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Core Optics Components Conceptual Design (1.06 μm)

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COC-DRR review board

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1 OVERVIEW

This document is to accompany the COC Design Requirements document (COC DRD: LIGO-E950099-01-D) as a package for presentation at the COC Design Requirements Review. Reference to sections of this DRD will be via a suffix “R” (viz. R3.2.1.1.3). Together these documents provide the fundamental guide for acquisition and implementation of the COC. This document specifies a design approach and fabrication and testing strategy which will produce COC whose performance satisfies the COC DRD requirements. The same conventions, acronyms, and assumptions stipulated (sections R1.3,4,5 and R2.4,5) in the DRD document are used here.

1.1. Ligo references (additional to R1.51)

1.1.1. COC Scalar Test Program LIGO-T960016-00-D0

1.2. Non-LIGO references (additional to R1.52)

1.2.1. C. Evans ,et. al., MS AO10260 and 9646 to be published in Applied Optics: Optical Technology (1996).

1.2.2. P. Hariharan, Opt. Eng. 35, 1 (1996).

1.2.3. Coating technology....

1.2.4. H. J. Kimball, ate al, Opt. Let., 17, 364, and 17, 640 (1992).

1.2.5. Z. L. Wu, Overview of photomurals..... (1995). Also: V. Loretta and C. N. Man (VIRGO), 8th Into. Topical MT. on Photoelectric and Photomurals Phenomena (1994).

1.2.6. V. Loretta, ate al, J. de Physique IV, C7-631 (1994)**.**

2 CONCEPTUAL DESIGN DESCRIPTION

A conceptual design for realizing the final COC will be discussed under the following headings. Section 3. will subsequently detail specifications under the same headings.

- Substrate materials
- Substrate processing (including polishing and figuring).
- Coatings
- Pathfinder mechanism
- Mounting, interfacing and stay clear considerations.
- Verification metrology
- Cleaning, handling and contamination.

2.1. Substrate material

FS will be the substrate material for all COC. The different physical type substrates are specified in table 1. Fine ground FS blanks are to be procured from suppliers of known high grade material according to the following considerations

2.1.1. Material types

two and possibly three^{TBD} types of FS will be needed to balance cost and requirement factors. This will possibly require more than one vendor to minimize cost.

2.1.1.1 ETM, RM, FM type (C)

here the transmissive properties are much less important and a nominally high bulk homogeneity quality material with no special absorption specification is adequate.

2.1.1.2 ITM type (B)

The ITM bulk material must have critical low and /or matched (arm to arm) inhomogeneity, scatter, and absorption for normal incidence beams. Silica produced by layered deposition technology (PF type) will be adequate.

2.1.1.3 BS type (A)

The adequacy of B type material for use with non-normal incidence beams is uncertain. Special “isotropic” process technology material may be necessary. The thinness of the BS (table R2) ameliorates this concern.

Table 1: Categorization of COC substrates

Physical Quantity	*Test Mass* *ITM*	*ETM*	*Recycling mirror*	*PF*	*Folding mirrors*	*Beam splitter*
Diameter of substrate, ϕ_s (cm)	25					
Substrate Thickness, d_s (cm)	10					4 **TBD**
Weight of Suspended Component (kg)	10.7					6.2
FS type	B	C				A^{TBD}
Wedge angle (Surf. 2)^{TBD}	≤3^o	≤ 3^o	≤ 3^o	2^o	≤ 3^o	< 1^o
R_{eff} (surface 1) 2000m IFO (km); sagitta (μm)	4.73 1.65	4.73 1.65	3.22 2.42	6.00 1.30	∞	
R_{eff} (surface 1) 4000m IFO (km); sagitta (μm)	7.4 1.06	14.54 0.54	5.03 1.55			

2.1.2. Blank sizes and selection

Material must be available in blank sizes which can be finished to the dimensions of table R2 in the type category of table 1.

2.1.2.1 BS size

The beam splitter blanks are for a single function, and are of unique thickness. The specification of this size blank can therefore be exacting.

2.1.2.2 xM size

All other COC are of the same size, but of differing material type. Some room will exist for special selection of individual blanks for specific IFO elements. For instance, amongst C type blanks, those designated for RM use would be selected for lowest central inclusion density.

2.1.3. Bulk homogeneity

Each procured blank will require measurement certification by the vendor to a certain columnar homogeneity (specific to size and type material).

