LIGO-T890044-00-R

#71

List of 4/06/89

Initial Assessment of Scattering Effects in Vacuum Enclosures of LIGO Interferometers Outside the Main Beam Pipes.

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(3/15/89) (Corrected)

Received 3/27/89
EJF

We consider the following main areas:

1. Within the mass tanks and the 6 foot manifold.
2. In the pipes between the mass tanks and the splitter chambers.
3. In the splitter tanks.
4. In the 12 meter input mode cleaners.
5. In the beam generating system.
6. In the output mode cleaner and tanks.

We first give in Part 1. an overall survey, and then in Part 2. a more detailed analyses of different cases. Our overall conclusion is that if some simple precautions are taken we do not expect serious problems from any of the scattering phenomena considered.

Part 1. Overall Survey.

1. Scattering Within the Mass Tanks, The 6 Foot Manifold, and the Transitions to the 4 Foot Beam Pipes.

The main ways in which scattering in this region might cause noise in the interferometer output may be summarized as:–

(a) Light scattered out of the main beam by a main cavity mirror is scattered (or reflected) by the vacuum wall of the 6 foot manifold, small objects within the manifold, the transition from the manifold to the 4 foot beam pipe, or the 4 foot beam pipe or associated baffles: and then this light is scattered a second time by the main cavity mirror so that some of it gets back into the operating cavity mode and contaminates it. If then the wall scattering region vibrates so that it Doppler shifts the scattered light, this varying phase pollution results in noise in the detector output.

(b) Light scattered out of the main beam by the main cavity mirror is scattered (or reflected) by the back of another test mass or associated equipment, and then is scattered a second time by the main mirror so that it gets into the main cavity mode and may contaminate it.

The mechanism (b) will take place, but we expect it to be unimportant, for the test masses and associated equipment are all sufficiently well seismically isolated, so that phase changes in the scattered light are very small at the gravity–wave frequency. If we take just the worst case, as an example, these might be scattering from a non–suspended shadow position detector associated with a mass just in front of the one being considered. The supported component would be mounted from the isolated structure from which the test mass is suspended by one additional pendulum wire suspension, so the motions at the gravity–wave frequency of the position detector would be at worst about 10^6 times larger than the motions of the test mass itself. With mirrors of total loss 50 p.p.m., the total light power scattered into all angles must be less than this loss. We estimate the total probability that the three successive scatterings involved will put light back into the main 4 km cavity mode is of order 10^{-12}, so we find that the maximum scattering effect is smaller by a factor of order 10^6 than the seismic noise of the test mass itself, and thus is unimportant.

The mechanism (a) might be more significant, since the walls may be moving with seismic or acoustic noise. Estimates of the magnitude of the effect can be made by adapting the techniques used to analyze scattering phenomena in the 4 km long beam pipes. In the 4 km studies, it was assumed that steps were taken to make specular reflection unimportant, and this would not automatically be the case unless we make the transition to the 4 foot pipe suitably tapered, or shielded by a tapered low–scatter cover (such as a foil of aluminized Kevlar), and use similar covers if necessary to shield other protruding objects. We will assume that this is done. (Blackening the walls of the manifold will also reduce scatter).

A very crude and simple comparison of the 4 km case and the present one can be made assuming an angular scattering distribution from the mirrors inversely proportional to the square of the scattering angle, and attenuation of the scattered light by distance alone. This simple approach suggests that the present scattering effect is of the same order of magnitude as that in the 4 km pipe. As the 4 km effect is several orders smaller than the ultimate sensitivity set by the standard quantum limit for 1 ton masses, when an output mode cleaner is used, this already suggests that the present effect is unimportant.

A more detailed and accurate analysis is presented in Part 2 of this report. This deals with cases without an output mode cleaner as well as with one. A slowly tapering shield is assumed over the transition region. The results confirm that the overall noise from this scattering mechanism is small enough to be unimportant even without any output mode cleaner, and is made smaller still with a mode cleaner.

We conclude that if simple precautions are taken, such as making sure that direct reflections are avoided and putting a simple low–scatter shield over the transition region, scattering phenomena inside the mass tanks and the 6 foot manifold are not expected to be a serious noise source.

2. Scattering in the Pipes Between the Mass Tanks and the Splitter Chambers.

Here the main effect is scattering of light from a mirror at either end, such as a 45 degree bending mirror or a beamsplitter, to the pipe wall; followed by scattering of that light by the moving wall to the same or another end mirror; followed in turn by a second mirror scattering to put some of the light back into the original mode being transmitted. There is a close analogy to the scattering phenomena in the 4 km cavities, with the main differences here that scattering angles are very much larger, while lengths are shorter. Analyses can be made using the techniques developed for the 4 km arms, and are summarized in Part 2. Here the relatively short length of the pipe limits the attenuation of light which moves from one mirror to the other by multiple specular reflection at the pipe walls, and we suggest blackening the inside of the pipe (possibly with Martin–Marietta black) to reduce this mode of propagation of scattered light. It is assumed that simple baffles are incorporated in the vacuum pipe to eliminate direct single bounce specular reflections from one mirror to another (and also to make initial beam alignment simpler).

