

1. 2.5 W of green light will be available at the mode cleaner output.

2. At least 95% of power in the beam will be mode matched to the interferometer.

3. A degree of optical isolation TBD will be provided between the mode cleaner and the interferometer.

4. Clear aperture of component will be 5 mm, except for the mode matching lenses.

5. The optics should not significantly increase the geometric beam fluctuations present at the mode cleaner output.

6. Upper limit for optical wave front distortion TBD, for each component.

5.2 Description

The lay-out for the optics between the mode cleaner and the interferometer is shown in Fig. 2. Again, beam steering mirrors will be needed, but are not shown. The lens at the mode cleaner output is meant to focus the beam through 5 mm clear aperture Faraday isolator(s).

This part of the optics will be in vacuum. Therefore, all components will have to be provided with remote control, for degrees of freedom TBD. It is TBD whether servo control of any optics is necessary.

Earlier analysis concluded that seating the components on a two layer stack provides sufficient seismic isolation, and that it is not necessary to suspend optics from wires. However, it is yet TBD whether wire suspensions are not providing an easier, or better way for remotely controlling the optics.

5.3 Control systems

TBD

5.4 Parameters

1. Optical components, except the mode matching lenses, will have clear aperture of 5 mm.

2. All components that are not at Brewster angle will be provided with narrowband AR coatings (V-coatings).

6 Suggested Experiments

Some of the assumptions used above are not well established. Also, pieces of analytical work used here do not have a solid experimental basis. Thus, it is felt that the following experimental/analytical work is absolutely necessary, in order to provide a sound foundation for input optics conceptual design:

1. Measurements on geometrical beam fluctuations, including:
   - Check of formula that describes spatial filtering by a cavity
   - Check of formula that describes the relationship between wiggle and frequency noise
   - Check whether one needs to spatially filter all the light, or only the RF sidebands
2. Experimental assessment of the need for temporal filtering of the beam. This is particularly important, since it is our current perception of this need, that dominates the storage time requirement for the mode cleaner.
3. Determination of upper limit for wave front distortion at optical components in Optics 2, by using Glad V
4. Assessment of seismic isolation needs for all components

7 TBD List

1. Frequency range for prestabilized laser frequency noise requirement
2. Upper limit and bandwidth for power fluctuations, at prestabilized laser output
3. Optical isolation requirement, before and after the mode cleaner
4. Steering mirror design, control
5. Mode cleaner mirror size, shape
6. RF2

7. Mode cleaner length, so that RF2 is transmitted
8. Upper limit for optical wave front distortion, at each optical component, between mode cleaner and interferometer
9. Remote, servo control needs for Optics 2
10. Type of support for components in Optics 2 (wire suspensions?)

