New Folder Name Phase Noise

Phase Noise Interferometer Design Review

5 May 1994

Phase Noise Interferometer

Research Objectives:

- Demonstration of LIGO initial phase noise sensitivity of $10^{-10}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$ in the shot-noise limited region of LIGO (above 150 Hz)
- Development of an interferometer in which subsystems and technologies can be tested with high phase sensitivity
- Development and testing of these technologies

Scope of Review:

- This review presents the technical design and research plans currently envisioned for the Phase Noise Interferometer Project for roughly the next two years
- Costing, scheduling, and manpower will be and have been discussed in separate meetings
- Topics:

  Interferometer configuration
  Research plans
  Optics
  Seismic Isolation
  Suspensions
  Alignment and pointing
  Noise sources
  Vacuum system & cleanliness

Interferometer Configuration

1. Simple Michelson:

   - Don't want displacement sensitivity
   - Phase noise determined by power on beamsplitter, avoids complications of cavities in arms
   - Smaller absorption, contrast defect loss than with cavities
   - 50 cm (average) arm length: keeps beamsplitter and MI mirrors on one table

2. Recycled:

   - Initial LIGO calls for approx. 70 W on beamsplitter
   - Expect recycling gain of at least 100
   - Expected losses:

     contrast defect: approx 10^{-3} (2×10^{-4} in FMI)

     mirror surfaces: 4 x 50 ppm = 200 ppm

     beamsplitter AR surface: $\leq$ 500 ppm (?)

   - Recycling mirror transmission: choose T = 1%; will give recycling gain up to 200; no chance of under-coupling

3. Signal readout: same as in LIGO $\rightarrow$ Michelson asymmetry (need to demonstrate that this scheme is capable of achieving phase noise goal)

   - Modulation frequency & recycling cavity length: $f_{mod} = c / 2\, l_{rec}$
   - l_{rec} = 6 m (distance between centers of central and end vacuum tanks); leads to f_{mod} = 25 MHz
   - LIGO f_{mod} = 37.5 MHz; assumption is that there is no meaningful difference between 25 and 37.5 MHz.

     l_{rec} = 4 m would give f_{mod} = 37.5 MHz as in LIGO, but 4 m not possible given vacuum system

     folding recycling cavity to 12 m could allow f_{mod} = 37.5 MHz, but folding not attractive

   - Asymmetry:

     approx. Δl = 10 cm

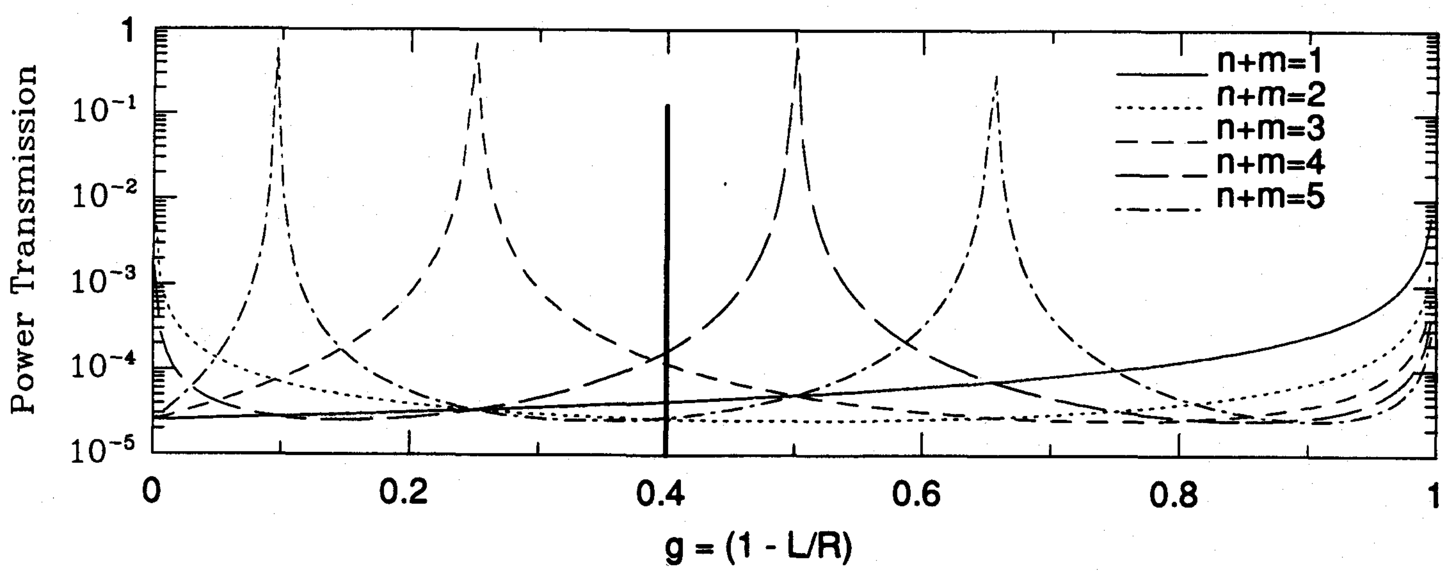
     optimum coupling of sidebands to output given by $\sin^2(4\pi\Delta l/\lambda_{\mathrm{mod}}) \approx T_{\mathrm{rec}}$

asymmetry will be set to allow for recycling cavity (reflection) error signal for common mode (i.e., finesses for carrier and sidebands will be sufficiently different)