We should point out that at this part of the optical system the sensitivity to phase noise is reduced by a factor equal to the effective number of bounces of the light in the main 4 km cavities from the sensitivity to phase noise of the 4 km cavity. The number of effective bounces ranges from 50 to 500 for gravity wave frequencies from 1 k Hz to 100

Hz, respectively. An initial analysis indicates that with blackened walls, baffles, and an output mode cleaner the scattering should be reduced enough to be unimportant. However further analysis may be necessary to be certain about this, since in this region the ratio of beam diameter to length is very different from that in the 4 km arms.

It may be noted that if it is found in practice that scattering is serious here, it may be countered by surrounding the beam by a seismically isolated screening pipe and other shields as required.

The situation at the link between the corner beamsplitter tank and the end of the 6 foot manifold is in many ways similar to that in the pipes just discussed. Here the scattering region is much shorter, but there is a danger point for specular reflection at the reduced end of the 6 foot manifold. We would propose screening this end by a tapered shield, in a way similar to that suggested for the transition at the beam end of the manifold, although in this case a steeper taper, up to 45 degrees, may be effective. It is recommended that the walls be blackened in this region also.

3. Scattering in the Splitter and Associated Tanks.

(a). The main scatter problem to be considered is scatter of light from (1) optical components, or, (2) from a region of the tank wall illuminated by a rejected or spurious reflected beam, which is then scattered by a moving tank wall, and thence gets to the output photodiode. With an output mode cleaner (the current design) there has to be at the last step a further scattering process at a piece of optics in the beam, to permit the spurious light to cause coherent interference at the diode. Thus for case (1) at least 3 scattering processes are required. This makes it similar to the case of scattering in the 4 km pipe, and we can use the detailed analysis made of that case to get an upper limit assessment.

First, the sensitivity to phase noise due to scattered light in the beamsplitter tank is smaller than the sensitivity of the 4 km cavities by a factor equal to the effective number of reflections in the 4 km cavities, a factor of around 50 near 1 kHz, and 500 near 100 Hz. Secondly, the total amount of scattered light reaching tank walls in the mode cleaner cavity is not greater than the amount reaching the walls of the main cavities, and is likely to be very much less. This follows from the fact that the total scattered light in each main cavity has to be less than half the total input power – and probably much less than this. The light power in the splitter tank is less than the total in the main cavities by a factor of from 50 to 500, but there are more optical surfaces. However most of the optical surfaces lie within the mounts of components or are screened by other parts from the tank walls, and the effective number of exposed surfaces is unlikely to make up for the power factors just given. As it has been shown that scattering in the main cavities will not degrade even the most sensitive interferometer, it is unlikely that the process just discussed will give significant problems.

The process (2) could give higher fluxes of scattered light, if there were any stray reflections which could reach the walls. In fact the optical system has been designed so that all major beams are caught be photodiodes, beam aligning units, or by beam dumps. In the final layout small additional beam stops will be added to catch secondary beams such as those off the brewster windows of Pockels cells. These will be mounted to the optical table, which with even one stage of rubber seismic isolation will have motions less than that of the tank walls by a factor of 100 at 100 Hz. Suspending the beam stops could reduce motion further, but is probably unnecessary. With these precautions, scattering from stray beams should be insignificant.

(b). Scattering of light directly from the optical table itself, without involving a tank wall, could be a larger effect, since the table surface is close to the beams, and subtends a large angle. This, and scattering off the numerous sensing and positioning devices mounted on it, may be difficult to deal with in any way other than making their motions small. In the tank housing the beamsplitters themselves, the need for good isolation for the prime beamsplitters is likely to be achieved in part with rubber–steel stacks in the optical table supports, and this should be adequate to cope with the scattering also. In the horizontal axis modules installation of 2 or 3 stages of steel–rubber isolation stacks in the table supports seems the simplest solution.

Altogether it appears that scattering effects can be made small enough to be insignificant in the beamsplitter tanks, provided the simple precautions mentioned are taken, and it is not recommended that anything more elaborate than this is done at this stage.

Although the estimates here suggest there is no reason to expect a serious problem, it should be pointed out that if some unforeseen phenomenon does make wall scattering much more serious in the working LIGO, a practical solution may be achieved, if needed, by adding a simple isolated false wall close to the tank walls to intercept the light. However it is not proposed worth while to add such a false wall at present, as the scattering does not seem serious enough to justify it.