Prestabilized Laser

AA, 6 March 1991

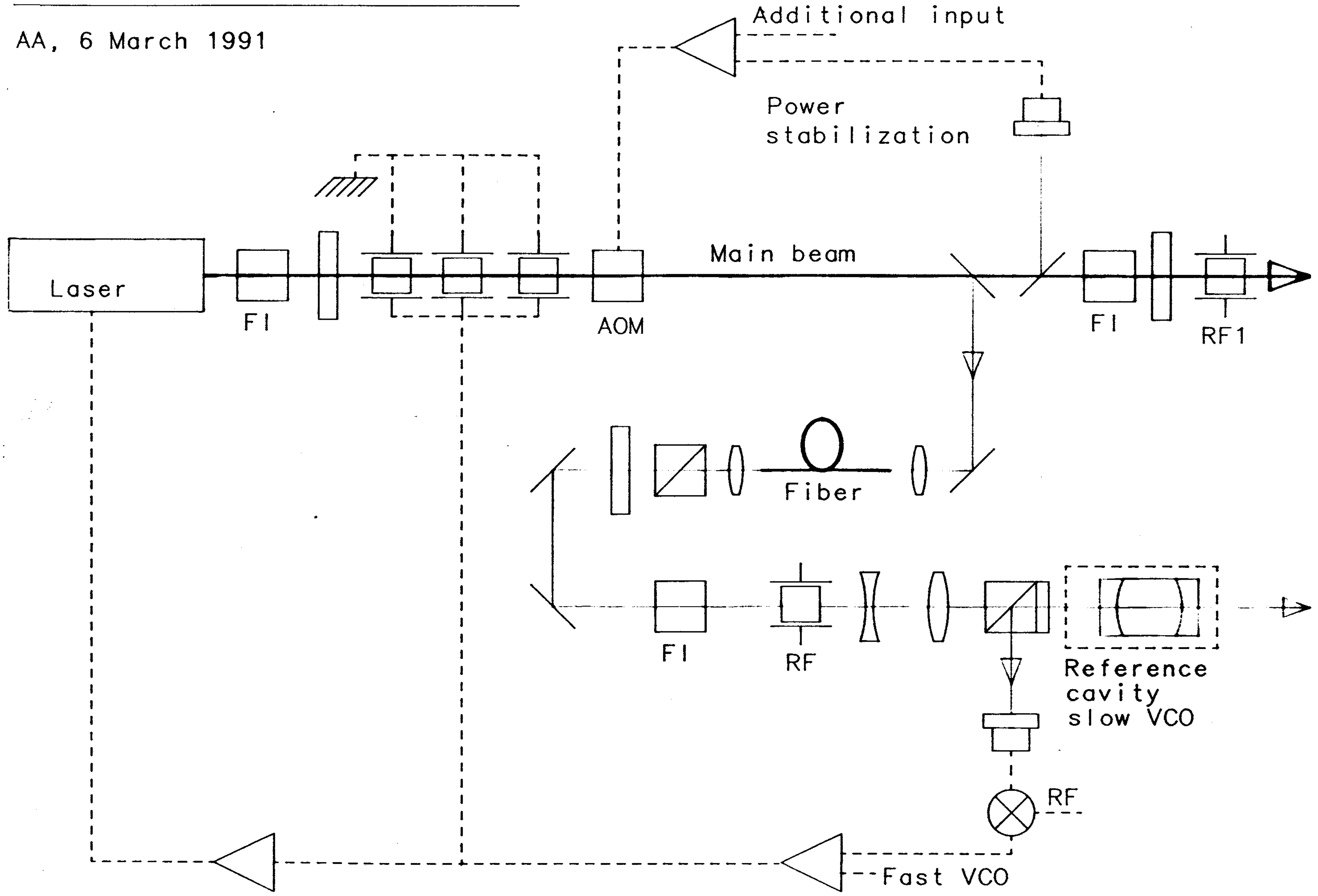

Fig. 1

Input Optics Lay-Out

AA 3-March-91

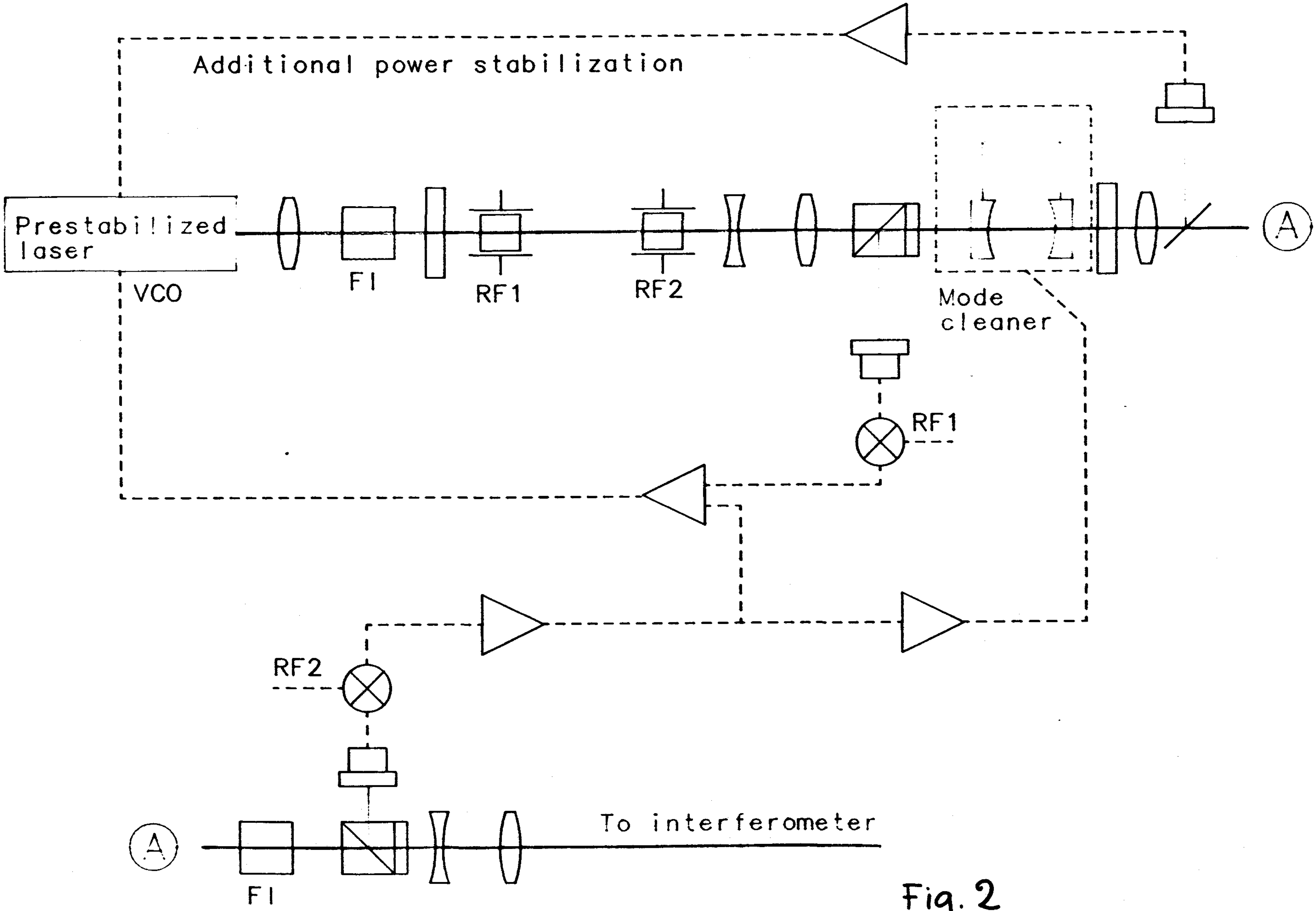

Fig. 2

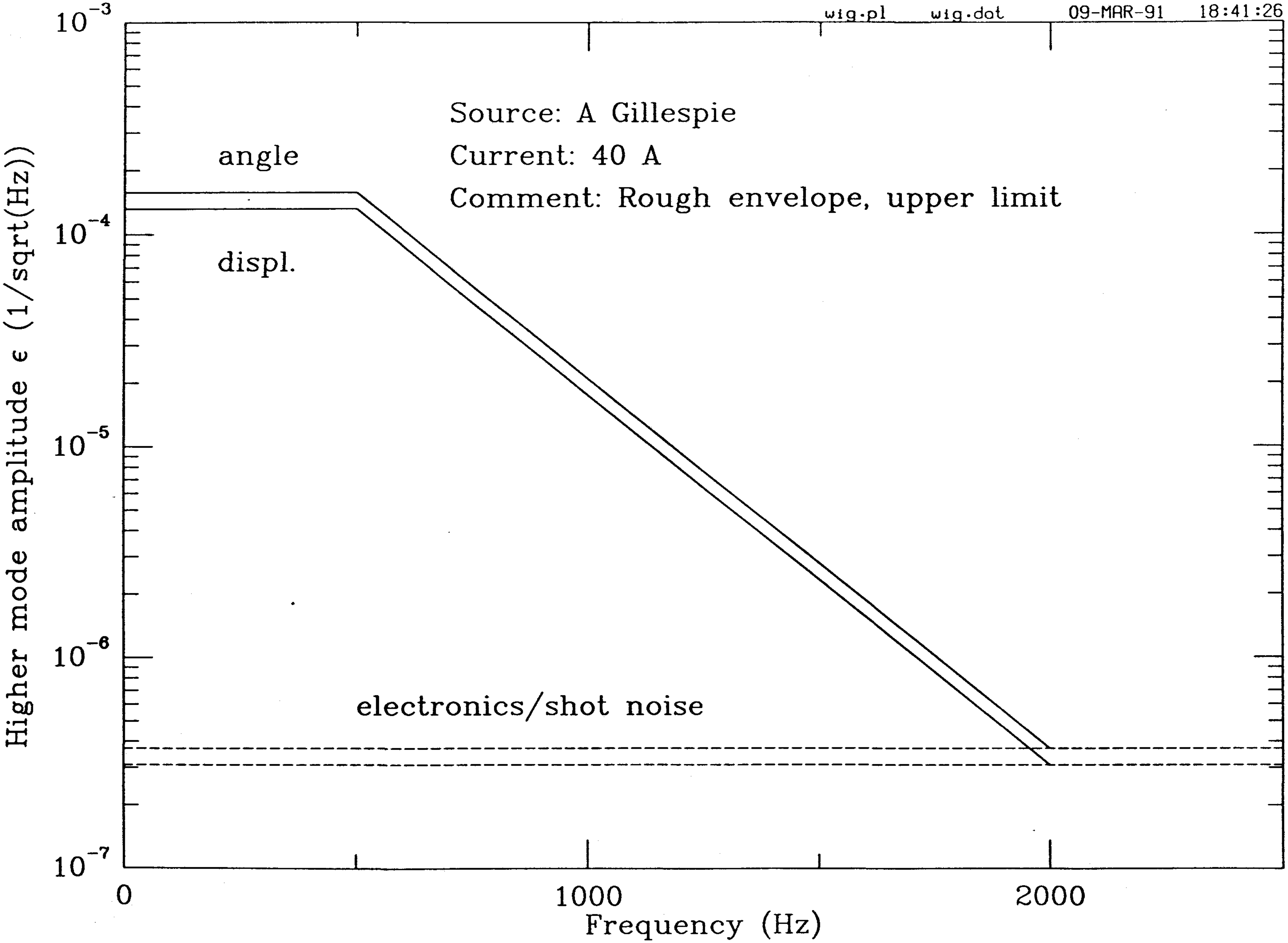
wig.pl
wig.dot
09-MAR-91
18:41:26
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Higher mode amplitude ε (1/sqrt(Hz))
Source: A Gillespie
Current: 40 A
Comment: Rough envelope, upper limit
angle
displ.
electronics/shot noise
0
1000
2000
Frequency (Hz)

Fig. 3

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Version 2 - May 1991

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Alex

LIGO Input Optics: Conceptual Design

Alex Abramovici

Part A, version 2, 22 May 1991

Abstract

This is an update of Version 1, of 9 March 1991. The main changes are:

- A ring configuration is considered for the mode cleaner, because it has been decided that such a cavity will be built and tested, for later use in the 40 m system.
- As a result of interaction with the suspension/control team, a concept for supporting, isolating and controlling mode cleaner mirrors has evolved, and is described in this document.
- The process of defining the mode cleaner parameters is now described, in some detail, in Appendices.
- A number of smaller changes have been made, following feedback from the ICD team

LIGO-T910030-00-D

Contents

1 Introduction

This document is a brief conceptual outline of the optics ahead of the LIGO interferometer proper. The optics is broken down as follows:

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- Optics 1, between the prestabilized laser and the mode cleaner
- Optics 2, between the mode cleaner and the interferometer

For each of the above items, whenever applicable, the following aspects are covered:

1. Requirements/assumptions
2. Description
3. Control systems
4. Parameters
5. Performance
6. Trade-offs

Optical isolation requirements are not addressed here. They are being covered under **Part B**, by Fred J. Raab.

As more conceptual design work on other interferometer subsystems becomes available, it is likely that the lay-out and some of the parameters defined here will have to be readjusted. One notable case is that of the servo that locks the frequency of the light to the interferometer, or vice-versa. The topology of the interferometer control system is still in the process of being defined. The approach taken here is that the servo systems relating to the input optics are self contained, and that some information about the state of the interferometer is being fed into generalized VCO inputs of these systems. For the time being, this serves the purpose of defining the relevant parameters.

Some of the assumptions and requirements are on anything but firm grounds. Topics, the investigation of which seems most urgent, are listed.

2 Prestabilized Laser

2.1 Requirements/assumptions

1. The light delivered to the input optical chain will have its frequency stabilized down to 10^{-2} Hz/Hz$^{1/2}$, above 1 kHz, and down to a limit that is slowly increasing towards lower frequencies[1] (Fig. 1).

ambig?
comp. to
40m /
achieved
Spectra
performance?

2. The optical power at the output of the prestabilized laser subsystem will be at least 3.5 W.

---

[1] frequency stability goal for the prestabilized Spectra Physics laser

3. Relative optical power fluctuations will be kept down to $3 \cdot 10^{-7}\,\mathrm{Hz}/\mathrm{Hz}^{1/2}$, above 1 kHz, and down to a limit that is slowly increasing towards lower frequencies[2] (Fig. 2), by use of a power stabilization servo.
4. The frequency prestabilization servo will have VCO inputs for both fast signals (up to hundreds of kilohertz) and slow signals (kilohertz), for further frequency stabilization using signals from the mode cleaner and/or the interferometer. The VCO inputs could also be used to phase lock different lasers.
5. Laser mode hopping will be minimized.
6. Component apertures of 5 mm should be sufficient.

