

# Manufacturing process for the WEAVE Prime Focus Corrector optics for the 4.2m William Herschel Telescope

Emilie Lhomé<sup>1a</sup>, Tibor Agócs<sup>b</sup>, Don Carlos Abrams<sup>a</sup>, Kevin M. Dee<sup>a</sup>, Kevin F. Middleton<sup>c</sup>, Ian A. Tosh<sup>c</sup>, Attila Jaskó<sup>d</sup>, Peter Connor<sup>e</sup>, Dave Cochrane<sup>e</sup>, Luke Gers<sup>e</sup>, Graeme Jonas<sup>e</sup>, Andrew Rakich<sup>2e</sup>, Chris R. Benn<sup>a</sup>, Marc Balcells<sup>a</sup>, Scott C. Trager<sup>f</sup>, Gavin B. Dalton<sup>c,g</sup>, Esperanza Carrasco<sup>h</sup>, Antonella Vallenari<sup>i</sup>, Piercarlo Bonifacio<sup>j</sup>, J. Alfonso L. Aguerri<sup>k</sup>

<sup>a</sup>Isaac Newton Group of Telescopes, Calle Alvarez de Abreu, 70, E-38700 Santa Cruz de La Palma, Canary Islands, Spain; <sup>b</sup>NOVA Optical Infrared Instrumentation Group at ASTRON, P.O. Box 2, 7990 AA Dwingeloo, The Netherlands; <sup>c</sup>RAL Space, STFC Rutherford Appleton Laboratory, Harwell Oxford, OX11 0QX, UK; <sup>d</sup>Konkoly Observatory, Hungarian Academy of Sciences, H-1121 Budapest, Konkoly Thege Miklós út 15-17, Hungary; <sup>e</sup>KiwiStar Optics - Callaghan Innovation, 69 Gracefield Road, P.O. Box 31-310, Lower Hutt 5040, New Zealand; <sup>f</sup>Kapteyn Institut, University of Groningen, Postbus 800, NL-9700 AV Groningen, The Netherlands; <sup>g</sup>Department of Physics, University of Oxford, Keble Road, Oxford, OX1 3RH, UK; <sup>h</sup>INAOE, Luis Enrique Erro # 1, Santa María Tonanzintla, 72840 Puebla, Mexico; <sup>i</sup>INAF, Astronomical Observatory of Padova, Vicolo dell'Osservatorio, 5, 35141 Padova PD, Italy; <sup>j</sup>GEPI, Observatoire de Paris, PSL Research University, CNRS, Université Paris Diderot, Sorbonne Paris Cité, 5, place Jules Janssen, 92195 Meudon, France; <sup>k</sup>Instituto de Astrofísica de Canarias, C/ Vía Láctea, s/n, E38205 La Laguna, Tenerife, Spain.

## ABSTRACT

In this paper, we detail the manufacturing process for the lenses that will constitute the new two-degree field-of-view Prime Focus Corrector (PFC) for the 4.2m William Herschel Telescope (WHT) optimised for the upcoming WEAVE Multi-Object Spectroscopy (MOS) facility. The corrector, including an Atmospheric Dispersion Corrector (ADC), is made of six large lenses, the largest being 1.1-meter diameter. We describe how the prescriptions of the optical design were translated into manufacturing specifications for the blanks and lenses. We explain how the as-built glass blank parameters were fed back into the optical design and how the specifications for the lenses were subsequently modified. We review the critical issues for the challenging manufacturing process and discuss the trade-offs that were necessary to deliver the lenses while maintaining the optimal optical performance. A short description of the lens optical testing is also presented. Finally, the subsequent manufacturing steps, including assembly, integration, and alignment are outlined.

**Keywords:** astronomy, ground-based telescope, multi-object spectroscopy, optical design, prime focus wide-field corrector, atmospheric dispersion corrector, large-size lens manufacturing and testing.

## 1. INTRODUCTION

WEAVE (WHT Enhanced Area Velocity Explorer) is the next-generation wide-field Multi-Object Spectroscopy (MOS) facility for the 4.2m William Herschel Telescope (WHT) at the *Roque de Los Muchachos* observatory on La Palma in the Canary Islands.