4. Scattering in the 12 Meter Input Mode Cleaners.

The magnitude of the wall scattering in the input mode cleaners may be estimated using the methods developed to analyze scattering in the 4 km pipes (see Part 2 of this report). For this to be valid baffles should be incorporated to prevent direct specular reflection off the walls, and we propose this be done in any case since this simplifies initial alignment and the operation of pointing control systems. The effect of what scattering does take place in the input mode cleaners is, however, very much smaller than scattering of the same magnitude would be in the 4 km arms. Firstly, the prime effect of the scattering will be to cause a fluctuation in the apparent frequency of the light feeding the interferometer. As this appears in both arms of the interferometer it has no first–order effect on the differential output, and only gives small second–order effects. And even these small effects are further reduced by the final frequency stabilization action of the high–frequency feedback trim signal from the 4 km main cavities or from the overall cavity formed by the recycling system. It is therefore concluded that, with simple baffles to remove direct specular reflection, scattering is unlikely to be significant in the input mode cleaners.

5. Scattering in the Beam Generating System.

The arguments given in Section 3 above relating to scatter in the beamsplitter and associated tanks apply also to the beam generating system. Here all the scattering phenomena are common mode to both arms of the interferometer, and moreover any frequency, phase, or other effects in the light are subsequently reduced by the 12 meter input mode cleaner. We therefore expect scattering effects here to have effects which are less by a factor of at least 100 over those in the system after the 12 meter mode cleaner and thus to be insignificant.

6. Scattering in the Output Mode Cleaner and Tanks.

Scattering in the output system can have a more direct effect on the detector noise than in the input optical system. At the output there is no common–mode cancellation effect, and scattered light which reaches the photodiode in a way which lets it interfere coherently with the normal light present can cause phase noise. In this part of the system, however, the intensity of the light is much less than that in the interferometer itself – with perfect contrast and optimally adjusted phase modulation it could approach zero. The importance of scattering here will therefore depend on the actual contrast achieved, which will depend partly on imperfections in the optical components. We might take as an example an intensity in the null of 1% of the input beam. And, as in Section 3 above, the relative effect of any phase noise due to scattering is reduced by a factor of from 50 to 500 of that in the main cavities. Thus overall it is expected that the scattering effect in the output mode cleaner will be reduced from that found by scaling the main cavity calculations by a factor of order 5000 to 50,000.

The assessment of the magnitude of the scattering effect in the output mode cleaner cavity itself can be done using methods similar to those developed for the main 4 km cavities, and this is being done. The result will then be reduced by the further large factor of around 10,000 just given. It seems likely that the overall contribution to system noise will be small – but we cannot be certain of this at present. Indeed the actual experimental contrast obtained in the real LIGO system will be an important relevant quantity; and there may also be a possibility that some stray light from the strongly illuminated beamsplitter region could get to the mode cleaner and contribute to scattering noise here.

In spite of the incompleteness of the result at this point we expect that if it is found in reality that scattering is a problem in the output mode cleaners, the effect can be overcome in a reasonably practical and simple way. An isolated screening tube can be suspended around the beam and end mirrors of each mode cleaner, damped magnetically or by servosystems if necessary, and this will prevent scattered light reaching the vacuum walls. This only requires enough space in the tubes surrounding the mode cleaners, and we would recommend increasing the diameter of these tubes to provide this. It is worth pointing out that this particular scattering effect can probably be fairly easily diagnosed by altering the contrast of the interferometer, and checking how this affects the noise. Thus, although full results are not yet available, we feel it likely that little risk will be incurred by making no system design changes at present other than allowing some extra space for an isolated screen in the mode cleaner pipes, and in the crossover regions with the input pipes. However this does seem to be the most dangerous place for scattering noise in the whole system outside the 4 meter arms.

Scattering off the vacuum tank walls of light from stray beams and scattered from optical surfaces in the output optics is another potential source of noise. The situation here is similar to that discussed in Section 3 above for optics near the beamsplitter tanks, the main differences being that the light power is smaller by a factor of about 100, and the number of reflecting surfaces is less. However for the optics after the mode cleaner, the filtering action of the mode cleaner is no longer available. We suggest taking similar precautions here to those mentioned in Section 3: fitting small isolated beam stops at all stray beams, and keeping the motions of the optical table small at gravity–wave frequencies, by use of at least 2 stages of rubber–steel isolation. It may be noted that a high–power beam dump is already included in the design to deal with the full beam power if the system jumps to a bright fringe, when the light is diverted to it by the intensity modulator preceding the chain of output Faraday isolators. This particular beam dump will be designed to minimize scattered light, which will not be large in normal operation, and of course will be suitably cooled to handle the power involved in a failure situation by conduction to the optical bench. We propose taking no more elaborate steps than these at this stage.