2.1.4. Bulk scatter

For the high quality FS LIGO considers, bulk scatter is anticipated to be near the Rayleigh limit (~ 2 ppm/cm, at 1064 nm). This is will be inconsequential as a power loss (compare to R3.2.1.5.4), and will be > 100 times less than the anticipated TIS from the adjacent TM ER coatings.

2.1.5. Inclusions

For each material type an inclusion specification will be imposed on the vendor. To keep this specification manageable it will be stated as a limit on the total geometrical cross section of those inclusions within the central Gaussian diameter. These inclusions would have two effects:

- TIS of energy out of the TEM_{00} beam in an amount approximately equal to sum of their geometrical cross sections weighted by the local beam intensity.
- The [far field] distortion to the TEM_{00} wave front due to absences of small (~geometrical cross section) patches of wave front.

However it can be shown that for the LIGO geometry, the CD due to the latter mechanism is given as an upper limit by the former.

2.2. Substrate processing

In this category we consider all other fabrication to the COC exclusive of the coatings (2.3) and all suspension attachments (2.5). Two stages may be distinguished:

2.2.1. Shaping to final size and rough polishing

After all appropriate blank inspections, tests and selection steps, they will be shaped to final substrate form by grinding and rough polishing (over 100% of surface area). This polishing stage will be the final one for all surfaces except the surface #1 and #2 faces. At this stage the substrates will be brought to the form described in figure 1 (this figure is equivalent to the pathfinder specification with ITM R_{eff}. Wedge angle and R_{eff} will vary appropriately for other COC).

2.2.1.1 Shapes.

The basic shape of all COC elements is taken to be the right circular cylindar.The exact right circular cylindrical shape will be modified in three ways:

- xM secondary surface wedge, < 3^{o}. The exact wedge angle will be determined by analysis of the entire IFO configuration and beams layout. Preliminary results of this analysis indicate that each COC will likely require a different specific wedge angle. Note that this does not increase the multiplicity of finished COC substrates (uncoated) when taking into account the differing R_{eff}.
- BS secondary surface wedge, <1^{o}. this angle is constrained to be smaller due to the thinness of the substrate. For mechanical integrity the plate should not become less than 10% thinner at one edge. Asymmetric thermal (from laser beam absorption) distortion (potato chip) could also result[TBD].
- Standard optic edge bevel, ~ 45^{o}, ~2-3 mm width.
- All primary face surfaces except for BS and FM will have spherical form, given by the values in table 1 (these are the R_{eff} values in the general case of face figures containing other aberrations than power). Since the full face ϕ_s sagitta is only ~laser wavelength, it is TBD whether this spherical form will be initial generated in the rough polishing stage or will be an integral part of the final figuring (may depend on the choice of 2.2.2 process).