- Contrast defect due to asymmetry: $\Delta\omega \rightarrow 1 - C = 2x10^{-5}$; $\Delta R \rightarrow 1 - C = 5x10^{-4}$

4. **Cavity Parameters**

- Flat/curved geometry: 10 m radius of curvature recycling mirror; flat MI mirrors (so cavities can be added with LIGO-like configuration)
- ω_0 = 0.9 mm; θ_D = 0.18 mrad; ω_1 = 1.4 mm
- $\rightarrow$ g = 0.4 ; low degeneracy for lower order modes. Plot shows transmission of higher order modes as a function of g for an aligned cavity made up of two 1% transmission mirrors:



Research Plan

1. Begin with fiber input for beam injection: simpler than suspended mode cleaner

2. Tests with simple Michelson: alignment, contrast, error signal generation

3. Recycled Michelson: establish control electronics (similar to Suspended Mode Cleaner, though finesse an order of magnitude lower → easier acquisition); Tests of:

   frequency and amplitude noise sensitivity
   beam position noise sensitivity
   influence of scattered light, parasitic interferometers

   Phase noise may be limited by power through fiber (at least 0.5 W at fiber output expected)

4. Replace fiber with suspended 3–mirror mode cleaner

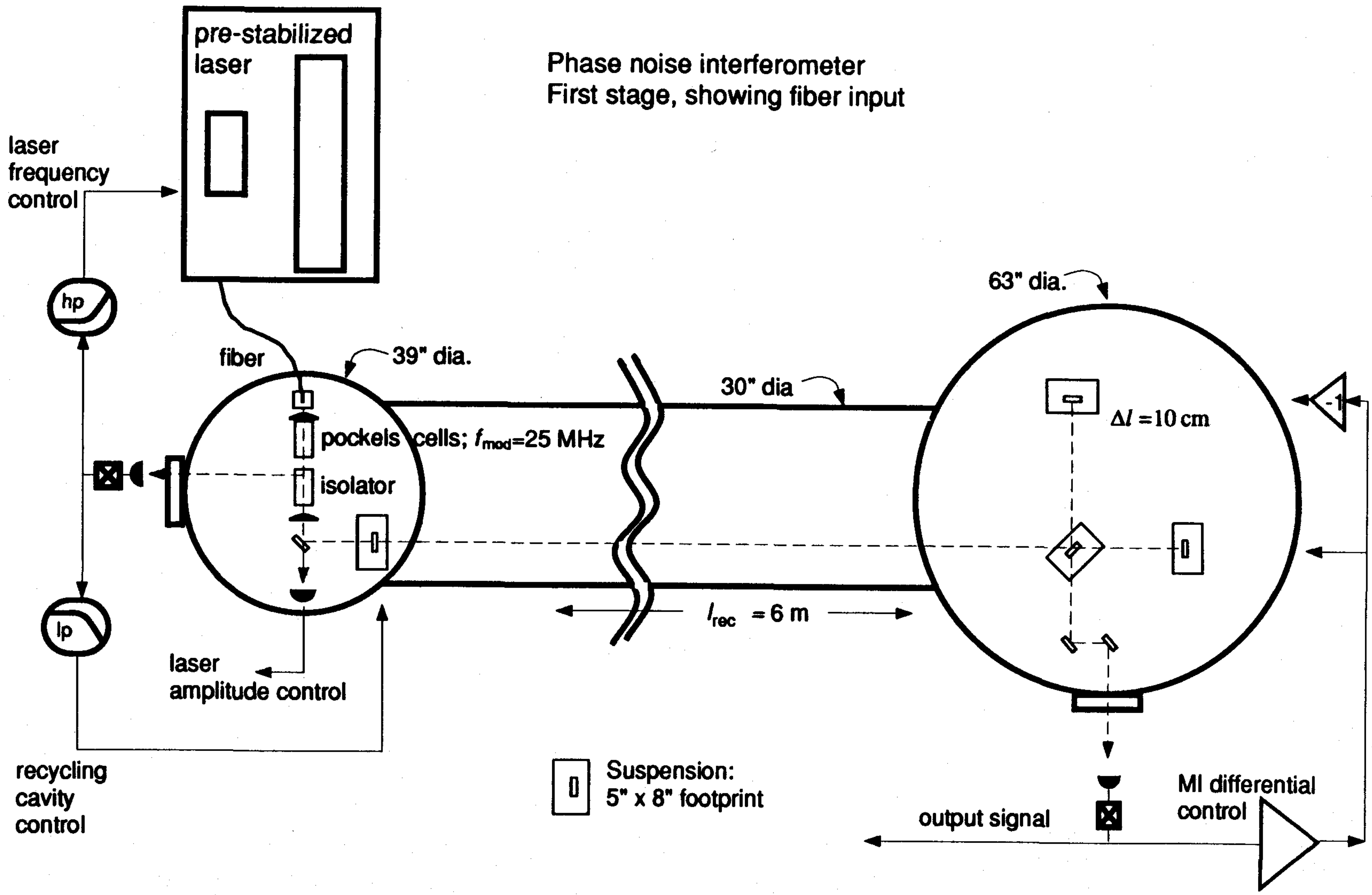
   - no power limitations
   - test beam position stabilization at high phase sensitivity
   - test passing of sidebands at high phase sensitivity