In this case of the output optical system, experimental diagnosis of the scatter noise seems easier than for some of the other phenomena discussed above, so we are more confident about avoiding any elaborate precautions at this stage. If wall scattering is found in practice to be serious in this part of the system, it would be practicable to screen the tank walls by an isolated false wall, as discussed in Section 3. Thus, although our estimates are incomplete at this stage, we have both suitable diagnostic techniques, and potential cures, available. We therefore do not expect serious problems from wall scattering in this output part of the interferometer.

Part 2. – More Detailed Analyses.

Summary of the Scattering Effects Analyzed in this Section with some Possible Strategies for Reducing Their Influence.

(1) Backscattering in the Transition from the 6 Foot to 4 Foot Pipe.

We recommend inserting a tapered smooth conical piece, such as aluminized Kevlar in the transition section at a minimum distance of 3 meters from the closest cavity mirror. (See pages 11-14).

(2) Scattering in Tubes Before the Beamsplitter in the Input Optics Train.

No special care is needed here as the dominant noise would be common mode. (See pages 15-16).

(3) Scattering in Tubes Between the Splitter Chambers and the Test Mass Chamber.

We suggest some care is needed here. There are three optical elements to scatter and recombine beams. Although the phase sensitivity to scattered light is smaller than in the main beam tubes by the ratio of the cavity finesse, there is no attenuation due to roughening and reflectivity loss. We recommend baffles and blackening in this tube. (See pages 17-18).

(4) Scattering in the Output Beam Tubes.

These tubes are a special place. The light intensity when the interferometer is locked on a dark fringe is small, the exact amount depending on the fringe contrast. The calculations for this section are more difficult and are not completed. At present the best guess is that these tubes should also be baffled and blackened.

PROCESSES THAT MAY CAUSE NOISE FROM SCATTERED LIGHT IN THE INSTRUMENTATION CHAMBERS AND ASSOCIATED VACUUM PIPES.

AREAS OF POSSIBLE CONCERN

1) TRANSITION FROM THE INSTRUMENTATION BUILDING VACUUM PIPE TO THE MAIN TUBES. PRIMARY MECHANISM IS BACK SCATTER TO THE MIRROR IN THE CLOSEST TEST MASS CHAMBER.

2) SCATTERING PATHS FROM THE BEAM SPLITTER CHAMBER, WHERE THE INTENSITY OF LIGHT IS HIGH, TO THE ANTISYMMETRIC OUTPUT, WHERE THE INTENSITY IS LOW, WHEN THE INTERFEROMETER IS LOCKED ON A DARK FRINGE. TWO CASES MUST BE CONSIDERED: WITH AND WITHOUT AN OUTPUT MODE FILTER.

3) SCATTERING IN THE MODE FILTER TUBES ANALOGOUS TO THAT IN THE MAIN TUBES INVOLVING SCATTERING BY A MIRROR, REFLECTION BY THE WALL, AND RECOMBINATION INTO THE PRINCIPAL MODE BY ONE OF THE CAVITY MIRRORS

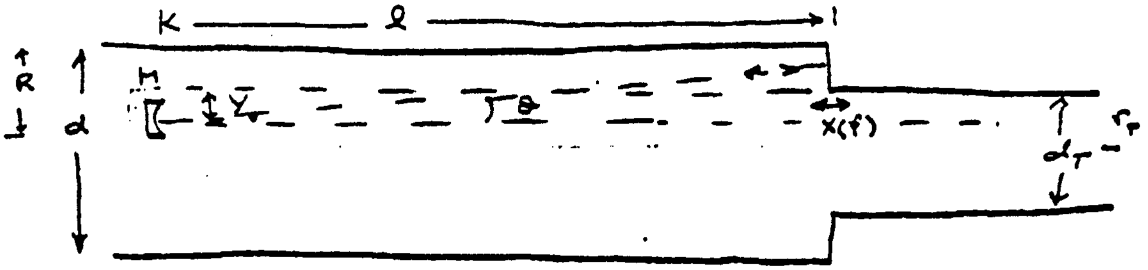
4) SCATTERING FROM THE MANY OPTICAL COMPONENTS IN THE INPUT AND OUTPUT TRAIN. AGAIN THE SCATTERING PATH BEING COMPONENT TO WALL TO COMPONENT

5) ADDITIONAL RECOMBINATION OF AMBIENT SCATTERED LIGHT BY THE OPTICAL COMPONENTS INTO THE PRINCIPAL MODE.