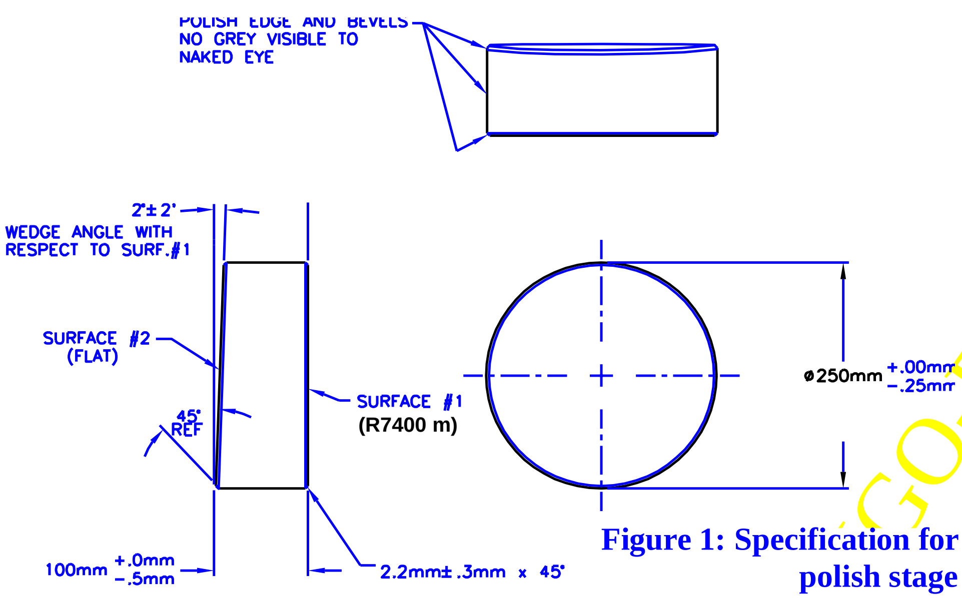


Figure 1: Specification for ITM to rough polish stage

2.2.2. Final precision polishing/figuring

All COC faces will be polished to a figure whose deviation from the exact values of table 1 is determined by the requirements of R3.2.1.4, as well as the final results of the PF process (2.4.2.1). In particular a final balance between specification of surface micro-quality (2.4.5.1) and figure errors awaits evaluation of actual process results. It is expected that some (and ideally sufficient for the requirements) level of interferometric testing of micro-quality and figure will be performed in process at this stage.

Our concept will be to have all faces finish polished to the most stringent specification implied by table R4 (i.e. that for the TM surface 1). In practice, since individual COC faces have sharply differing requirements, a strategy for selection of [partially] polished substrates ear marked as particular elements will be advantageous. Key to this will be adequate in process metrology.

2.3. Coatings.

All COC optical coatings are to be of the hard oxide dielectric type. The coating technique is to be sputter ion beam technology. It is known (1.2.3) that this technique yields the highest uniformity and lowest loss coatings. The coatings will be of two types:

2.3.1. ER (enhanced reflectivity) coatings.

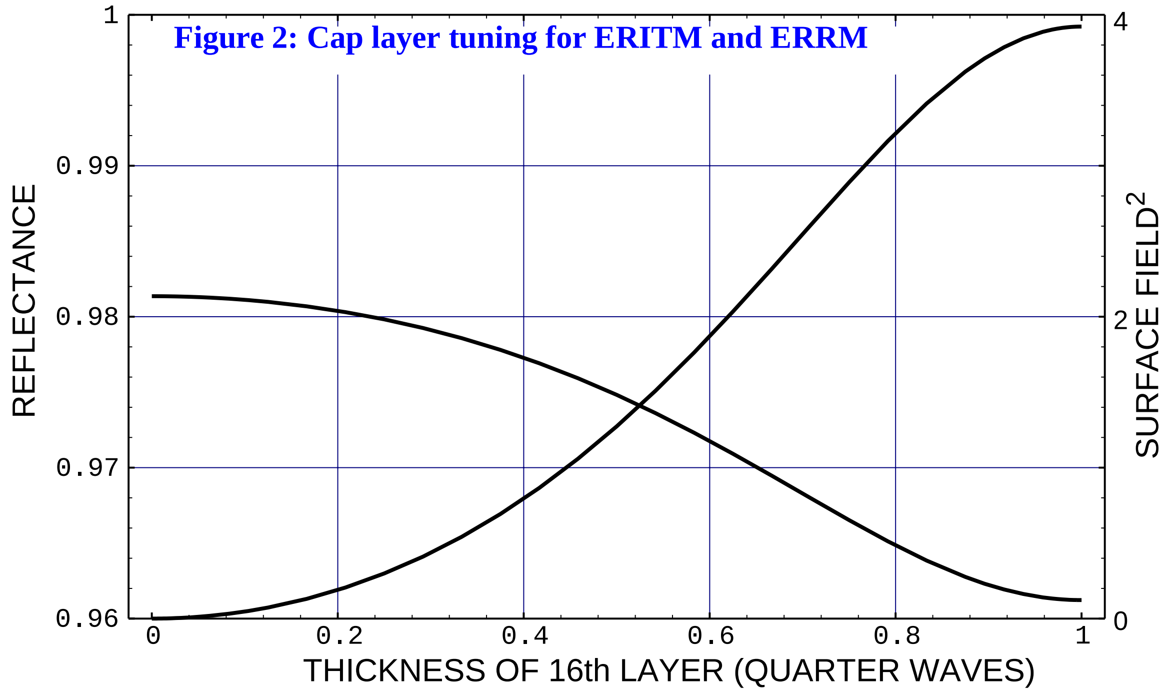
These coatings will provide front surface mirrors for the IFO cavities and the 50/50 beam splitter. They will be of multi quarter wave thickness stack design of up to 40 layers deep (in the ETM case). The design will be of alternating SiO_2 and Ta_2O_5 layers.