5. Develop subsystems and technologies and use the interferometer to test them:

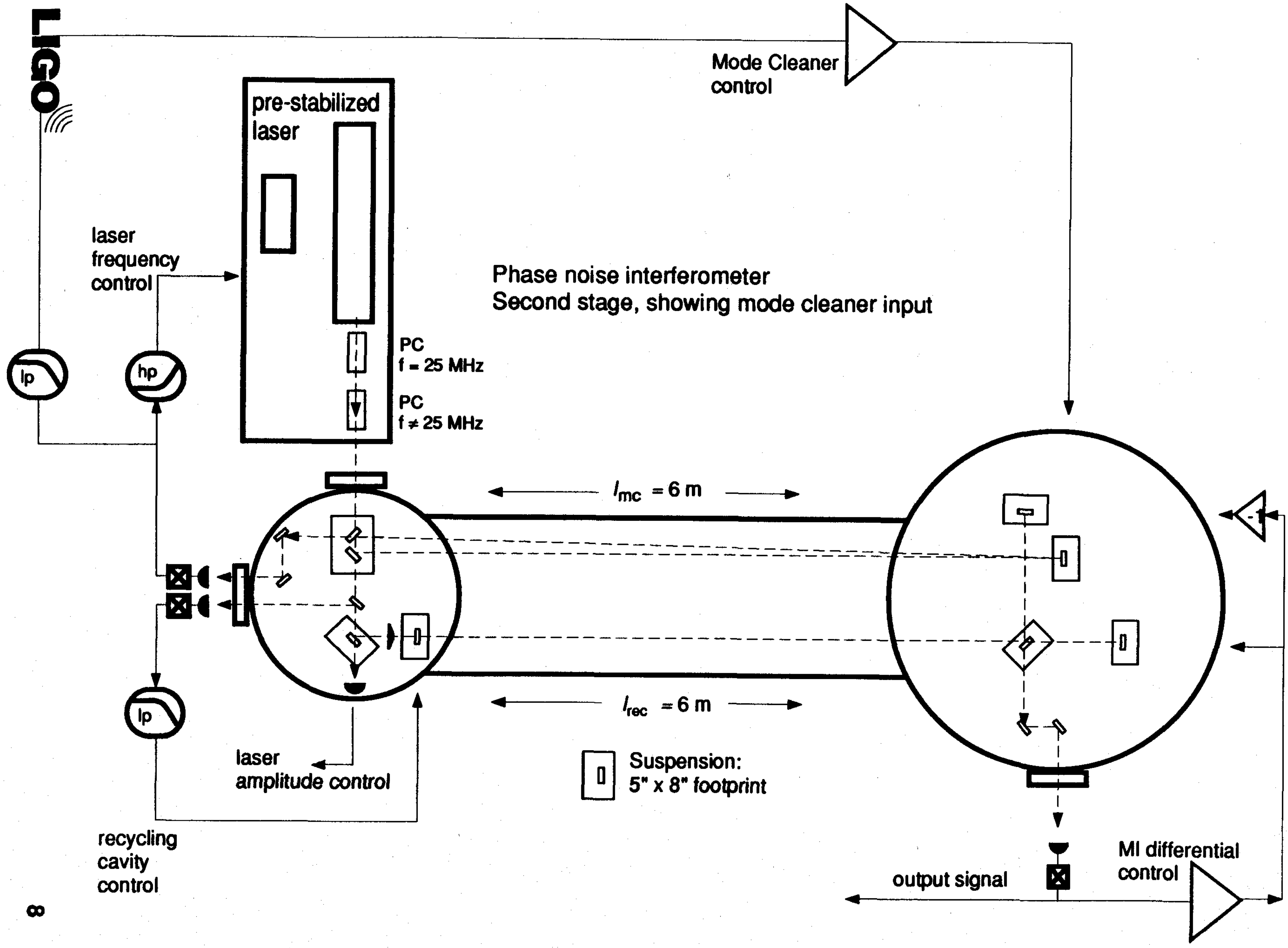
   - Photodetection system
   - Modulation system
   - Laser amplitude stabilization
   - Beam dumps

   FSSC generation technology
   Output mode cleaner
   Pointing system
   Alignment system

Phase noise interferometer
First stage, showing fiber input



Phase noise interferometer
Second stage, showing mode cleaner input



Interferometer Optics: Substrates and Coatings

1. **Substrates:**

- 3″ diameter: compatibility with suspended mode cleaner mechanics
- 1″ thick: thermal noise considerations (see below)
- need 3 ifo and 2 mode cleaner flats: procure 9
- need 1 ifo, 1 MC sphericals: procure 3 (substrates polished in multiples of 3)
- have (expired) quotes from GO and REO for specs as shown in Table 1 (3 month delivery quoted)

Quantity:	9	
Dimensions:	3.0" diameter (+0/-0.005"), 1.0" thickness (±0.010") at thickest point	
Surface #1:	Flat to $\lambda/15$ over central 1" diameter	
Surface #2:	Flat to $\lambda/15$ over central 1" diameter	
Surface roughness:	surface #1: surface #2:	super-polish (< 1 Å) on all flats super-polish (< 1 Å) on 3 of the 9 flats polish to < 5 Å on 6 of the 9 flats
Wedge angle:	30 minutes ± 3 minutes	
Side polishing:	Polish to transparency, no grey visible to the unaided eye	
Bevel:	Both faces beveled with a 1 mm ± 0.3 mm polished bevel	
Material:	0A grade fused silica	
Arrow:	Etch, grind or sand blast an arrow approximately 5 mm long at the top (thinnest) part of the blank (± 1 mm) pointing towards surface #1. Arrow centered between the two faces.	