6) SCATTERING IN THE TUBES COUPLING THE SPLITTER CHAMBERS AND THE TEST MASS CHAMBERS; PARTICULARLY, THE INTERSECTION POINTS OF INPUT OPTICS BEAM TUBES WITH THE THE TEST MASS / SPLITTER CHAMBER TUBES

BACK SCATTERING FROM THE TRANSITION SECTION OF PIPE IN THE INSTRUMENTATION BUILDING TO THE NEAREST MIRROR IN A TEST MASS CHAMBER

GEOMETRY



CALCULATION FOLLOWING KST P40

ASSUME: SCATTERING HAS THE FOLLOWING MECHANISM

1) SCATTERING BY MIRROR M
2) DIFFUSE REFLECTION BY TRANSITION WITH LONGITUDINAL MODULATION X
3) RECOMBINATION INTO MAIN MODE AT MIRROR M

SCATTERED BRIGHTNESS BACK TO MIRROR

$$-\frac{dP_{scat}}{P\, dA\, d\varphi\, df} = \frac{\alpha \bar{I}}{\ell^2 \theta^2} \underset{\substack{\| \\ G_{surface}}}{\left(\frac{dP(\theta)}{P\, d\Omega}\right)_{surface}} \frac{R(R-r_T)}{\ell^2} \left[4\pi \frac{x(f)}{\lambda}\right]^2$$

$$h(f) = \left[\int_0^{2\pi} P_{recombination} \frac{dP_{sc}/dA\, d\varphi\, df}{P/\lambda L}\, d\varphi\right]^{1/2} \frac{\lambda f}{c}$$

INTEGRAL OVER THE TRANSITION SECTION, φ, HAS A MAXIMUM NEAR $\varphi = 0$ AND A BAND OF $\Delta\varphi \approx 2Y_0/R$

<u>TWO CASES</u> : <u>WITHOUT OUTPUT MODE FILTER</u>

$$P_{REC} = \frac{(1-\eta)^2}{2\theta}\left(\frac{\lambda}{L}\right)^{1/2}$$

$$h(f) = \frac{\alpha^{1/2}}{\theta^{3/2}} \frac{(\lambda L)^{1/2}(R(R-r_T))^{1/2}}{\ell^2} G^{1/2} (1-\eta)\left(\frac{\lambda}{L}\right)^{1/4}\left(\frac{\lambda f}{c}\right) 4\pi \frac{x(f)}{\lambda}\left(\frac{2Y_0}{R}\right)$$

USE FACT THAT $\theta \sim \frac{Y_0}{\ell}$ NEAREST POINT ON BEAM TO TRANSITION

$$h(f) = \alpha^{1/2}(1-\eta)\left(\frac{2\,.\,(R-r_T)}{\ell}\right)^{1/2}\left(\frac{\lambda L}{Y_0}\right)^{1/2}\left(\frac{\lambda}{L}\right)^{1/4} G^{1/2}\left(\frac{\lambda f}{c}\right)4\pi\,\frac{x(f)}{\lambda}$$

USE $\alpha = 1\times10^{-6}$ $\quad L = 4\times10^{5}$ cm $\quad R = 3$ ft $= 91$ cm

$\eta = .9$ $\quad Y_0 = 20$ cm $\quad r_T = 2$ ft $= 61$ cm

$\lambda = 5\times10^{-5}$ cm

$x(f) = 10^{-5}/f^{2}$ cm/Hz$^{1/2}$ (SEISMIC NOISE)

$$h(f) \cong \left(\frac{G}{\ell}\right)^{1/2}\frac{2.4\times10^{-21}}{f}$$

SO TO STAY AT LESS THAN $\frac{1}{10}\,h(f)_{gw} = \frac{4\times10^{-24}}{f}$

$$\boxed{\left(\frac{G}{\ell}\right) < 3\times10^{-6}}$$

ONE MUST BE MORE CAREFUL HERE THAN FOR THE STANDARD BAFFLE IN THE 4Km TUBE. TYPICAL VALUES TALKED ABOUT AT END OF THIS SECTION

WITH OUTPUT MODE FILTER

$$P_{rec} = \frac{2\alpha}{\theta^2}\,\frac{\lambda}{L}$$

AGAIN USING $\theta = \frac{Y_0}{\ell}$

$$h(f) = 2\alpha\left(\frac{\lambda}{L}\right)^{1/2}\frac{[\lambda L R(R-r_T)]^{1/2}}{Y_0^{2}}\left(\frac{Y_0}{R}\right)^{1/2}G^{1/2}\left(\frac{4\pi\,x(f)}{\lambda}\right)\left(\frac{\lambda f}{c}\right) \Rightarrow \propto \frac{1}{\theta^2}$$

RESULT BECOMES INDEPENDENT OF ℓ

$$h(f) = G^{1/2}\,\frac{2.6\times10^{-26}}{f}$$

TO STAY AT LESS THAN $\frac{1}{10}\,h(f) \sim \frac{4\times10^{-24}}{f}$

NO SPECIAL REQUIREMENT ON THE TRANSITION SECTION

SINCE G IS ALLOWED TO BE LARGER THAN 1

SUMMARY OF REQUIREMENTS ON TRANSITION SECTION

1) WITHOUT MODE CLEANER

$$\frac{G}{l} < 3 \times 10^{-6}$$

USING BLACK SURFACE LIKE ANODIZED ALUMINIUM (MARTIN-MARIETTA BLACK)

