**New Folder Name** Test Mass Design

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# Test Mass Design

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**Abstract**

After reviewing the status of specifications for LIGO monolithic test masses (Section 2), we list the steps that are needed in order to define the specifications (Section 3).

## 1 Introduction

The use of monolithic test masses is assumed for the initial LIGO interferometers. Since they are the "front end" of the interferometer towards the gravity waves, the mechanical design has to ensure that their intrinsic displacement noise is compatible with the initial sensitivity goal. The test masses at the inputs to the 4 km cavities are also optical elements, since they are traversed by the light beams; their optical properties should be such as to allow for the phase sensitivity necessary to measure the change in interferometer arm length that corresponds to the initial sensitivity goal.

Section 2 lists the already known test mass specifications and the test mass parameters that are still unspecified, accompanied by short explanations of the way they relate to displacement and phase noise. Section 3 proposes a sequence of steps for generating test mass specifications from the optical and mechanical requirements.

## 2 Test Mass Parameters

The parameters of the test masses are listed in Table 1, with nominal specifications.

| Parameter | Value |
|---|---|
| Material | Fused silica |
| Density of defects | TBD |
| Reflective coating loss | $\leq$50 ppm |
| Reflective coating absorption | TBD |
| Coupler transmission | 1.3% |
| Coating uniformity | TBD |
| Loss at AR coating | $\leq$100 ppm |
| Coating diameter | 18 cm |
| Test mass diameter | 20 cm |
| Test mass wedge | TBD |
| Test mass thickness | TBD |
| Surface figure | TBD |
| Test mass front microroughness | 0.1 nm rms |
| Test mass back microroughness | 0.3 nm rms |
| Curvatures | 3 km, 1.5 km |

Table 1: Test mass parameters

### 2.1 Material

After having reviewed a range of materials, we believe that fused silica is the best suited for LIGO test masses. Fused silica is more homogeneous than other optical materials and has very low residual birefringence[1]. Two samples of Corning fused silica 7940 have been subjected to interferometric tests at Zygo Corp.; analysis of the data by M. Burka shows that the actual measured parameters are slightly better than the specs.

Other parameters are:

[1]index of refraction inhomogeneities less than $10^{-6}$ and residual birefringence less than 1 nm/cm for fused silica 7940, grade 0A made by Corning

- Density and size of bubbles and inclusions

  These defects distort and scatter the light beam [2] and thus reduce contrast at the beam splitter directly, and also indirectly, by degrading the mode matching between the beam and the cavities. To specify this parameter, the amount of scattering and beam distortion have to be estimated.

- Absorption

  Measurements in our lab, at $\lambda = 514.5$ nm, on a sample of the best grade fused silica, yielded an upper limit on absorption consistent with $\sim 50$ ppm/cm [3].

## 2.2 Coatings

- Loss: $\leq 50$ ppm
- Absorption: TBD such that the beam distortion due to heating does not preclude achieving the specified recycling factor.
- Transmission: consistent with highest possible reflectivity, for the far test mass, and $T = 1.3\%$ for the coupler[4].
- Coating uniformity: TBD by computer simulation. Non-uniform coatings affect contrast.
- Antireflection coatings should be provided on the non-reflective side for both the far mass and the coupler. The lowest possible reflectivity of $\sim 100$ ppm should be required.
- Coating diameter: 18 cm. This allows the beam to be moved off center by $\sim 2$ cm while diffraction losses are kept below 1 ppm[5].

[2] when it passes through the test mass that acts as coupling mirror

[3] further measurements should be carried out, in order to learn what the absorption really is

[4] corresponding to a storage time of 2 ms (December 1989 Proposal, henceforth to be referred to as Proposal)

[5] calculation by R. E. Spero

## 2.3 Mechanical Parameters

- Diameter: 20 cm (Proposal)
- Wedge: TBD e. g. such that the beam reflected off the back of the test mass will not interfere with the main beams. The actual lay-out of interferometer components has to be known.
- Thickness: TBD taking into account the following:

  1. Bulk absorption and thickness dependent effects that degrade contrast (birefringence, inhomogeneity, thermal lensing) should be kept at a level were the recycling factor 30 (Proposal) is not compromised.
  2. The frequency of the lowest acoustic modes of the mass should still be high enough, so that thermal noise is kept at a reasonable level.
  3. Distortion of the suspended mass under its own weight should not affect adversely the surface figure specification (see below).
  4. Type of suspension.
  5. Coating chamber constraints.
  6. Delivery time and cost constraints.