Table 1 Polishing specifications for flat mirrors

Quantity:	**3**	
Dimensions:	**3.0" diameter (+0/-0.005"), 1.0" thickness (±0.010") at thickest point**	
Surface #1:	**10 meter radius of curvature, concave ±0.5 m deviation from sphericity: $\lambda/10$ over central 1" diameter**	
Surface #2:	**Flat to $\lambda/10$ over central 1" diameter**	
Surface roughness:	**surface #1:** **surface #2:**	**super-polish (< 1 Å)** **polish to < 5 Å**
Wedge angle:	**30 minutes ± 3 minutes**	
Side polishing:	**Polish to transparency, no grey visible to the unaided eye**	
Bevel:	**Both faces beveled with a 1 mm ± 0.3 mm polished bevel**	
Material:	**0A grade fused silica**	
Arrow:	**Etch, grind or sand blast an arrow approximately 5 mm long at the top (thinnest) part of the blank (± 1 mm) pointing towards surface #1. Arrow centered between the two faces.**	

Table 2 Polishing specifications for spherical mirrors

2. Coatings:

1. **Maximum reflectors: 3 flats, 1 spherical**
2. **50/50 beamsplitter: 2 flats**
3. **1% Transmission: 1 spherical**
4. **approx. 0.1% transmission at 45° inc (MC): 3 flats**
5. **AR, normal incidence: 3 flats, 2 sphericals**
6. **AR, 45° incidence: 5 flats**

- **Polarization: 'p' allows lower AR on 45° inc surfaces**
- **REO: choice of big or small (cheaper, faster, only 4 pcs/run) coating chamber**

Pre-Interferometer Optics

Laser

- Construct a prestabilized large frame laser following example in OTF (present laser is low power — 200 mW; has large frequency drift, frequent mode hops; not set up for feed-around frequency correction)
- Preference is for Spectra 2080 for compatibility with OTF laser (2040E has been replaced by 2080)
- Question: which design of the reference cavity to use?