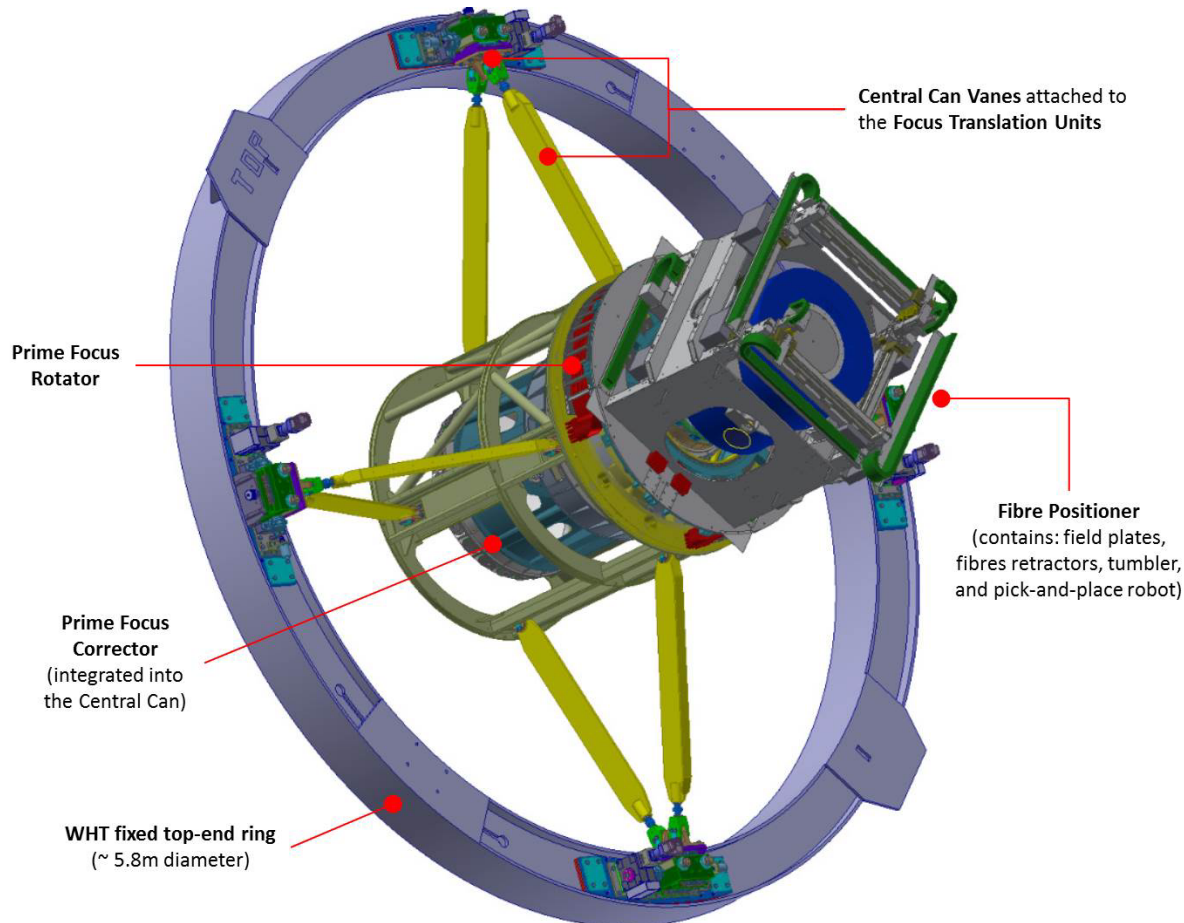
The instrument comprises a new two-degree field-of-view optical Prime Focus Corrector (PFC) with a 950-multiplex pick-and-place fibre positioner integrated into a new top-end focusing assembly<sup>[8]</sup> (Figure 1) and feeding a dual-beam spectrograph that will provide full coverage of the majority of the visible spectrum in a single exposure at a spectral resolution of ~5000 or modest wavelength coverage in both arms at a resolution ~20000.