2.2 Description

The optical and control lay-out of the prestabilized laser subsystem is shown in Fig. 3. It is the same as the one considered for the Spectra Physics laser prestabilization, and it strongly resembles the arrangement currently used in the 40 m lab, with the following notable differences:

- A fiber[3] is provided for spatially filtering the beam, so that beam jitter will not be converted into frequency noise.
- The rigid reference cavity will not be used as a mode cleaner. Approximately 0.5 W of green light will be diverted to the reference cavity path. While diverting 0.5 W would not significantly reduce the power delivered to the mode cleaner, it will help making up for losses in the fiber and the Faraday isolator and the polarizer behind it.

The laser will be rebuilt with increased emphasis on thermal stability.
Al optical components will be in air, bolted to an optical table.

2.3 Control systems

Frequency prestabilization is done with a wide band servo system that uses slow and a fast piezo mirrors in the laser and phase correcting Pockels cells as correction transducers.
Power stabilization is carried out by using an acousto-optic modulator (AOM). An input is provided for signals derived further downstream in the optical chain.

2.4 Parameters

1. Optical components will have clear aperture of 5 mm.
2. All components that are not at Brewster angle will carry narrowband AR coatings (V-coatings).

---

[2] power stability goal for the prestabilized Spectra Physics laser

[3] the fiber can be inserted in the reference cavity path, because the optical power there is less than 0.5 W, and the optical efficiency in that path is not critical

2.5 Performance

With the laser delivering 5 W of raw power, and taking into account the power diverted to the reference cavity, and also the power reduction that makes the use of the AOM possible, the prestabilized laser should perform as follows:

1. 3.5 W of green light should be available at the output of the prestabilized laser subsystem.
2. The frequency noise, at that point, should be less than 10^{-2} Hz/Hz$^{1/2}$, above 1 kHz (Point 2.1.1).
3. Relative power fluctuations are reduced to $3 \cdot 10^{-7}$ Hz$^{-1/2}$, above 1 kHz (Point 2.1.3).
4. Mode hopping will be minimized.

3 Optics 1

3.1 Requirements/assumptions

1. 3 W of green light will be available at the mode cleaner input.
2. At least 95% of the power in the beam will be mode matched to the mode cleaner.
3. A degree of optical isolation TBD will be provided between the output of the prestabilized laser subsystem and the input of the mode cleaner.
4. Component apertures of 5 mm should be sufficient.

3.2 Description

The optics in this part of the system (Fig. 4) is meant to:

- mode match the beam to the mode cleaner
- provide the necessary optical isolation between the prestabilized laser and the interferometer, by using Faraday isolator(s)
- impress RF phase modulation on the beam, by using a Pockels cell

Some beam steering capability is needed, in order to correctly point the beam towards the mode cleaner. Steering mirrors are not shown in Fig. 4, for simplicity. The steering mirrors, design TBD, have to be provided with remote control, and possibly with servo control.

3.3 Parameters

1. Optical components will have clear aperture of 5 mm.
2. All components that are not at Brewster angle will be provided with narrowband AR coatings (V-coatings).

4 Mode Cleaner

4.1 Requirements/assumptions

1. LIGO interferometer target performance and parameters are as in Fig. III-2. p. 18 of the December 1989 Proposal, Vol. 1.
2. Geometric fluctuations of the laser beam impinging on the mode cleaner are as in Fig. 5.
3. Geometric laser beam fluctuations have to be reduced to a level, compatible with LIGO target performance.
4. At the mode cleaner output, the frequency noise has to be reduced to a point where the gain available in the 4 km system servo(s) is sufficient to further reduce frequency noise to a level, compatible with LIGO target performance. This sets requirements on:
    - Mode cleaner shot noise limit.
    - Available gain/bandwidth in the servo that locks the frequency of the light to a mode cleaner resonance.
5. For best passive filtering, the bandwidth of the MC should be made as narrow as allowed by the maximum admissible circulating power, determined by the threshold for the onset of mirror heating effects.
6. The RF modulation sidebands, required for the servos in the interferometer, should be passed by mode cleaner resonances, adjacent to the one, the carrier frequency is locked to.
7. Mode cleaner mirror curvatures should be such as to minimize beam jitter induced by mirror wobbling, excited by seismic noise.
8. Thermal effects should not exceed a level, where 95% mode matching can still be maintained by refocusing the beam with spherical lenses.
9. Mirror loss will be less than 100 ppm/mirror.

4.2 Description

The mode cleaner consists of three mirrors, two flat and one curved, forming a ring cavity (Fig. 4). Each mirror is suspended from a single loop of wire, attached to a platform, which is supported by four posts (Fig. 6). The support structure will be located atop a seismic isolation stack.

The mode cleaner and all subsequent optics will be housed in vacuum.

4.3 Control systems

Frequency control is carried out by two distinct, but interacting control systems:

Table 1: Essential mode cleaner parameters

$$\tau_e = \frac{\frac{l}{c}}{\underbrace{1-r_1r_2}_{2000ppm}} = 20\mu s$$

	Parameter	Value
1	Bandwidth	8 kHz
2	Storage time	20 μs
3	Mirror transmission	2,000 ppm
4	Length	12.165 m
5	Mirror curvature	20 m
6	Beam radius w_0	1.26 mm
7	Mirror diameter	7.5 cm
8	Mirror thickness	5 cm
9	Mirror material	Fused silica
10	Servo bandwidth	100 kHz
11	Modulation depth	TBD

optical?

4kHz!

why not 1MHz?

- One system keeps the mode cleaner in resonance with the light com~~m~~ing from the prestabilized laser. This servo (Fig. 4), is medium fast, and has reasonably high gain. The correction signals are applied to the VCO inputs of the prestabilized laser.
- Another sytem, shown in Fig. 4, locks the frequency of the light to the interferometer. This system is shown only as a place holder, merely illustrating the need to make the mode cleaner resonance track some frequency defined by the interferometer, or vice-versa. The actual philosophy and topology for this control system are still being developed, by another conceptual design team.

Power stabilization: an additional path for power stabilization is carried in Fig. 4 as a place holder, for the case additional power stabilization will be found necessary.

Pointing control of mode cleaner mirrors will be done with optical levers and OSEM coils (Fig. 7).

Axial position control and damping of mode cleaner mirrors will be done with OSEM's (Fig. 7).

Lateral damping will be done with an OSEM assembly (Fig. 7).

4.4 Parameters

Essential parameters of the mode cleaner and mode cleaner locking servo are given in Table 1. For details, se Sections 9.1, 9.2. Some of the possible trade-offs are listed below, in Section 4.6.

4.5 Performance

The performance of the mode cleaner outlined above, can be characterized as follows (for details, see Section 9.3):

1. The first higher transverse mode will be suppressed by a factor ~ 900. Most higher transverse modes will be suppressed by factors in excess of 200. This, combined with the additional beam jitter suppression by the recycling cavity, would allow the target sensitivity to be reached. rel'n to ifo sens'ty? calc?
2. The frequency noise, related to a beam jitter as in Fig. 5, interacting with the mode cleaner, is:

   ? Fig. 5 does not mention $S_y^{1/2}$.

   - $\nu(f) \sim 2 \cdot 10^{-4}$ Hz/Hz$^{1/2}$, below 500 Hz
   - $\nu(f) < 5 \cdot 10^{-7}$ Hz/Hz$^{1/2}$, above 2 kHz

   This level of frequency noise is low enough not to affect interferometer sensitivity (see Table 3).
3. The shot noise limit of the mode cleaner itself is at a level TBD.
4. 3 W at the mode cleaner input will cause no visible mirror heating effects.
5. The power of the beam delivered at the mode cleaner output will be 2.5-3 W, including the modulation sideband.

4.6 Trade-offs, Comments

The requirements listed in Section 4.1 can be met in more than one way. Here are some possible trade-offs:

1. The actual length of the mode cleaner will be determined from the requirement that the modulation sidebands be passed by an adjacent resonance. Increasing the length, for example, makes the following trade-offs possible:
   - Increasing mirror transmission by the same factor keeps the shot noise limit, the bandwidth unchanged, increases the power handling capability, but reduces the spatial filtering and increases the sensitivity of the mode cleaner to input beam wiggle.
   - Keeping transmission constant reduces bandwidth, improves the shot noise limit within the bandwidth, and decreases the sensitivity of the mode cleaner to input beam wiggle. The spatial filtering capability is unchanged, if the ratio between length and mirror curvature is kept constant.
   - Increasing the length leads to a wider beam.
2. Mirror size and shape determines the location of mechanical resonances, which in turn affects the servos that rely on pushing the mirrors directly, e. g. with coil/magnet arrangements.

5 Optics 2

5.1 Requirements/assumptions

1. 2.5 W of green light will be available at the mode cleaner output.
2. At least 95% of power in the beam will be mode matched to the interferometer.
3. The optics should not significantly increase the geometric beam fluctuations present at the mode cleaner output.
4. Upper limit for optical wave front distortion TBD, for each component.