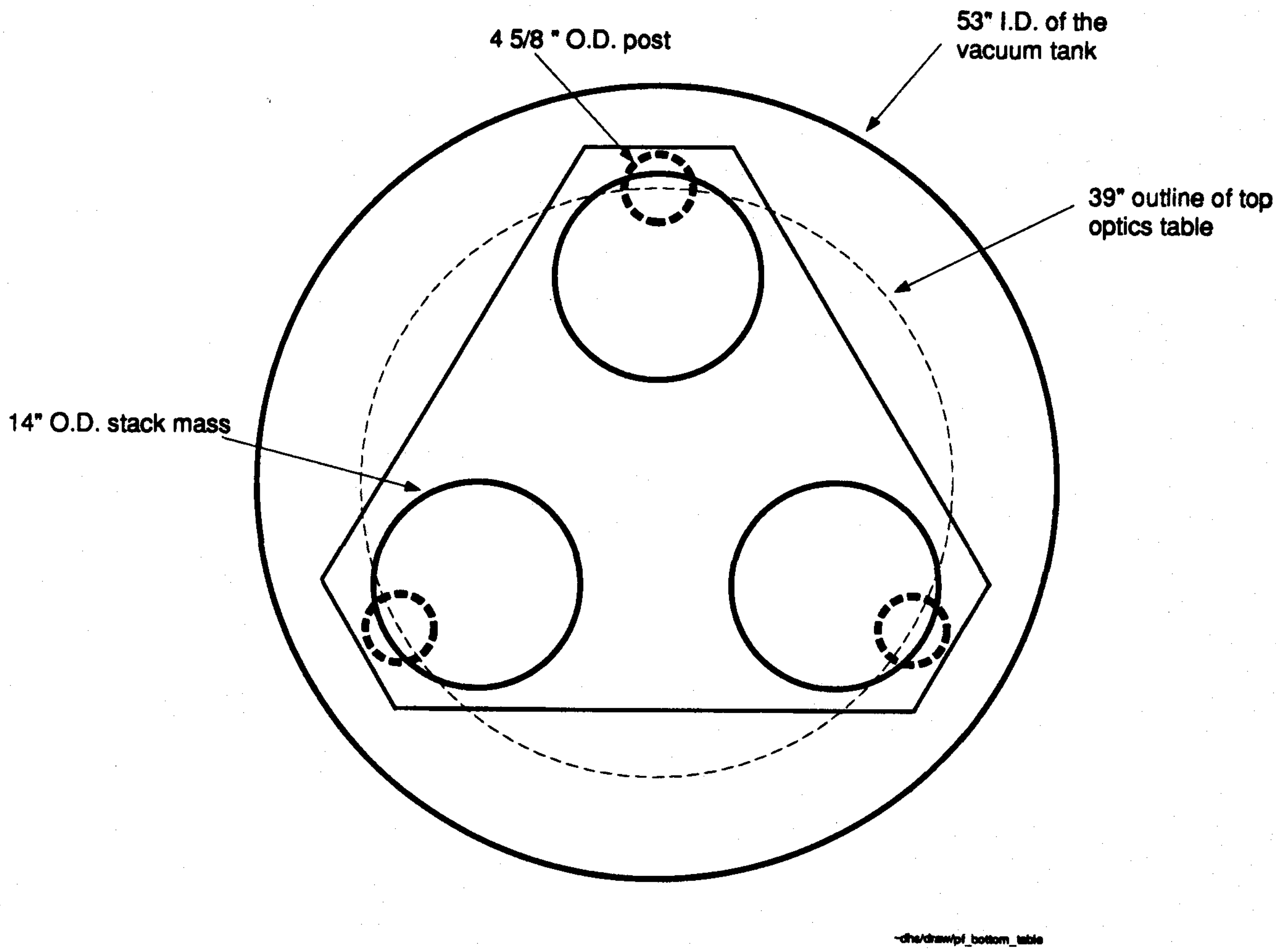
In-vacuum Input Optics

- Fiber, Pockels cells, Faraday rotator, 2 polarizers, 2 lenses, possibly waveplate
- No suspended components: phase (frequency) noise from stack-mounted components much smaller than prestabilized laser frequency noise
- No motorized mounts: all components on same stack — can align in air and correct with suspended components; no need for remote mode-matching
- Mounted on rail system as in MarkII — unless a vacuum compatible commercially available solution can be found

Seismic Isolation

Stacks: as in Mark II, with different support structure and increased table size for central tank.

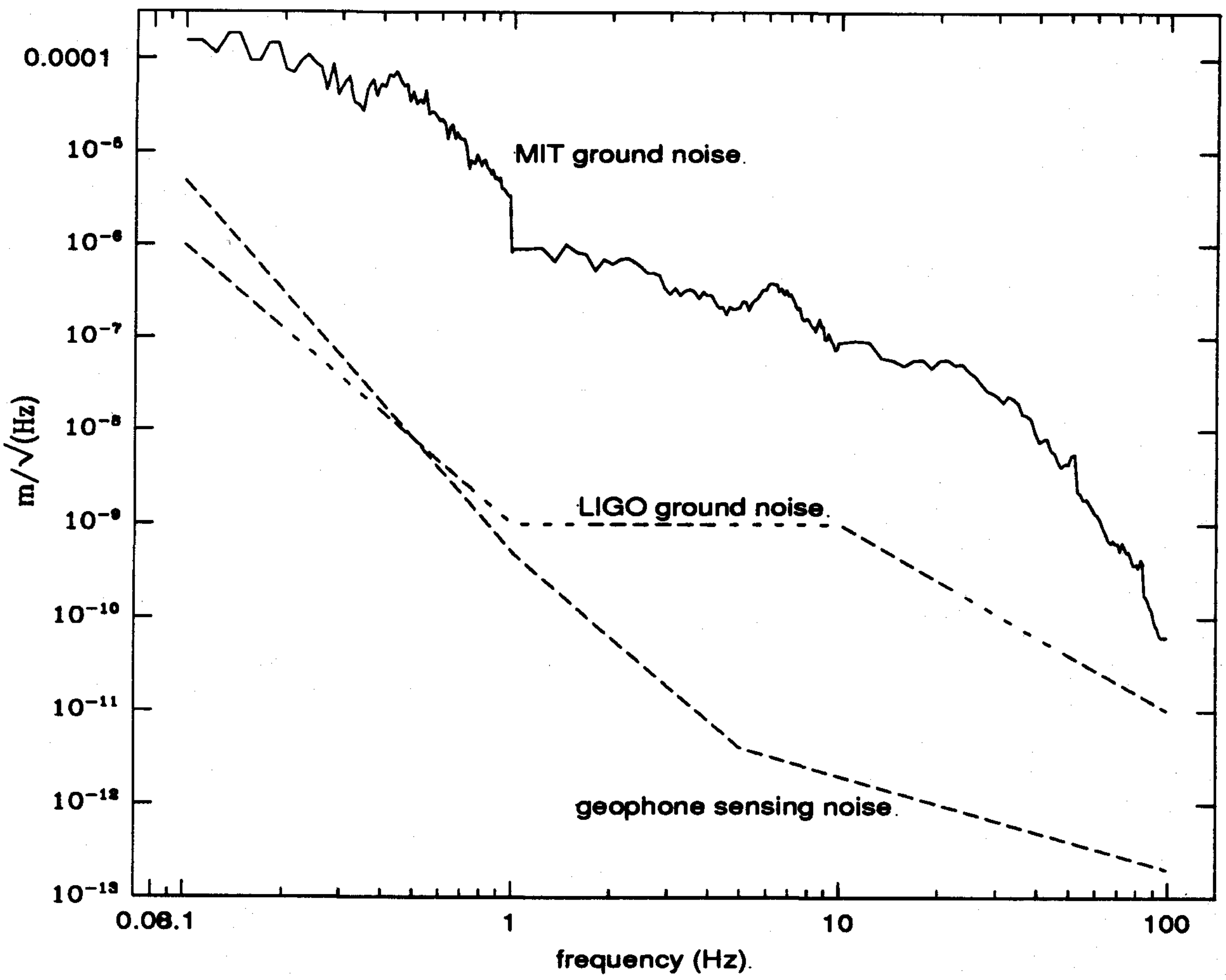
- **3 vertical support tubes**
- **3″ thick triangular Al stack support table**
- **Small tank top table: 39″ diam, 3″ thick Al (modes of plate at 500 Hz, 870 Hz, ...)**
- **Central tank top table: 63″ diam, 3″ thick Al**
- **Question: does central tank table require stiffening ? (modes otherwise at 200 Hz, 335 Hz, ...)**
- **Use all viton springs: lower Q's desirable; don't need the increased isolation of a viton/RTV stack**