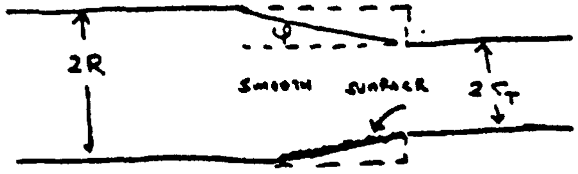
θ = ANGLE OF INCIDENCE

$|R|$ = REFLECTIVITY $\sim 3 \times 10^{-3}$ $\quad 0 < \theta < 80$ DEGREES

$G \sim |R|$ FOR THIS MATERIAL

$l \geq 1 \times 10^{3}$ cm $\sim$ 10 METERS

USING SMOOTH SURFACE, TAPERED



SMALL φ BRINGS SCATTERED RAYS FROM MIRROR CLOSER TO SMALL GRAZING ANGLE,

$g = \left(\frac{2\pi\sigma}{\lambda}\varphi\right)^2$ $\qquad g < 1$ FOR SMOOTH SURFACE

$G(\pi - \varphi) \simeq \left(\frac{2\pi\sigma}{\lambda}\right)^2 e^{-\left(\frac{2\pi\sigma}{\lambda}\right)^2}$ $\qquad T/\lambda >> 1$ DIFFUSE COMPONENT [illegible]

TYPICAL NUMBERS: IF $\varphi \sim 0.1$ (TRANSITION TAKES PLACE OVER A LENGTH OF 10 feet)

$\sigma/\lambda \sim 1$ STILL SATISFIES SMOOTH SURFACE APPROXIMATION THAT $g < 1$ AND IF $T/\lambda >> 1$

$G(\pi - \varphi) \sim 10^{-16}$ PRETTY GOOD ENOUGH

CONCLUSION: IF SMOOTH SURFACE CONDITION IS SATISFIED BY TAPERING THE TRANSITION, THE $G/l < 3 \times 10^{-6}$ IS EASILY SATISFIED.

A POSSIBLE SUGGESTION IS TO USE ALUMINIZED "KEVLAR" CONE. ONLY REASON FOR CAUTION WOULD BE DIRT COLLECTING ON THE SURFACE. DUST WILL

WITH MODE CLEANER

NO SPECIAL CONDITION REQUIRED

RECOMMEND: TAPERED SECTION WITH SMOOTH SURFACE

$$\frac{2\pi\sigma}{\lambda}\varphi < 1$$

AND DISTANCE GREATER THAN 3 METRES FROM LAST MIRROR TO GIVE TOLERANCE FOR DUST

3) SCATTERING IN MODE FILTER AND COUPLING TUBES

a) TUBES INVOLVED WITH INPUT OPTICS

1) FREQUENCY MODULATION OF THE PRINCIPAL MODE BY SCATTERED RAYS THAT HAVE HIT MOVING WALL SURFACES AND ARE SUBSEQUENTLY RECOMBINED WITH THE MAIN MODE BY SCATTERING BY AN OPTICAL COMPONENT ARE LESS IMPORTANT THAN OTHER SCATTERED BEAMS IN THE LIGO. THE FREQUENCY MODULATION IS COMMON TO THE BEAMS THAT ARE ULTIMATELY DIVIDED BY THE BEAM SPLITTER AND THE EFFECT IS THE SAME AS FREQUENCY NOISE IN THE LASER

THE EFFECT CAN BE CRUDELY ESTIMATED BY EVALUATING THE FREQUENCY NOISE FROM A SCATTERED BEAM AND COMPARING IT TO THE FREQUENCY NOISE PERMITTED AT MAXIMUM SENSITIVITY

IF THE MAIN BEAM HAS A POWER P AND THE SCATTERED POWER INTO THE MAIN MODE IS P_{SCAT}, THE FREQUENCY NOISE IN THE RECOMBINED BEAM IS

$$\nu(f) = \left(\frac{P_{SCAT}}{P_{MAIN}}\right) \nu_0 \frac{2\pi f}{c} x(f) \qquad \boxed{\text{INCOHERENT ADDITION}} \qquad (1)$$

$x(f)$ = AMPLITUDE SPECTRAL DENSITY OF WALL MOTION $\sim 10^{-5}/f^2$ cm/Hz$^{1/2}$ $f > 10$ Hz

ν_0 = LIGHT FREQUENCY $\sim 6 \times 10^{14}$ Hz

THE STRAIN SENSITIVITY LIMITED BY FREQUENCY NOISE IS

$$h(f)_{\text{FREQ NOISE}} = \frac{\nu(f)}{\nu_0}\left[\frac{\Delta F}{F} + \frac{\Delta \ell}{\ell}\right]$$