5.2 Description

The lay-out for the optics between the mode cleaner and the interferometer is shown in Fig. 4. Again, beam steering mirrors will be needed, but are not shown. The optics consist of a number of pick-off mirrors, the mode matching lenses, and, possibly, a circulator for reflection locking the recycling cavity (not shown). The pointing reference beam will be used to monitor the pointing of the green beam. The error signal thus generated, with respect to a reference point tied to the ground, can be used to keep the beam pointing from drifting.

no circ'n pol'n in ifo!

This part of the optics will be in vacuum. Therefore, all components will have to be provided with remote control, for degrees of freedom TBD. It is TBD whether servo control of any optics is necessary.

Earlier analysis concluded that seating the components on a two layer stack provides sufficient seismic isolation, and that it is not necessary to suspend optics from wires[4]. However, it is yet TBD whether wire suspensions are not providing an easier, or better way for remotely controlling the optics.

5.3 Control systems

TBD

5.4 Parameters

All lenses will be provided with narrowband AR coatings (V-coatings).

6 Suggested Experiments

Some of the assumptions used above are not well established. Also, pieces of analytical work used here do not have a solid experimental basis. Thus, it is felt that the following experimental/analytical work is absolutely necessary, in order to provide a sound foundation for input optics conceptual design:

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[4] A. Abramovici, LIGO Optics Vibration Levels Equivalent to Shot Noise in the Advanced Detectors, 24 February 1989, and A. Abramovici, P. R. Saulson, Report on Vibration Isolation Requirements for LIGO Optical Components, 2 March 1989

1. Measurements on geometrical beam fluctuations, including:
    - Check of formula that describes spatial filtering by a cavity
    - Check of formula that describes the relationship between beam jitter and frequency noise
2. Determination of upper limit for wave front distortion at optical components in Optics 2, by using Glad V
3. Assessment of seismic isolation needs for all components

7 TBD List

1. Priority 1:
    - Optical isolation requirements
    - Mode cleaner shot noise limit
    - detuning of sidebands from resonance
    - Modulation index
2. Priority 2:
    - Upper limit for optical wave front distortion, at each optical component, between mode cleaner and
    - Steering mirror design, control interferometer
    - Remote, servo control needs for Optics 2
    - Type of support for components in Optics 2 (wire suspensions?)

8 Appendix A: Servo Gain and Bandwidth Considerations

8.1 4 km Interferometer

what about freq dep'ce of sensitivity to freq noise (at cav's) (at rec. cav. – filtering action.

1. According to Fig. III-2, p. 18 (1989 Proposal), the highest sensitivity is projected at 44 Hz, rising as f^1 (when thermal noise is disregarded), such that $h(f) = 2 \cdot 10^{-23} \times (f/44Hz)\ \mathrm{Hz}^{-1/2}$, above 44 Hz. $S_x^{1/2}(f) \approx 8000\,m \cdot 10^{-23}/\sqrt{Hz} \approx 8\times10^{-20}\,m/\sqrt{Hz}$
2. The corresponding limit to frequency noise, above 44 Hz, is $\nu(f) = 5.7 \cdot 10^{-9} \times (f/44Hz)\ \mathrm{Hz/Hz}^{1/2}$. $S_\nu^{1/2} = \frac{1}{2}\nu S_h^{1/2}$
3. Assuming a common mode noise rejection factor of 100, due to symmetry between the interferometer arms, the upper limit to residual frequency noise, inside the interferometer, becomes $\nu(f) = 5.7 \cdot 10^{-7} \times (f/44Hz)\ \mathrm{Hz/Hz}^{1/2}$, above 44 Hz. $S_\nu^{1/2} \approx \nu \frac{S_x^{1/2}}{4000\,m}$
4. Assuming a unity gain frequency of 30 kHz,[5] a possible gain build-up towards lower frequencies is listed in Table 2.

Table 2: Example of gain/frequency choice for the 4 km arms servos

Range (Hz)	Slope (dB/dec)	Gain at high end of range (dB)
10,000-30,000	20	0
3,000-10,000	40	10
1,000-3,000	60	30
10-1,000	80	60
DC-10	0	220

18°

Table 3: Upper bound for admissible frequency noise at the interferometer input. This is also the requirement on residual frequency noise, at the mode cleaner output

Frequency (Hz)	Gain (dB)	Frequency noise ($\mathrm{Hz/Hz}^{1/2}$)
50	164	10^2
100	140	13
1,000	60	$1.3 \cdot 10^{-2}$
3,000	30	$1.2 \cdot 10^{-3}$
10,000	10	$4 \cdot 10^{-4}$

---

[5] The view taken here is that it is not practical to exceed the free spectral range of a cavity, which, for the 4 km arms, is 37.5 kHz. For details, see M. Regehr, Laser-Locking Bandwidth Limitations Imposed by the Response of a Fabry-Perot Cavity, March 19, 1991

5. Combining the residual frequency noise requirement of Point 3 above, with the figures in Table 2, yields the upper bound for admissible frequency noise at the interferometer input, as shown in Table 3.

8.2 Mode Cleaner

free-running? No.

From the assumption that residual laser frequency noise, at 10 kHz, is 10^{-2} Hz/Hz$^{1/2}$, and from the last line of Table 3, it results that the mode cleaner servo has to have a gain of 25, at 10 kHz. This can be achieved with a unity gain frequency of 100 kHz, and with a gain build-up as illustrated in Table 2.

9 Appendix B: Mode Cleaner Parameters, Performance

Note: Except for throughput calculation, mirror losses are disregarded, throughout this section, for simplicity.

9.1 Optical Parameters

The mode cleaner is characterized by the round trip optical path and by mirror transmission. These are determined as follows:

1. The requirement that the RF phase modulation sidebands be passed by the mode cleaner is met by chosing the free spectral range approximately equal to the modulation frequency[6]. For a modulation frequency of 12.33 MHz, the round trip optical path is 24.33 m. Since the two flat mirrors are close to each other, this is approximately equal to twice the mode cleaner length.
2. The curved mirror at the apex of the mode cleaner (Fig. 4) is chosen as a high reflector, while the two flat mirrors are assigned equal transmissions. The value for the transmission is derived from two requiremnts:
   - The cavity bandwidth, $\delta\nu = cT/\pi l_{rt}$, where l_{rt} is the round trip path, should be as low as possible, for maximum passive filtering.
   - The one way circulating power, $P_c = P_{inc}/T$, should not exceed 1.5 kW, which is the maximum level achieved in the lab, without causing mirror heating effects.

   For 3 W incident power, the latter condition yields $T = 2000$ ppm which, combined with the round trip path of 24.33 m, gives a cavity bandwidth of ~ 8 kHz.

---

[6] A slight detuning, TBD, of the sidebands, from resonance, is needed, in order to use the same modulation for locking the mode cleaner

9.2 Mirror Size, Shape

1. A mirror diameter of 7.5 cm can accomodate the OSEM assemblies and still provide plenty of clear aperture for the beams.
2. A mirror thickness of 5 cm will bring the frequency of the lowest bending mode up to ~ 23 kHz[7]. This should make it possible to achieve a servo bandwidth of ~ 1.5 kHz, for the servo that relies on pushing a mode cleaner mirror.
3. Two of the mirrors will be flat. The curvature of the mirror at the mode cleaner apex (Fig.4) can be selected as follows:
   - In order to minimize astigmatism, the radius should be as high as possible, without making the cavity unstable, though.
   - The radius that minimizes output beam jitter[8], induced by mirror wobbling, from Fig. 8, is 1.1×the cavity length (d =12.165 m).

   $R = 20$ m looks like a reasonable choice.

9.3 Performance

1. The amplitude of a higher transverse mode, with the sum of mode indeces N, is suppressed, by the mode cleaner, by a factor[9]:

$$\left[1+\frac{4\sqrt{r_1 r_2}}{(1-\sqrt{r_1 r_2})^2}\sin^2\frac{\phi_N}{2}\right]^{\frac{1}{2}} \tag{1}$$

where $r_{1,2}$ are the amplitude reflectivities, and:

$$\phi_N = 2N[\tan^{-1}(z_2/z_0) - \tan^{-1}(z_1/z_0)] \tag{2}$$

and:

$$z_0^2 = \frac{d(-R_1-d)(R_2-d)(R_2-R_1-d)}{(R_2-R_1-2d)^2} \tag{3}$$

$$z_{1,2} = \frac{1}{2}\left(R_{1,2} \pm \sqrt{R_{1,2}^2 - 4z_0^2}\right) \tag{4}$$

$R_{1,2}$ being the mirror radii, and d the cavity length.

With the parameters selected in Sections 8.1,2, the supression factor for the first higher transverse mode is ~ 900.