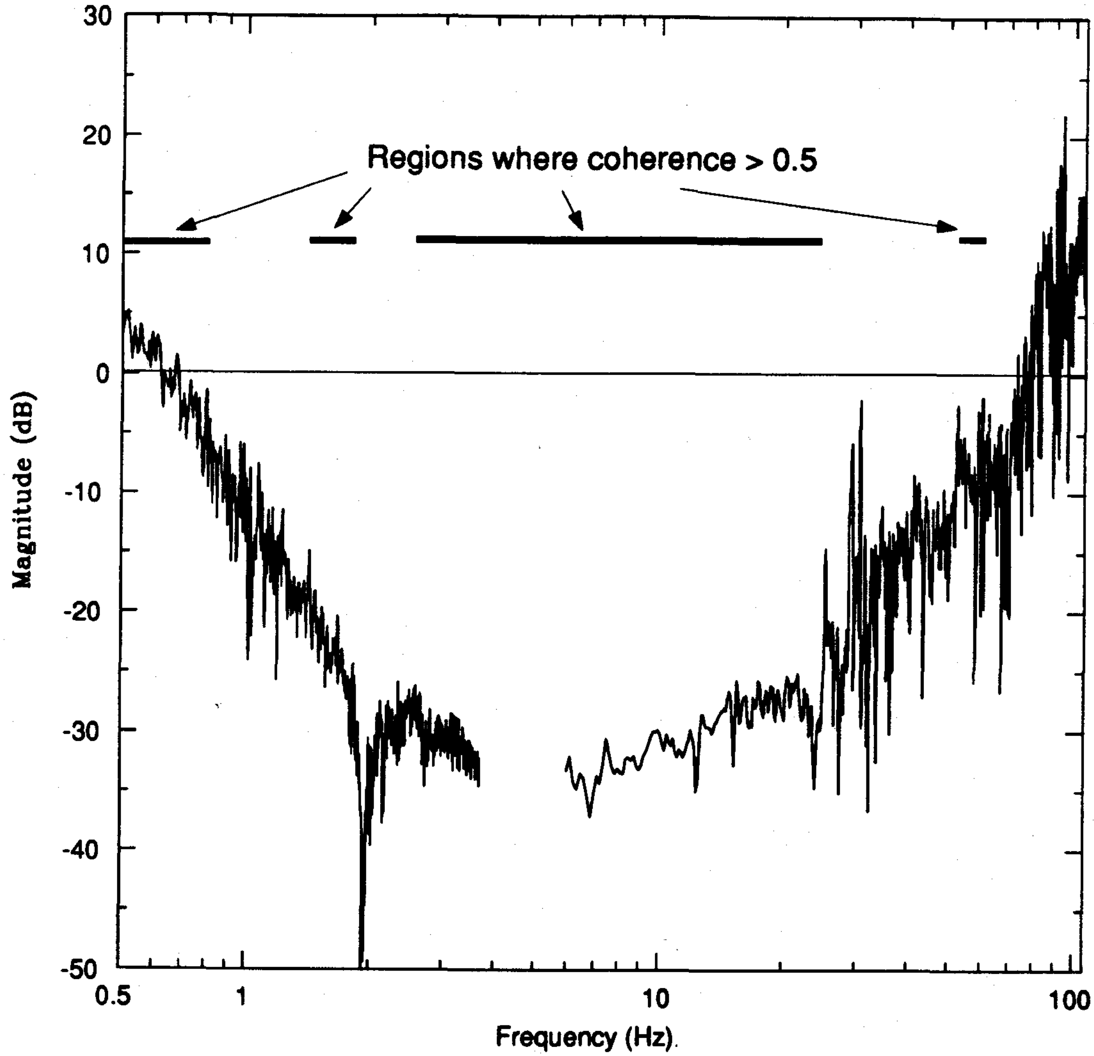
Barry Controls Active Isolators

A. Impact on seismic noise:

- reduce rms seismic noise in the 1 Hz-and-up band (in 6 d.of.) by a factor of nearly 30 →easier to acquire lock
- reduce seismic impulses: there are dozens of 10–20 μm p-p, 4–5 Hz characteristic frequency events per day; these will be reduced by a factor of 30 (maybe 100) →longer lock times
- make insignificant the alignment fluctuations on short time scales (see section below on pointing/alignment requirements)