---

<sup>1</sup> [elhome@ing.iac.es](mailto:elhome@ing.iac.es)

<sup>2</sup> now at GMTO

The WEAVE MOS instrument is expected to be on-sky for the beginning of 2018 and will provide unique capabilities in the Northern hemisphere for scientific exploitation of European-led surveys, e.g. spectroscopic follow-up of the fainter end of the Gaia astrometric catalogue, chemical labelling of stars to  $V \sim 17$ , and spectroscopic analysis of substantial numbers of sources from the medium deep LOFAR surveys<sup>[1], [2], [3], and [4]</sup>.



**Figure 1: A 3D opto-mechanical layout of the WEAVE instrument installed at the WHT prime focus assembly.**

This paper describes the process for delivering the six PFC lenses, from the optical design prescriptions (section 2), through the manufacturing trade-offs for the blanks and lenses (section 3), to the as-built feedback and design re-optimisation (section 4). The optical testing is detailed in section 5 and a short description of the lens mounting and alignment philosophy is outlined in section 6.

Throughout this paper, the six glass blanks are named B1, B2, B3, B4, B5, and B6. The six lenses built from these blanks are respectively labelled L1, L2, L3, L4, L5, and L6.

The six blanks are already delivered and the six lenses are currently being manufactured.

## 2. OPTICAL DESIGN CHARACTERISTICS

The new Prime Focus Corrector (PFC) for the William Herschel Telescope (WHT) was specially designed for the WEAVE instrument. As the corrector will be located at the prime focus of the 4.2-meter diameter parabolic mirror of the WHT, the main purpose of the PFC is to correct for the geometrical aberrations in the two-degree field-of-view. The

light collected by the telescope primary mirror and transmitted through the PFC will be fed into  $950^3$  optical fibres (each fibre is 1.3 arcsec field-of-view diameter on-sky) configured in a 400-mm diameter focal plane. To ensure that sufficient star light is injected into each individual fibre, the PFC also includes an Atmospheric Dispersion Corrector (ADC) consisting of a pair of counter-rotating and air-separated doublets which compensate for atmospheric dispersion whilst the telescope is moving in elevation (see Figure 2).

To meet the science requirements, it has been determined that the PFC image quality (including star drift) must be better than 1-arcsec diameter (80% of the encircled energy) over a two-degree field-of-view diameter, over a wavelength range from 370nm to 1000nm, and for zenith angles up to 65 degrees (35 degrees elevation). This allocated budget includes the design performance as well as the manufacturing and alignment errors for the blanks and lenses<sup>[5], [6], and [7]</sup>. Furthermore, the PFC must perform within a thermal environment ranging from  $-5^{\circ}\text{C}$  to  $+25^{\circ}\text{C}$ .

The WEAVE PFC is a unique and innovative optical system, based on non-standard lenses. Not only are the optical elements large (the manufacturing limit for “standard” optics is about 600mm), but each of the lenses has at least one challenging feature:

- The lens L1 is a 230kg meniscus of 1.1m diameter.
- The large diameter of lens L2 and the long radius of curvature of its convex surface ( $\sim 6\text{m}$ ) make the lens wedge difficult to measure.
- The lenses L3 and L4 are wedged lenses with both surfaces tilted with respect to the PFC optical axis.
- The concave surface of lenses L5 and L6 is aspherical.
- The ADC units are rotating elements.

The main physical characteristics of the six PFC lenses are detailed in Table 1.

**Table 1: The main physical characteristics of the PFC lenses.**

	Lens L1	Lens L2	Lens L3	Lens L4	Lens L5	Lens L6
<b>Substrate</b>	Corning C79-80	Ohara S-BSL7	Ohara PBL1Y	Ohara PBL1Y	Schott N-BK7	Ohara SK1300
<b>Shape</b>	Surface 1: Convex Surface 2: Concave				Surface 1: Convex Surface 2: Concave asphere	
<b>Diameter (mm)</b>	1100	661	632	602	612	586
<b>Central thickness (mm)</b>	116	68	65	65	68	97
<b>Radius of curvature (mm)</b>	880.3	5624.7	604.4	1677	1696.2	591.7
	918.9	606.8	595.4	1659.5	3620.8	5948.2

The optical layout of the PFC is described in Figure 2. The ADC comprises two distinct counter-rotating units; ADC1 consists of lenses L2 and L3, and ADC2 of lenses L4 and L5. The back focal distance (BFD) is an external interface constraint as the focal plane is constructed in the system which positions the fibres on the field plate. The beam aperture delivered by the PFC is F/2.8 (the beam aperture at the bare prime focus of the 4.2m WHT is F/2.5).