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[7] G. W. McMahon, Experimental Study of the Vibrations of Solid, Isotropic, Elastic Cylinders, J. Acoustical Soc. America, **36**, 85 (1964)

[8] as described by ϵ, the vector sum of amplitudes of higher modes, corresponding to lateral beam displacement and angular wiggle

[9] see A. Rüdiger et al, Optica Acta **28**, 641 (1981)

2. When the laser frequency is locked to a cavity, the presence of a higher transverse mode with static amplitude ϵ_0, and fluctuating amplitude with spectral density $\epsilon(f)$, generates frequency noise with spectral density[10]:

$$\nu(f) = \frac{\pi c}{2d\mathcal{F}^2} \cdot \frac{\epsilon(f) \mid \epsilon_0 \mid \sin \phi_N}{1 + r_1 r_2 - 2\sqrt{r_1 r_2} \cos \phi_N} \tag{5}$$

   where the *finesse* of the cavity is defined as $\mathcal{F} = \pi/(1 - \sqrt{r_1 r_2})$.

   With the higher mode amplitudes of Fig. 5, the residual frequency noise, due to beam jitter, is, for $N = 1$:

   - $\nu(f) \sim 2 \cdot 10^{-4}$ Hz/Hz$^{1/2}$, below 500 Hz
   - $\nu(f) < 5 \cdot 10^{-7}$ Hz/Hz$^{1/2}$, above 2 kHz

3. A knee frequency of 44 Hz coresponds to a storage time of 1.8 ms and a finesse $\mathcal{F} = 424$

4. Using that finesse, Eqs. (2-5), The frequency noise requirement of Point 8.1.2, and a static higher transverse mode amplitude $\epsilon_0 = 0.3$, yields $\epsilon(f) = 8.3 \cdot 10^{-8} \times (f/44Hz)$ Hz$^{-1/2}$, for the 4 km arms[11].

5. The beam jitter suppression requirement is derived by comparing the above figure with the measured beam jitter (Fig. 5). The toughest requirement is at 44 Hz, where a suppression factor of 2,500 is needed

6. For a recycling factor $n_r > 1$, the beam jitter suppression factor of Eq. (1) above can be written as:

$$n_r \sin \frac{\phi_N}{2} \tag{6}$$

   $\sin(\phi_1/2) = 0.32$ for a recycling cavity 10 m long and a recycling mirror curvature of 100 m. With a recycling factor $n_r = 30$, the additional beam jitter suppression factor is ~ 10.

7. From points 1,6 above, results that the mode cleaner and the recycling cavity, as defined, provide a beam jitter suppression factor in excess of 2,000 for most higher transverse modes.

   It is stressed that the presence of a beam jitter suppression by the recycling cavity depends on the recycling mirror curvature.

8. Shot noise limit: TBD

9. The cavity throughput is, for the mirror parameters as above, $[1+L/T]^{-2} \times$(mode matching ratio) = 88%

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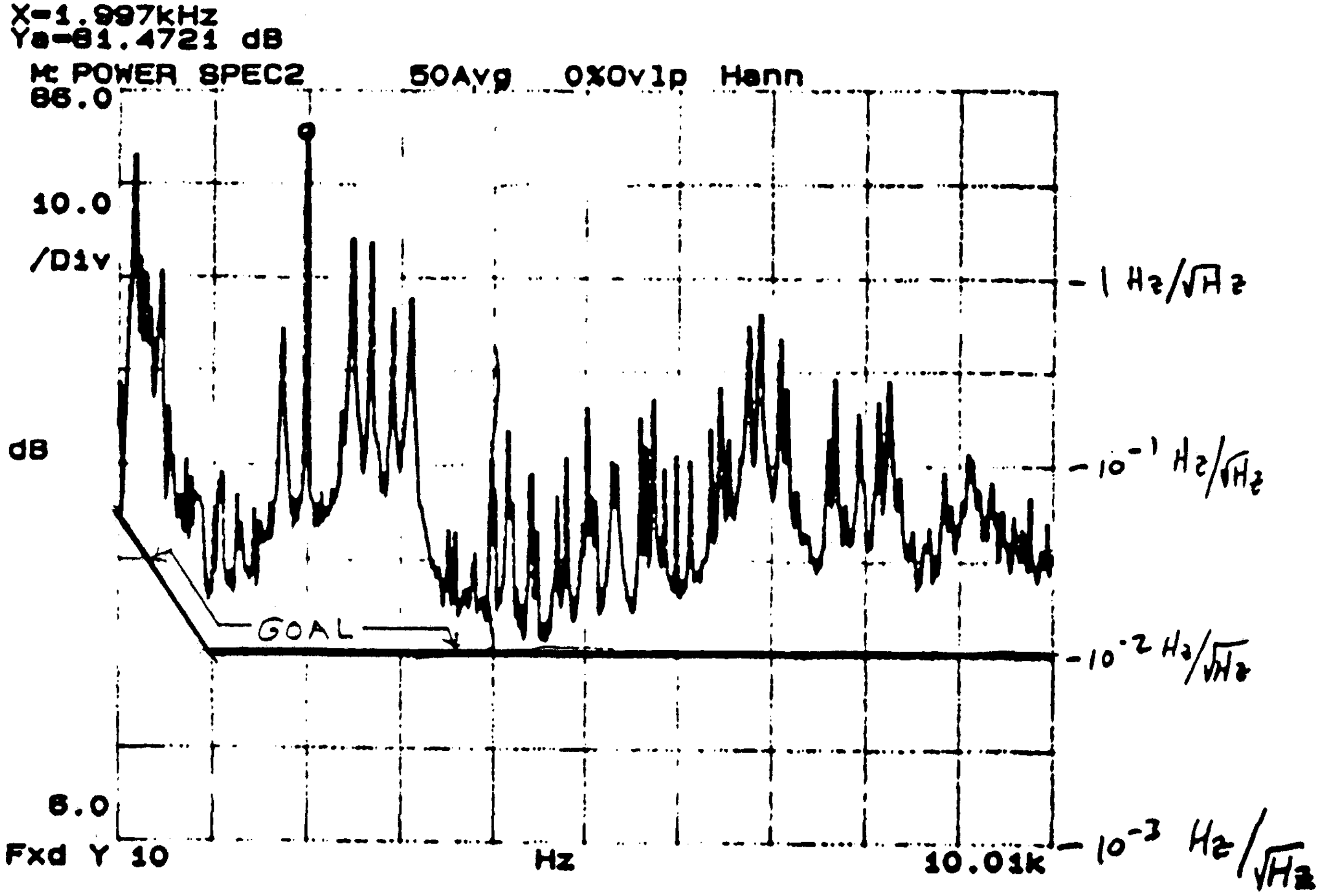
[10] A. Abramovici, Do Wiggle Effects Depend on Mode Cleaner Length?, 6 October 1988