2.3.1.1 ERETM and ERFM

At 1064 nm a 40 layer stack coating would ideally give T= 10.6 ppm. It remains to be seen what practical transmissivities can be achieved (at 850 nm T< 2 ppm has been achieved, with 42 layers, 1.2.4). A remaining parameter TBD for this coating is the desirability of a low index (SiO_2) cap layer (standard practice has been a half wave layer for protection and to allow a field node at the surface).

2.3.1.2 ERITM and ERRM

In this case the number of quarter wave layers is dictated by the desired reflectivity (R =0.97 is best approached by a 16 layer quarter wave stack). The simplest method of tuning the stack to an arbitrary R would be to vary the top (SiO_2)“cap” layer thickness.



2.3.2. AR (anti-reflectance) coatings

These coatings will be on all secondary (wedged) surfaces. They serve to limit the beam power diverted to ghost reflections. The design will be two layers, of SiO_2 and Ta_2O_5, with appropriate thicknesses to meet the specifications of section R3.2.1.3.4.

2.4. Pathfinder mechanism

The COC design concept assumes that the requisite optics can be fabricated by existing techniques using industry fabrication facilities. A pathfinder (PF) process, whose purpose is to have full scale optics (illustrated in figure 1) fabricated, polished, coated and tested by existing techniques, will serve to verify whether this premise can be realized within the requirements, and under stipulated schedule and budget constraints. PF will be made up of:

2.4.1. FFT data

A closely related purpose of the pathfinder process is to provide reliable, absolute metrological data of all the optical imperfections of typical candidate COC which will accurately represent the actual optic's performance in FFT code modeling (R1.5.1.10).

2.4.2. Independent metrology (I and II)

The full optical aperture wave front distortions of the PF will be mapped by reflected and transmitted phase front interferometry at a designated independent metrology contractor. The design and development of this metrology is to provide the basis for eventual similar testing of production (2.6) COC. This will be performed in two phases:

2.4.2.1 Metrology I

The final polished PF test substrates will be absolutely surface mapped by reflection interferometry before any coating. Transmission OPD maps will similarly be made through the bulk substrates at normal incidence (to surface 1).

2.4.2.2 Metrology II

The measurements of 2.4.2.1 will be repeated on the same final coated PF substrates. In order to implement this program with existing metrology interferometers it will be necessary that the PF coatings for this work be designed for 633 nm (HeNe) light. Analysis shows that such measurements with HeNe interferometers cannot yield unambiguous results when performed on 1064 nm coatings.

2.4.3. Polishing selection

One or two PF substrates will be finished polished and figured (to stage of 2.2.2) by prospective vendors. At least one flat and one radiused surface will be produced. The vendors will be encouraged, but not required to apply their best metrological capability to describe their finished surfaces. The final arbiter of all the polished PF surfaces will be 2.4.2. and 2.4.5.1.

2.4.4. Coating development

The coating of PF and eventually of the COC will be performed by REO. A contracted coating development program will be performed. Coatings meeting the requirements of R3.2.1.4.4,and R3.2.1.5.2,3 have been achieved by REO on small diameter surfaces (< 2 cm). The development program will verify that coatings of the same quality and uniformity can be produced on COC scale surfaces. It is anticipated that the exact specification of the COC coating designs (e.g. numbers of layers, cap layer desirability, AR design, BS design) will be arrived at during this phase. REO will also provide test samples of coatings needed for related tests (2.4.2 and 2.4.5).

2.4.4.1 Coating of PF substrates

Most PF substrate faces (including all radiused faces) are to be coated with 34 layer ER stacks tuned for R_{max} at 633 nm. The crucial issues of multilayer stack uniformity over large diameters should not depend on the exact wavelength and layer design. The remaining faces should be representative 633 nm AR and 1064 nm 40^{TBD}layer ER coatings. 1064 nm ER coatings are desirable to directly confirm the scattering loss (cannot be extrapolated from 633 nm measurements) of mirrors with COC candidate substrate surface micro-quality.

2.4.5. Scalar tests

Measurements needed to confirm performance of the PF optics other than those in 2.4.2 will be performed by a combination of in house (LIGO facilities) tests and contracted measurements (see 1.1.1 for an outline).The scope of these measurements remains TBD. The infrastructure and methodology of these tests are to provide the basis for 2.6.2. The essential areas of testing to be performed are:

2.4.5.1 Micro-roughness/diffuse scatter

The micro-quality of the PF final polished surfaces must be measured. This needs to be done directly or correlated to a scale that provides a measure of the diffuse surface scatter loss to be expected from such surfaces in the LIGO IFO. A comparison of un-coated surface profile with subsequently coated surface TIS will be undertaken, using standard test samples. These standards can then be used to categorize the diffuse scatter of coated PF faces (1064 nm).