<sup>3</sup>The average of the number of MOS fibres on the two plates (there are two plates; one with 960 fibres and the other with 940 fibres).

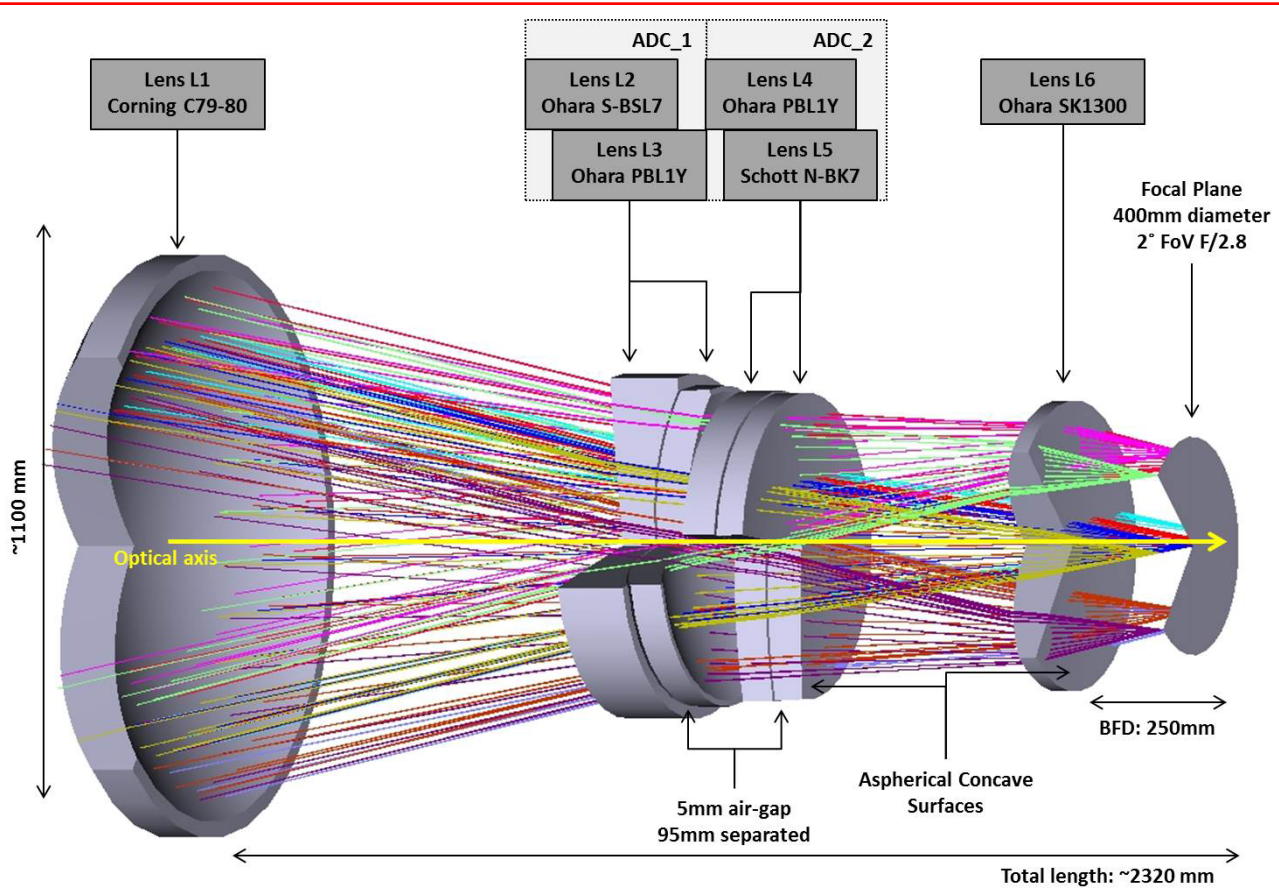


Figure 2: The optical layout of the WEAVE Prime Focus Corrector. The ADC doublets are counter-rotated by 35.5 degrees about the PFC optical axis (corresponding to a 53-degree telescope elevation). The lenses are  $\frac{3}{4}$  drawn for a better representation of the ADC counter-rotation angles.