[11] with one mirror flat, and the other one with a radius of curvature of 6 km

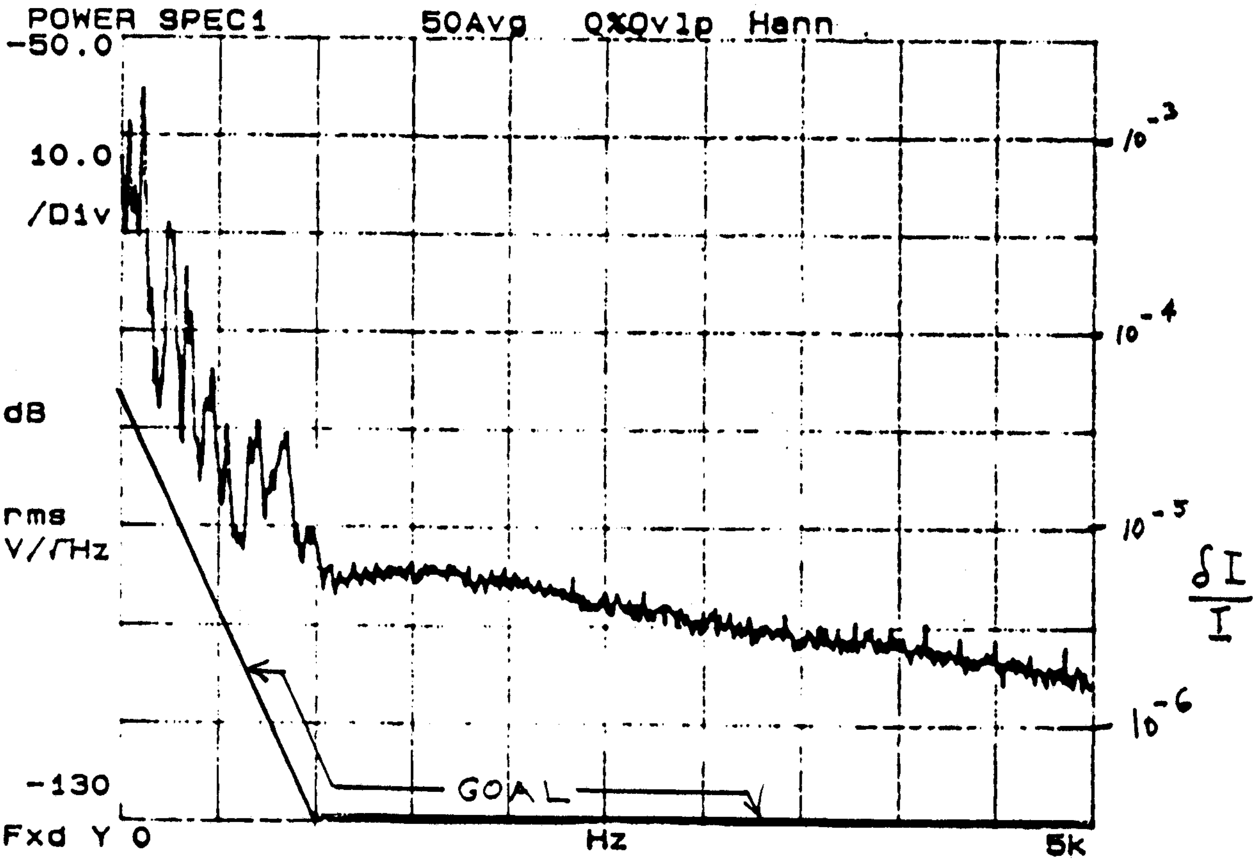
40-METER NOISE SPECTRUM



FREQUENCY NOISE

Fig. 1

40-METER NOISE SPECTRUM



INTENSITY NOISE

Fig. 2

Prestabilized Laser

AA, 6 March 1991

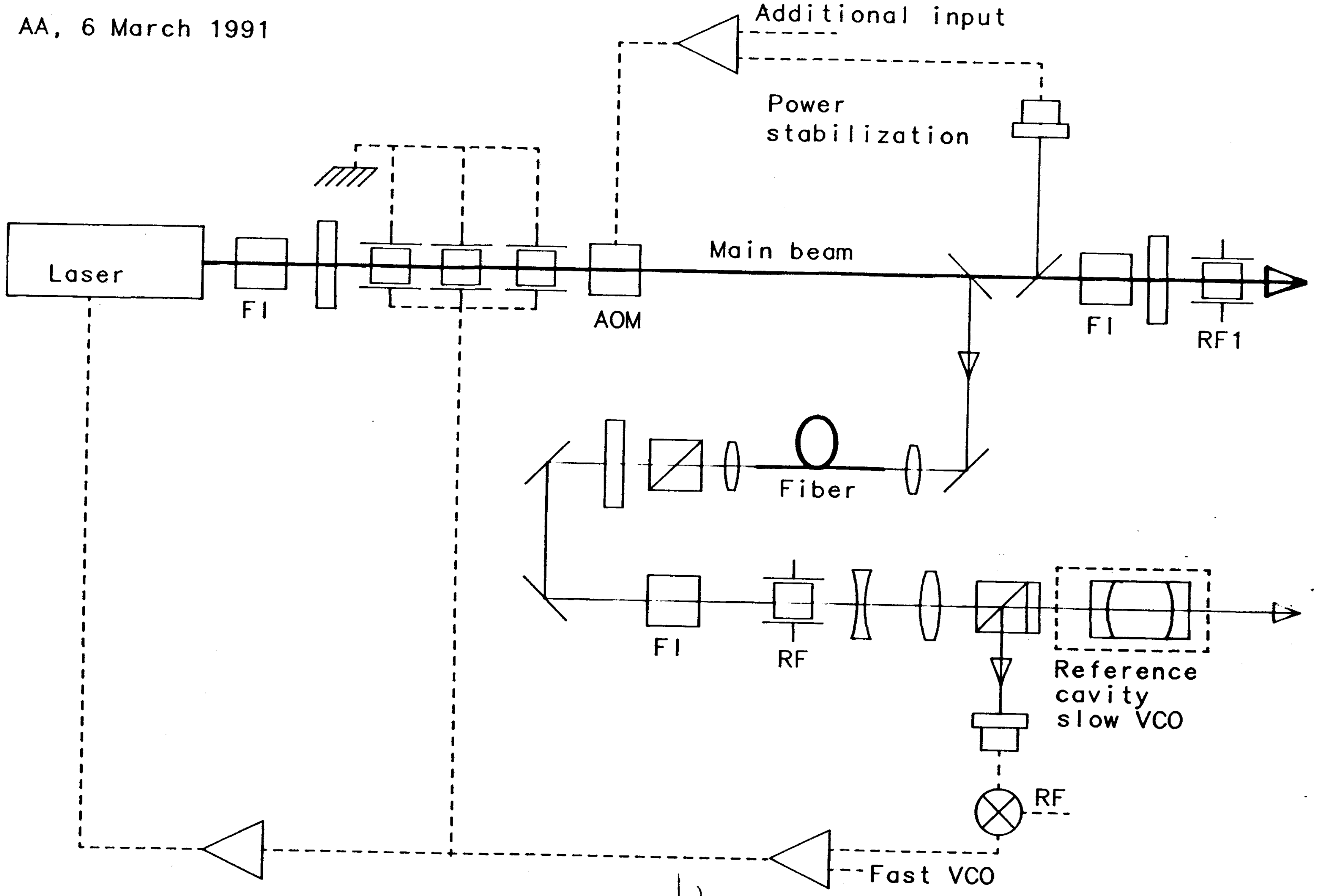


Fig. 3

INPUT OPTICS LAY-OUT

AA, 13 May 1991