2.4.5.2 Bulk Absorption

Final choice of ITM and BS FS is TBD. Primarily this is due to uncertainty about the level of absolute bulk absorption (1064 nm) dissipated as heat. A program will be conducted to establish the full extent of knowledge in this regard, and possibly to conduct new measurements on representative FS samples (using the photo thermal method 1.2.5). Warranted measurements will be performed at outside laboratories.

2.4.5.3 Surface (coating) properties

Here, measurements will be performed on 1064 nm coatings exactly duplicating the anticipated COC designs (where necessary on specially coated samples). Some measurements may be at 633 or 514 nm due to the insensitivity of the measurement to wavelength (e.g. AR reflectivity), coating availability (e.g. 633 nm PF final coatings, per 2.4.4.1), or laser sources.

2.4.5.4 Blemishes

Individual scatter centers on both coated and uncoated faces will be identified (at least statistically). Methodology will be appropriate to reveal their origin (e.g. poor substrate surface micro-quality, coating run problem, etc.) and become the basis for process control in COC production.

2.4.5.5 Q measurements

These are to be adequate to assure that Q's of PF substrate internal mechanical modes are maintained sufficiently high through the various stages of COC processing so that the thermal noise requirements of R3.2.1.2 can be satisfied (h_{equiv} @100Hz ~ $Q^{-1/2}$).

2.5. Mounting and Stay-clear

COC will finally be used in the mounted configuration illustrated in figure 3. Strictly the components shown, other than the coated COC substrate itself are excluded from this design. however crucial account of this mounting must be taken in the following respects:

2.5.1. Effect of appendages on Q.

The expected degradation of substrate mechanical Q (R3.2.1.2.2.3) must be carefully monitored. The PF optics will be used for this purpose after all optical tests have been performed.

2.5.2. Adhesive contamination

Thorough studies will be performed to assure compatibility of adhesives and methodology used to interface COC (R3.2.2.1) with COC cleaning procedures and requirements for limiting long term contamination. The candidate procedures and materials will all be tested on fully dressed PF optics under LIGO operational conditions.