WHERE $h(f)$ IS THE LIMITING SENSITIVITY AND $\Delta F/F$ IS THE FINESSE BALANCE OF THE CAVITIES AND $\Delta \ell/\ell$ THE LENGTH BALANCE OF THE CAVITIES

ASSUME $h(f) < 3 \times 10^{-25}$ STRAIN/Hz$^{1/2}$ BEST 9L SENSITIVITY

$$\left[\frac{\Delta F}{F} + \frac{\Delta \ell}{\ell}\right] \sim 10^{-3}$$

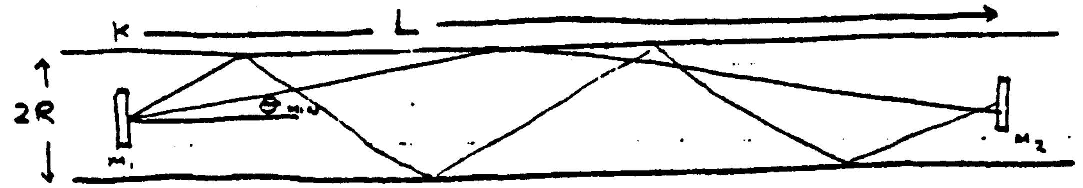
$\nu(f) < 1.8 \times 10^{-7}$ Hz/Hz$^{1/2}$ [WITHOUT ELECTRONIC COMMON MODE SUBTRACTION]

EVALUATING THE AMOUNT OF SCATTERED LIGHT PERMITTED IN THE INPUT OPTICS

$$\frac{P_{scat}}{P_{main}} < \left(\frac{\tilde{v}(f)}{\tilde{v}_0}\,\frac{c}{2\pi f\, x(f)}\right) \sim 1.4\times10^{-7} f \qquad f > 10\,Hz$$

THE ATTENUATION OF SCATTERED LIGHT THAT IS "RECOMBINED" WITH THE MAIN BEAM SHOULD BE 60 db AT 10 Hz.

THE SCATTERED - REFLECTED - RECOMBINED POWER IN A TYPICAL INPUT BEAM TUBE



THE WORST CASE IS THAT AROUND $\theta_{min} \sim \frac{2R}{L}$.

SCATTERING BY THE INPUT MIRROR m_1

$$\frac{dP_R(\theta)}{d\Omega\, P} = \frac{\alpha}{\theta^2} \qquad \alpha = 10^{-6}$$

ASSUME SPECULAR REFLECTION FROM WALL <u>WITH NO LOSS</u>.

$$\frac{P_{scat\ recombined}}{P} \cong \int_{\theta_{min}}^{\pi/2} \frac{\alpha}{\theta^2}\,\frac{2\alpha}{\theta^2}\,\frac{\lambda}{L}\,d\theta \simeq \frac{6^3\alpha^2}{\theta_{min}^3}\,\frac{\lambda}{L} = \frac{3}{4}\,\frac{L^2\lambda}{R^3}\,\alpha^2$$

FOR $L = 12$ meter

$R = 9'' \Rightarrow 23$ cm

$\alpha = 10^{-6}$

$$\frac{P_{scat\ recomb}}{P} \sim 4\times10^{-15}$$

THE ATTENUATION OF SCATTERED LIGHT IN THE INPUT MODE FILTER TUBE IS SUFFICIENT TO ALLOW FOR COHERENT SUPERPOSITION IN EQ 1.

b) TUBES INVOLVED WITH COUPLING SPLITTER CHAMBERS TO TEST MASS CHAMBERS

THE SCATTERING IN THESE TUBES COMES AFTER THE BEAM SPLITTER WHERE THE INTERFEROMETER BECOMES FIRST ORDER SENSITIVE TO PHASE FLUCTUATIONS INDUCED BY THE RECOMBINATION OF SCATTERED BEAMS WITH THE MAIN BEAM. THE EFFECT OF SCATTERING IN THIS REGION, BEFORE THE MAIN CAVITY, IS LESS SENSITIVE THAN IN THE MAIN CAVITY BY THE FINESSE OF THE CAVITY. THIS IS SEEN BY NOTING THAT, THE PHASE SHIFT IS APPROXIMATELY GIVEN BY

$$\Delta\varphi = \frac{\mathcal{E}_{\substack{\text{SCAT}\\ \text{RECOMBINED}}}}{\mathcal{E}_{\text{MAIN}}}$$