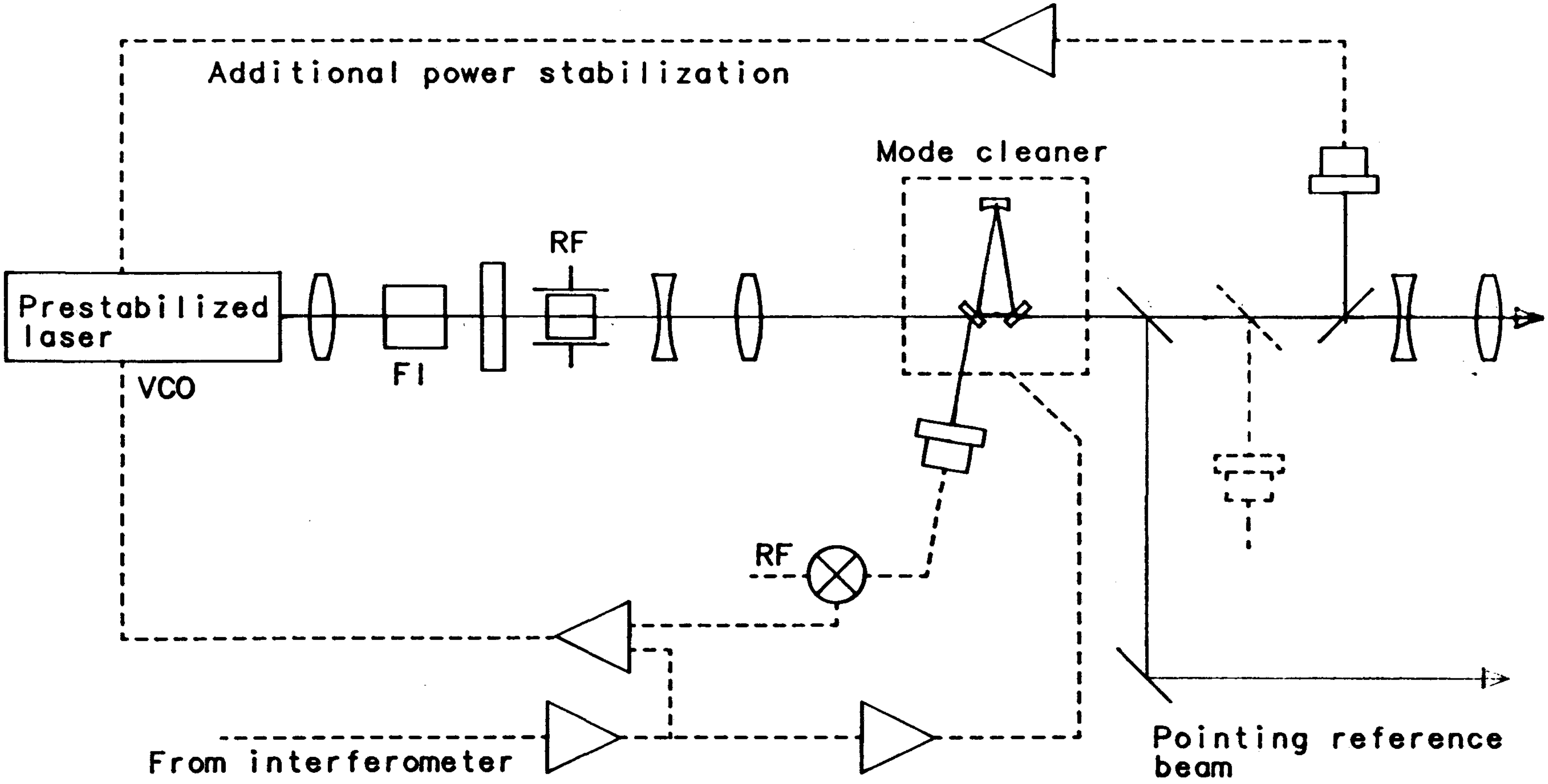


Fig. 4

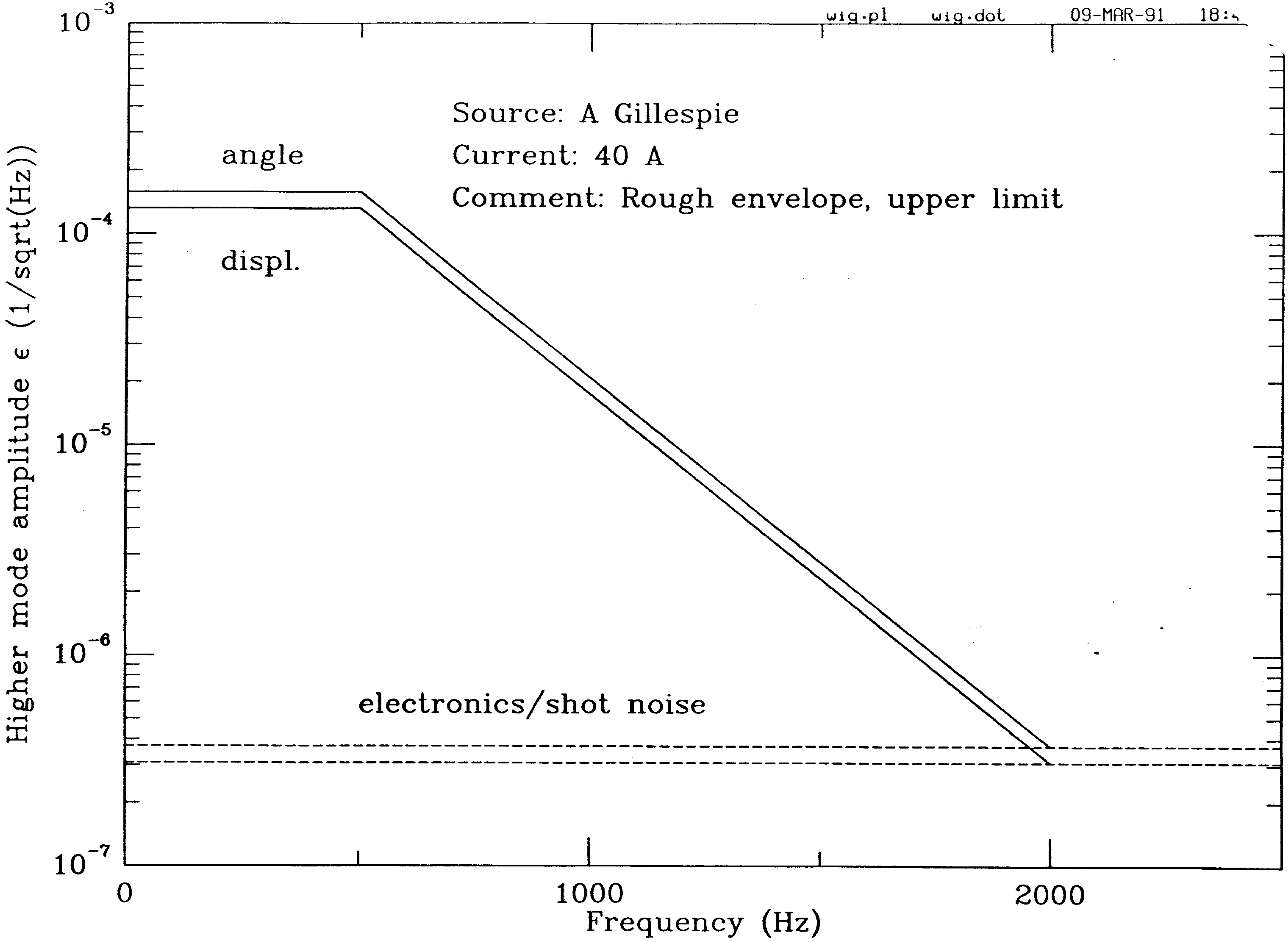

wig.pl
wig.dat
09-MAR-91
18:
Source: A Gillespie
Current: 40 A
Comment: Rough envelope, upper limit
angle
displ.
electronics/shot noise
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Higher mode amplitude ϵ (1/sqrt(Hz))
0
1000
2000
Frequency (Hz)