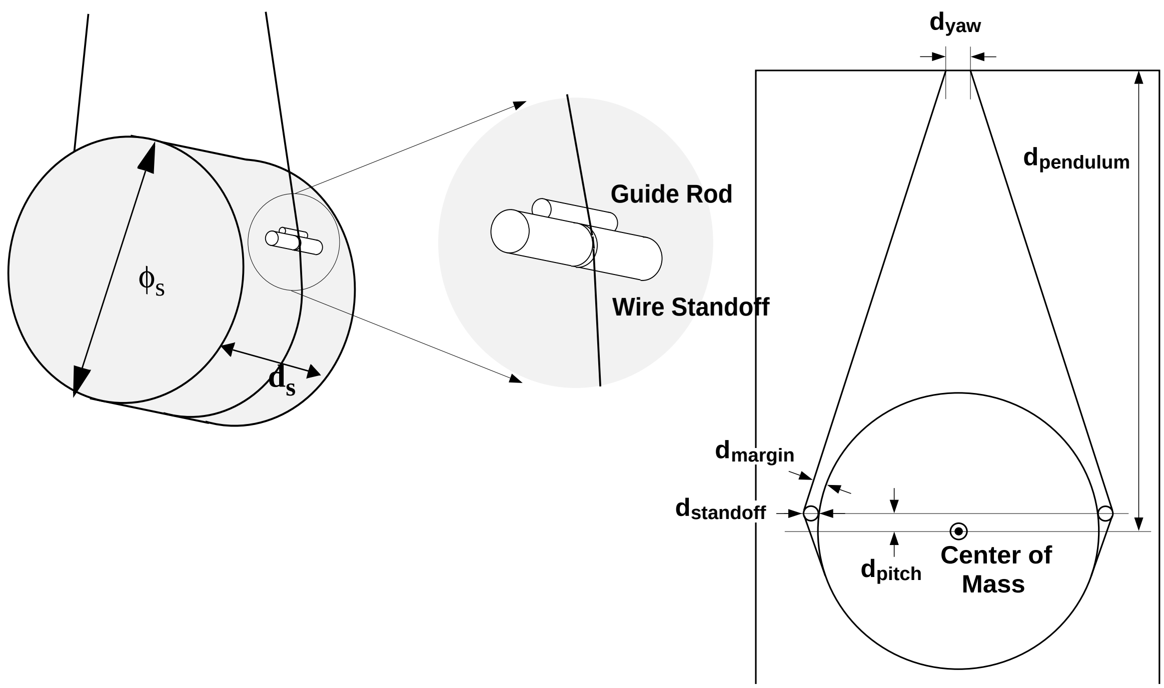


Figure 3: COC, as suspended

2.5.3. Stay-clear

For all COC suspension components must be designed to stay adequately clear of the beam envelopes adjacent to the substrates.

2.5.3.1 ETM

This element presents no problem, since only the primary surface is of critical concern. Actuator magnets, OSEMs, and any close proximity support structure can be arranged to be at the secondary (AR) face side.

2.5.3.2 ITM

This element requires critical stay clear on both faces, but the beam foot print is smaller here. The situation is illustrated in figure 4, where it is apparent that an adequate margin exists.

2.5.3.3 BS

The situation here is complicated by the 45^{o} incident beams. The farthest beam extents are shown in figure 4. Properly oriented OSEM arrangements will be possible.

Figure 4: AR face of BS and ITM with 10 ppm beam foot prints.