- Surface figure: TBD by computer simulation so that it is consistent with contrast requirements set by the recycling factor 30 and with the requirement for mirror losses $\leq 50$ ppm.
- microroughness: 0.1 nm rms on the front[6], 0.3 nm rms on the back.
- Curvatures: 3 km for full length interferometers, 1.5 km for the half length interferometer (Proposal).

[6] typical microroughness for substrates used to make mirrors with losses $\sim 30 - 50$ ppm

# 3 Proposed Design Work

It follows from Section 2 that some test mass parameters still need to be specified:

1. Density of defects (bubbles and inclusions)

2. Coating absorption

3. Coating uniformity

4. Wedge

5. Thickness

6. Surface figure

In order to define the above parameters, we suggest that the following work be carried out:

- Refinment of the statistical model of a transparent test mass [7], to include bubbles and inclusions, an uneven surface and a nonuniform coating.

- Use of the statistical model in conjunction with a wavefront tracing code (GLADV) to estimate the effect of the various imperfections upon mode matching and contrast.

- Specify the uniformity of the coating to achieve the desired recycling factor.

- Estimate the thermal lensing and other causes of wave front distortion caused by absorption in the coating and in the bulk of the test mass; estimate the resulting degradation of fringe visibility, then further estimate its effect on interferometer sensitivity. This may set an upper limit to test mass thickness.

[7] developed by M. Burka, using the Zygo test data

- Use a wavefront tracing code in order to estimate the effect of test mass (mirror) surface figure errors upon cavity losses and coupling of transverse test mass motions into the interferometer signal. Determine the surface figure consistent with the sensitivity goal.

- Consider a model suspension and check that deformation of the test mass under its own weight does not spoil the required surface figure, homogeneity and birefringence properties.

- Analyze the acoustic mode patterns and frequencies. Optimize the test mass thickness to balance contrast loss due to inhomogeneity and birefringence against noise due to thermal excitation of the the acoustic modes of the mass.

- Determine the wedge angle.

- Check with the manufacturers whether delivery times and costs for the blank, the polishing and the coating are not prohibitive, and if, indeed, it is practical to make test masses at the specifications resulting from the above analysis.

- In order to test the design procedure and the resulting test masses, specify a set of test masses appropriate for use with the 40 m prototype (see the Appendix).

## Appendix: Test Masses for the 40 m Prototype

Specifying monolithic test masses for the 40 m system is different from specifying LIGO test masses in several respects:

- It is imperative to test monolithic test masses in the 40 m prototype before going ahead full steam with the ordering of LIGO test masses, in order to check the design procedure and the suitability of the test mass material.
- Computer simulation[8], using data provided by the Zygo test, suggests that homogeneity of fused silica is appropriate for test masses of the size currently used in the 40 m prototype, in the sense of allowing a recycling factor of $\sim 25$.

In view of the above and considering the long lead time involved, we recommend that 4" diameter, 3.5" thick test masses[9] made of fused silica be ordered as soon as possible, after evaluation of the following items:

1. Loss of contrast due to birefringence.
2. Thermal lensing due to absorption in the test mass and its effect on coupling the laser beam into the cavity.
3. Estimate of stress birefringence, induced by heating due to absorption in the test mass and by the weight of the mass.
4. Estimate of surface figure error due to deformation of the test mass under its own weight.

Upon receiving the polished substrates, they should be subjected to interferometric homogeneity and birefringence tests and to a direct beam distortion test.

Before installation into the 40 m prototype, the coated test masses should be subjected to the standard battery of mirror tests.

[8] by M. Burka

[9] same as for current prototype test masses