Transfer function between ground motion and stack support table motion

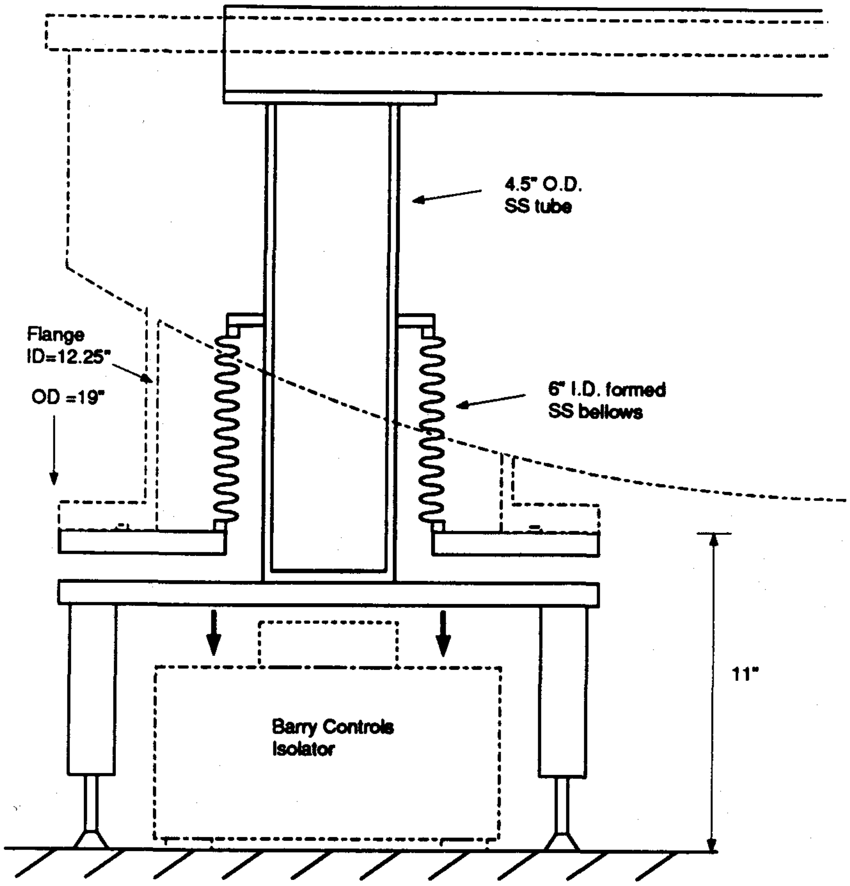


B. Integration with stack support structure

- **support structure doesn't rely on Barry isolators; can attach support directly to ground**
- **bellows connection to ground: ground induced motion is**

$$\frac{x_{\text{support}}}{x_{\text{ground}}} = \frac{k_{\text{bellows}}}{k_{\text{B.mount}}} = \frac{100\ \text{lbs/in}|_{\text{v}}}{20,000\ \text{lbs/in}} = \frac{1}{200}$$

(could use welded bellows if a softer spring is needed)


4.5" O.D.
SS tube
Flange
ID=12.25"
OD =19"
6" I.D. formed
SS bellows
11"
Barry Controls
Isolator

Suspensions

Mechanical: starting point is Suspended Mode Cleaner design (1.4 Hz suspension) for OSEM cage and tower, with some modifications

- modify for 1″ mirror thickness
- better control of OSEM axial position in cage
- more compact tower design: 5.25″ x 6.5″ footprint in recent KDR design
- perhaps provision for coarse azimuthal adjustment
- Question: coarse attitudinal control; how to adjust wire take-off point ?

Electronics: same controllers, OSEMs as for Suspended Mode Cleaner

- Coil/magnet: 0.066 N/A
- Driver noise that of the 2k source impedance (see discussion of noise sources below)

Cabling:

- Use (properly made) Ultimate cables between OSEMs and bottom of stack
- Use diallyl phthalate D-connectors between existing teflon-insulated wires and ends of Ultimate cables
- Existing Teflon insulated wires come out thru 55–pin Amphenol
- Big cables between tanks and controllers (let's make smaller, more flexible cables next time!)

Alignment and Pointing Strategy

What we've learned from the suspended 6m long cavity:

a. **short term misalignments produce 15% reduction in cavity power (see graph) → due to cavity optic axis angle fluctuations of $\theta = 0.4\theta_D = 7 \times 10^{-5}\mathrm{rad}$, or optic axis displacements of $\Delta = 0.4\omega_0 = 3 \times 10^{-4}\mathrm{m}$ on these time scales**

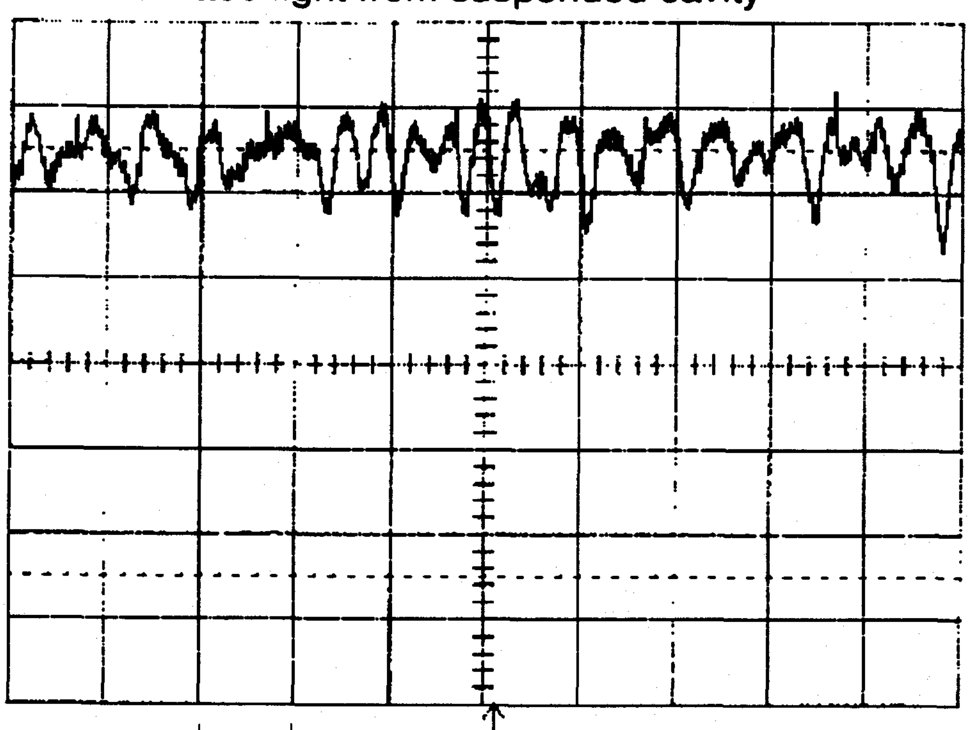
b. **long term alignment drift: Cavity power fluctuations due to alignment are < 3 % over a 10 minute time scale**