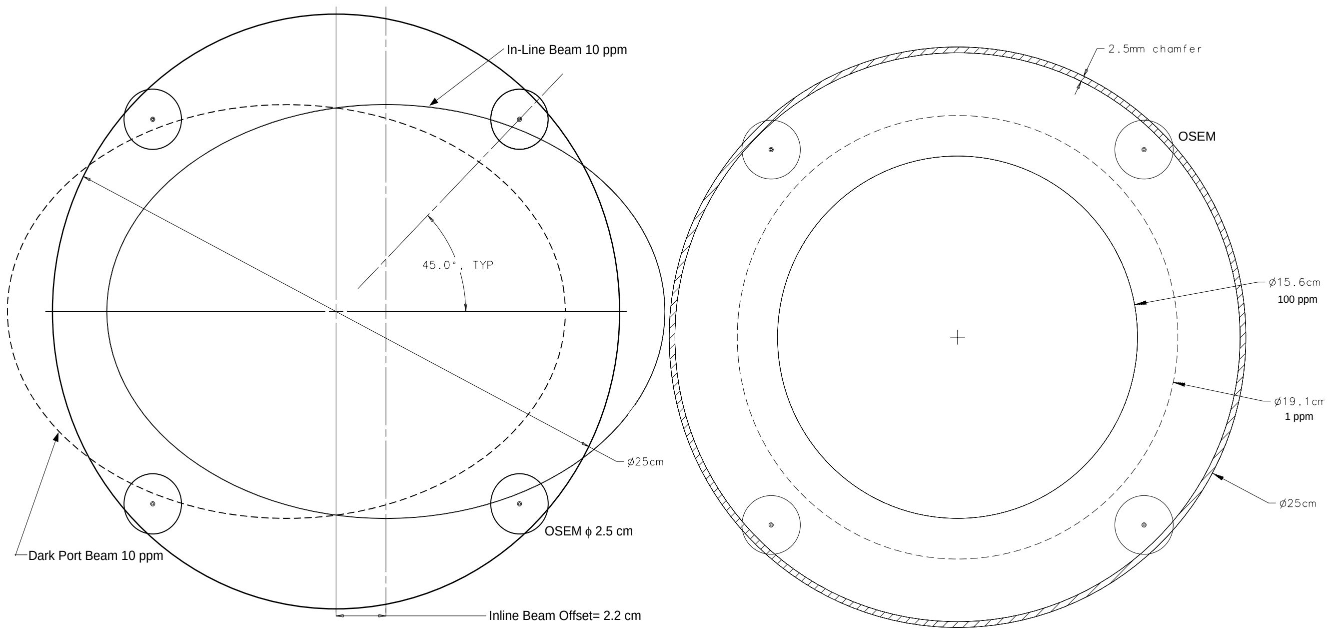
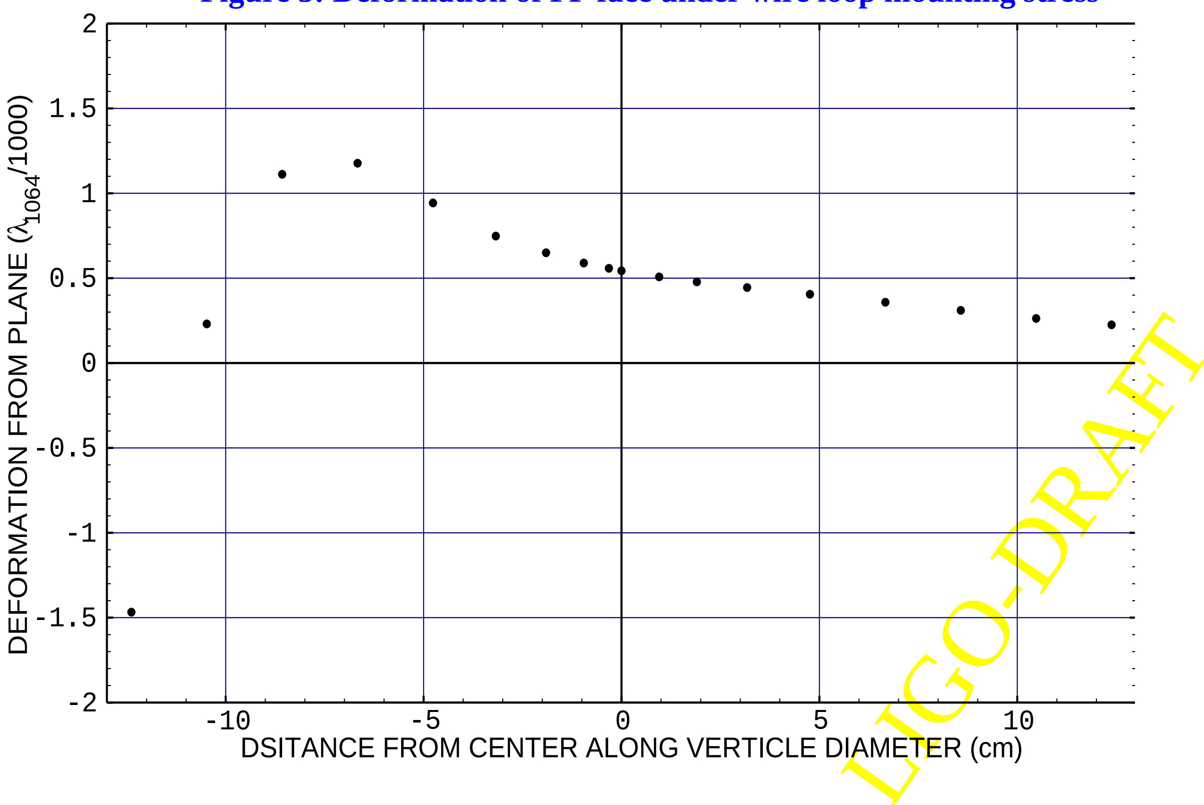


Figure 5: Deformation of PF face under wire loop mounting stress



2.5.4. Gravitational loading strain

The wire loop suspension laces a highly asymmetric stress on the COC. The ideal elastic strain induced has been studied by FEA. A profile of the resulting face profile deformation is illustrated in figure 5. Although within the figure requirements for TMs (R3.2.1.4) this deformation is perhaps observable and may need to be taken into account in metrology (i.e. mounting design for 2.4.2) and FFT modeling.

2.6. Verification metrology

Technical development through the PF mechanism should allow all production COC to be specified and measured to a level satisfying the optical performance requirements. Several measurements will be developed beyond the PF level to be better suited to volume measurement of the final COC.

2.6.1. Automated mirror parameter measurement

It will be desirable to fully characterize COC by automated scan measurements of their (coated) faces. This would include blemish mapping, reflecivity, transmission and surface scatter. This program will be fully developed for 1064 nm.

2.6.2. 1064 nm phase front interferometry.

To take advantage of available facilities, PF metrology (2.4.2) is to be conducted at 633 nm. Proper verification of the 1064 nm production coatings should be done with 1064 nm phase front interferometers. Plans exist to develop these facilities

2.6.3. QC program

It will not be possible to fully study each COC surface for all important optical properties. A strategy for effective QC sampled measurements must be arrived at to monitor the polishing and coating fabrication on a rapid enough time scale to catch problems in process.