Fig. 5

SEISMIC ISOLATION

AA, 21 May 1991

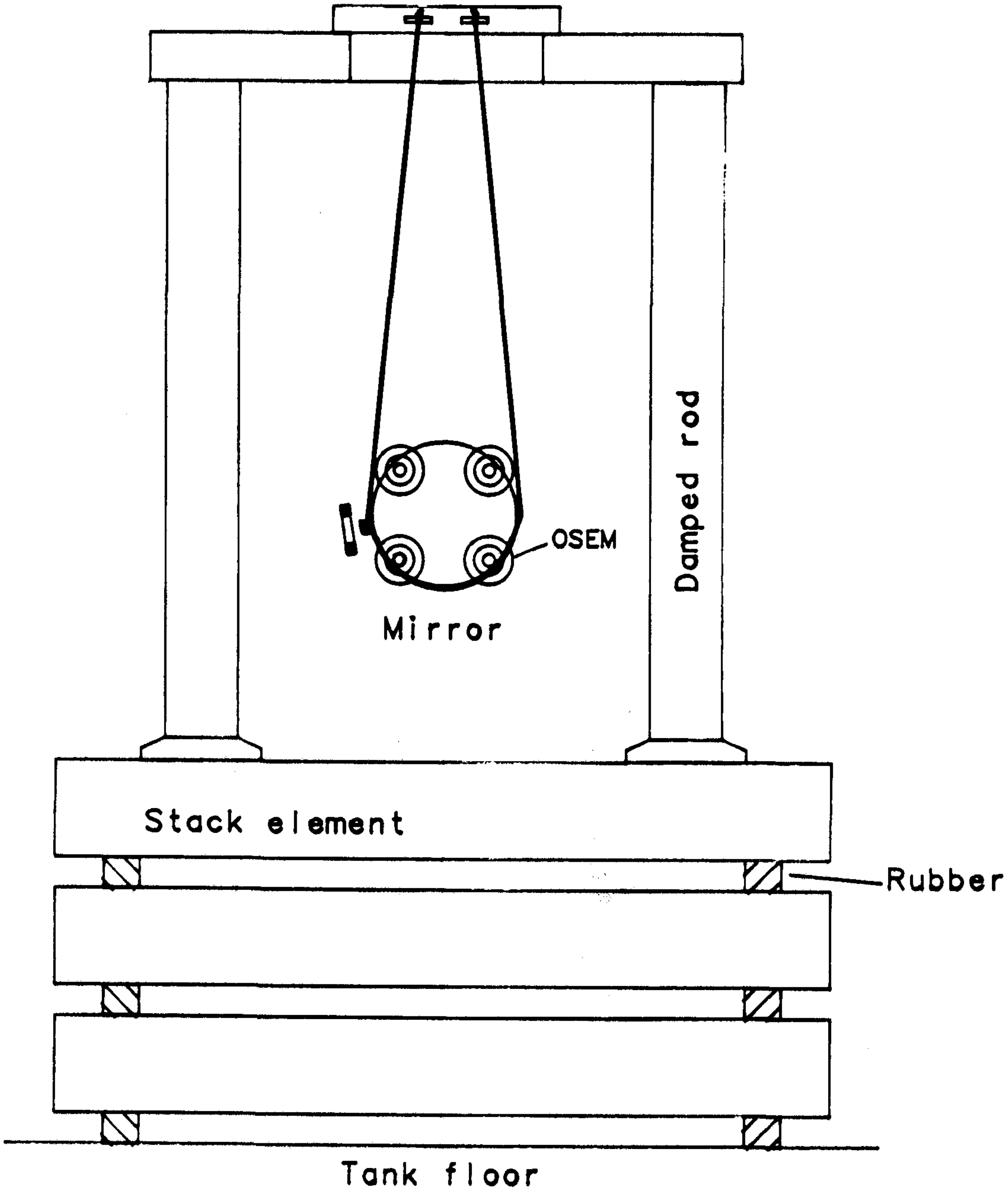
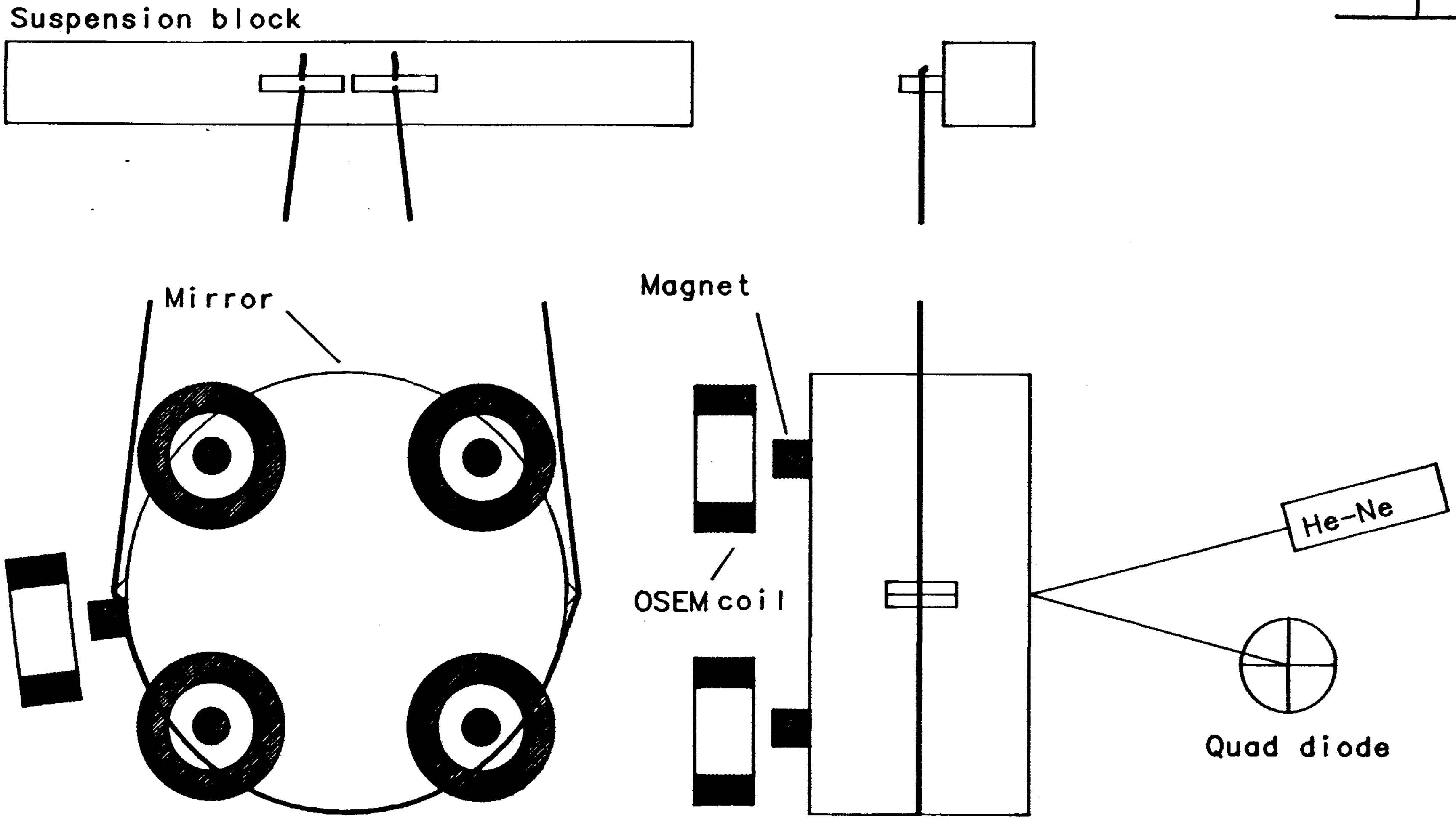


Fig. 6

MIRROR SUSPENSION AND CONTROL

AA, 17 May 1991

Fig. 7



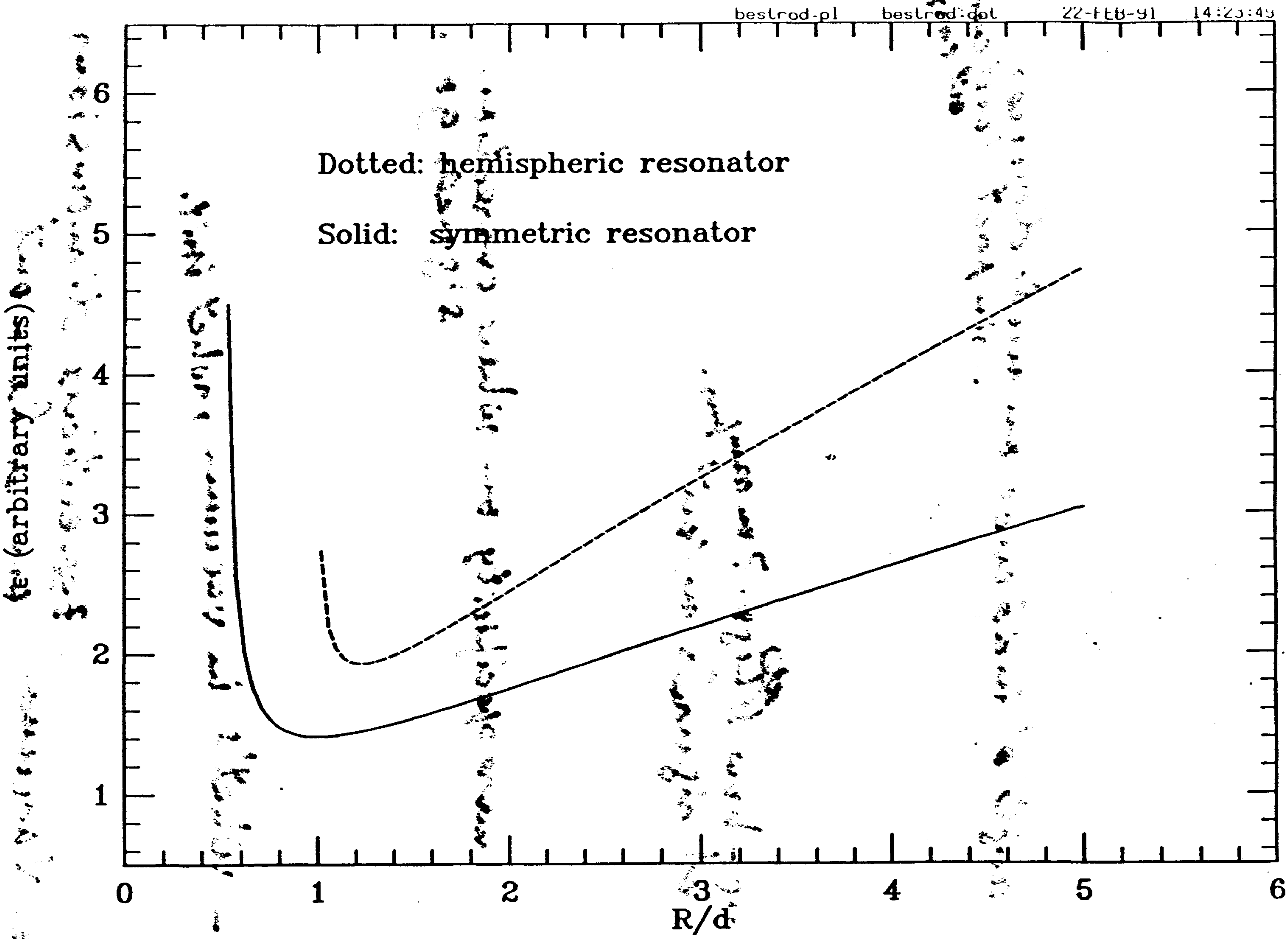

bestrod.pl bestrod.dot 22-FEB-91 14:23:49
Dotted: hemispheric resonator
Solid: symmetric resonator
te (arbitrary units)
1
2
3
4
5
6
0
1
2
3
4
5
6
R/d

Fig. 8

Meeting on In Op 20-Sept-91

- - Future demands on facility
(from higher perf. interfs)

- angle of incidence on mode cleaner
- in fact (and conf
at corn
- 1/4 of free s.r. is safe & conservative.

recyc cavity
m.c. } do they filter
f - noise.

- Testing - how (Ligo? on campus.
- list of signals in/out
- 10 kHz - shot noise limited
performance required.
- more specificity on where correction
signals go.
- Better labelling.

- All comps after mode cleaner:
- what's in vacuum, what isn't. suspended, specify degree of control.
- Photodiodes: in vacuum.

~~Vacuum~~ - Essentials dimension
on a lay-out