WHICH IS TRUE BOTH INSIDE AND OUTSIDE OF THE MAIN CAVITY, THE BUILD UP OF THE FIELD IN THE CAVITY INCREASES BOTH NUMERATOR AND DENOMINATOR. THE IMPORTANT DIFFERENCE IS THAT A PHASE SHIFT IN THE BEAM OUTSIDE OF THE CAVITY IS INTERPRETED AS A CAVITY MIRROR DISPLACEMENT OF $\Delta x_m = \frac{\Delta\varphi_{\text{OUTSIDE}}\,\lambda}{2\pi \quad F}$ WHILE A PHASE SHIFT OF THE TOTAL BEAM INSIDE THE CAVITY IS INTERPRETED AS A MIRROR MOTION

$$\Delta x_m = \frac{\Delta\varphi}{2\pi}\lambda$$

AS A CONSEQUENCE THE INFLUENCE OF A SCATTERED FIELD RECOMBINED WITH THE MAIN BEAM IN THESE COUPLING TUBES IS LESS IMPORTANT BY A FACTOR $1/F$

F WILL BE 30 (1KHz ANTENNA) → 300 (100Hz ANTENNA)

ESTIMATE OF $h(f)$ LIMIT DUE TO SCATTERING IN THE COUPLING TUBES <u>NO BAFFLES</u>

WITHOUT EXIT MODE FILTER

$$h(f) \sim \sqrt{\frac{2}{3}}\,\frac{\alpha^{1/2}(1-\eta)}{F^2}\left[\left(\frac{\lambda L_{\text{MAIN}}}{R}\right)^{1/2}\right]^{3/2}\theta_{\text{MIN}}\,\mu(f)$$

KST 3.21 MODIFIED

$L_{\text{MAIN}} = 4\,\text{Km}$ (BEAM HAS BEEN EXPANDED)

R = RADIUS OF COUPLING TUBE = 15" = 38.Cm

$\mu(f) = 2\times10^{-9}/f \; \frac{\text{RADIANS}}{\text{Hz}^{1/2}}$ AMPLITUDE OF TUBE SLOPE SPECTRUM

$h(f) = 8 \times 10^{-19}/f$ **NOT ADEQUATE**

WITH EXIT MODE FILTER

$$h(f) = \frac{2}{\sqrt{2}} \frac{\alpha}{F^2} \left[\frac{(\lambda L_{\text{mode}})^{1/2}}{R}\right]^{3/2} \left[\frac{\lambda}{L}\right]^{1/4} \theta_{\text{min}}^{1/2} \mu(f)$$

KST $\underset{\text{MODIFIED}}{3.23}$

$$= 1.1 \times 10^{-22}/f$$

NOT ADEQUATE

CONCLUSION COUPLING TUBES NEED TO BE BAFFLED OR BLACKENED

NOT SURE THAT EXTENDING KST CALCULATION TO THIS SHORT TUBE WITH VERY DIFFERENT L/R IS CORRECT HOWEVER - THE BEAM DIAMETER IS LARGER IN THIS TUBE AND THERE ARE 3 SCATTERING AND RECOMBINING SURFACES IN THE OPTICAL TRAIN.

$\left\{\begin{matrix}\text{BLACKENING}\\ \text{BAFFLING}\end{matrix}\right\}$ SHOULD IMPROVE THE LIMITS BY A FACTOR OF 10^5 FOR BOTH CASES: WITH AND WITHOUT OUTP. MODE FILTER.

THE BAFFLING SHOULD BE DESIGNED TO AVOID DIRECT REFLECTION FROM THE WALL BETWEEN THE MIRRORS. IN THIS SHORT TUBE ONE CAN'T USE THE SAME STRATEGY AS IN THE LONG BEAM PIPES. THE BAFFLES AND WALL SHOULD BE BLACK. I WILL HAVE TO CHECK IF CORRUGATING THE WALLS HELPS HERE

c) THE OUTPUT TUBES

THESE TUBES ARE A SPECIAL CASE. THE LIGHT INTENSITY IS LOW WHEN THE INTERFEROMETER IS LOCKED WHICH MAKES THE SCATTERED LIGHT MORE CRITICAL SINCE THE MAIN BEAM IS REDUCED IN INTENSITY BY

$$I_{ANTISYM.} = (1-c)\, I_{IN} .$$

c IS THE CONTRAST OF THE FRINGES DEFINED AS

$$c = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}}$$

WHERE I_{MAX} IS THE INTENSITY ON A BRIGHT FRINGE
I_{MIN} IS THE INTENSITY ON A "DARK" FRINGE

THE HOPE IS TO HAVE $1-c < 0.1$

THE PHASE SENSITIVITY TO SCATTERED LIGHT IS DOWN BY A FACTOR $1/F$ RELATIVE TO THE SCATTERING IN THE MAIN BEAM TUBES.

AS OF 4AM 3/15/89 NO GOOD ESTIMATE IS YET AVAILABLE OF THE EFFECT OF SCATTERING IN THIS REGION OF THE LIGO. THE EXPECTATION IS THAT SCATTERING MAY BE TROUBLESOME.