For the phase noise interferometer:

a. **short term fluctuations will be greatly reduced by Barry isolators; factor of 10 reduction in angle or displacement gives factor of 100 reduction in power coupling fluctuations**

b. **long term drift: servo not included at outset; could include developments (pointing/auto-alignment) from alignment task later)**

Transmitted light from suspended cavity



Fringe Sensing Noise Sources

Frequency Noise

- **With 10 cm asymmetry, $\delta\nu = 2.5 \times 10^{-2}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ produces $\delta\phi = 10^{-10}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$**
- **Want $\delta\nu = 5 \times 10^{-3}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ or less (1–2 orders of magnitude lower than prestabilized laser)**
- **Stabilization to recycling cavity: shot noise limit for F= 300, perfectly matched, optimally modulated cavity with 0.5 W incident power is $\delta\nu_{sn} = 3.5 \times 10^{-5}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$: leaves a factor of 150 for imperfect matching, visibility, modulation**
- **Simple model shows we need beam displacement noise $< 10^{-7}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ and beam angular noise $< 10^{-8}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$ to reach required frequency noise level; beam position noise out of the laser is bigger than this at low frequencies (< 500 Hz) → need for fiber . . . mode cleaner**

Amplitude Noise

- **Require that light at anti-symmetric output is shot noise limited**
- **Several mechanisms, worst may be AM produced by phase modulator; if P_{ω_m}/P_0 is the fractional AM produced by the modulator, and I_{det} the current detected at the output, we need**

$$\left(\frac{P_{\omega_m}}{P_0}\right)\left(\frac{\delta P(f)}{P_0}\right) < \sqrt{\frac{2e}{I_{det}}}$$

P_{ω_m}/P_0 may be 10^{-3}, or better ?

Beam Position Noise

- **Beam position stabilized by fiber (mode cleaner) and recycling cavity — effect on phase noise should not be a problem**
- **To measure ifo sensitivity to beam position, must put transducer (PZT) on fiber or folding mirror: is it worth it?**
- **Phase noise proportional to MI alignment offset: could probe influence by adding offset**

Mirror Displacement Noise

Requirement: Optical phase of 10^{-10} radians is produced by mirror motion of 4×10^{-18} m

Seismic Noise: equal to $4 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$ **at approximately 80 Hz:**

- **ground noise:** $3 \times 10^{-10} \mathrm{m}/\sqrt{\mathrm{Hz}}$**; stack attenuation: 10^{-4}; pendulum attenuation: 3×10^{-4}**

Thermal Noise:

- **AG & FJR's model, summing up first 20 modes, gives (constant ϕ assumption):**

$$x_{th} = 2.4 \times 10^{-18} \left(\frac{100\mathrm{Hz}}{f}\right)^{1/2} \left(\frac{\phi}{10^{-4}}\right)^{1/2} \mathrm{m}/\sqrt{\mathrm{Hz}}$$

- **Prediction for 0.5″ thick masses is a factor of 6 higher → reason for going to 1″ mirrors**

OSEM Driver noise:

- **Coil driver noise (from 2k resistor →** $3 \times 10^{-12} \mathrm{A}/\sqrt{\mathrm{Hz}}$**) produces** $x(f) = 3.8 \times 10^{-18}\ (100\ \mathrm{Hz}/f)^2 \mathrm{m}/\sqrt{\mathrm{Hz}}$

Radiation pressure:

- **For 10% power imbalance in arms, induced differential mirror motion is**

$$x(f) = \frac{\delta P(f)}{P} \frac{2(0.1 P_{\mathrm{mirror}})}{mc(2\pi f)^2} = 2.5 \times 10^{-18} \left(\frac{\delta P/P}{10^{-5}}\right) \left(\frac{100\ \mathrm{Hz}}{f}\right)^2 \mathrm{m}/\sqrt{\mathrm{Hz}}$$

Vacuum System and Cleanliness Strategy

Will adopt in-vacuum parts preparation and handling procedures of the Mark II

Will build medium size vacuum oven (25″ long, 10″ tube o.d.)

Vacuum System:

- Volume = 15,000 liters
- Surface area of empty system = 5 x 10^5 cm^2
- Two 1500 l/s turbo pumps, conduction limited to 480 l/s
- Ion pump: 480 l/s

Will pump out cleaned (remove grease from 0–ring grooves, bake new viton o-rings), empty system to get baseline RGA spectrum

Intensity in recycling cavity: 3 kW/cm^2 (compared to 70 kW/cm^2 in the 40m)

Note: recycling cavity can tolerate an additional 10^{-3} loss; not the mode cleaner, though

General lab cleanliness:

- Environment will be kept clean, similarly to 40m lab
- Soft wall clean room enclosures will be built around tanks

Schedule Overview

Construction and assembly: 8–9 months

First Phase research (fiber input): 6 months

Second Phase research (suspended mode cleaner): 9 months

Technical developments carried out in parallel