### 3. MANUFACTURING TRADE-OFFS FOR BLANKS AND LENSES

The Prime Focus Corrector was designed in such a way that it provides high flexibility in terms of relaxation of manufacturing tolerances, as-built re-optimisations, and availability of compensators.

The optical design went through a final design review process in the first stages of the WEAVE project, allowing early procurement of the six glass blanks which had significantly long production times when compared to the global WEAVE project timeline.

The performance of several optical designs was assessed, leading to a choice of combinations of glass materials for the ADC lenses. Because the blanks were very large and the lenses were demanding to manufacture, then it was decided to enter into discussions with glass vendors to review the main optical prescriptions. Simultaneously, discussions were initiated with lens polishers to assess the compromises between image quality and manufacturability.

#### 3.1. Manufacturing specifications for the blanks

##### 3.1.1. Choice of glass material

The greatest challenge was the production of high-quality glass blanks with a high homogeneity of refractive index. After several discussions with selected glass vendors, it was necessary to review and relax the initial specifications because they were deemed to be too demanding especially for such large pieces of glass. As a compromise between manufacturing risks, costs, and time versus optical performance, it was decided to aim for a homogeneity grade of 10 ppm peak-to-valley (PV) or  $\pm 5 \times 10^{-6}$  PV, corresponding to a class 2 according to the ISO 10110 standards (class 5 being the best grade achievable).

The lenses L1 and L6 were chosen to be made from fused silica as this material offers excellent glass properties, mostly due to the well-controlled manufacturing process:

- Even for such large blanks, the homogeneity of fused silica is generally of a higher grade than standard amorphous glasses.
- Fused silica has an excellent internal transmittance close to 99.9% leading to better instrument throughput.
- As lens L6 is the closest lens to the focal plane, a substrate made from fused silica, with its greater internal quality (i.e. fewer bubbles), reduces stray-light issues.
- Fused silica is a material that is relatively quick and easy to manufacture compared to standard amorphous glasses (no annealing process is required).
- The manufacturing of fused silica is a well-controlled process and the quality variation between batches is negligible. Therefore, most of the glass properties can be taken as per catalogue, and no melt-fit re-optimisation is required.

To correct for atmospheric dispersion, the design of the ADC requires a combination of a crown (such as lenses L2 and L5) and a flint (such as lenses L3 and L4) glasses. Several combinations of ADC materials were evaluated, and the choice was driven by the available glasses on the market at that time. To achieve the required homogeneity grade for such large amorphous glasses, two annealing processes were required leading to a rather long delivery time.

### 3.1.2. Size of the glass blanks

The diameter and thickness of each blank were calculated to ensure that just enough material was available to manufacture the lens. Indeed, over specifying the diameter and thickness of a blank would have led to a large quantity of useless glass material to be removed at the beginning of the lens manufacturing process, thus increasing the lead time and associated risks and costs.

In the case of the ADC lenses, the blank thickness also included an extra margin to account for the edge thickness difference (wedge-induced difference between the thinnest and thicker edge of the lens).

The diameter of a blank was specified so that a comfortable margin (about 4% of the lens diameter) could be included beyond the lens clear aperture, allowing for:

- Optical design re-optimisation of the as-built lens radii of curvature (see section 4) which could lead to an increase in the lens clear aperture diameter.
- Polishing roll-off. To account for this effect, the clear aperture diameter specified for the polishing process was 2mm larger than the optical design foot-print.
- A flat annulus on the concave surface of the lens which will be used for handling and supporting during manufacturing and integration processes.
- The inclusion of chamfers to reduce potential defects on the lens edge (i.e. chips, cracks, etc.).
- The coating diameter was specified to be 2mm larger than the polished area.
- The gluing of the Room Temperature Vulcanising (RTV) mounting pads (silicon rubber) on the convex surface.

### 3.1.3. Shape of the glass blanks

The shape of the five blanks B2 to B6 was specified as plano-cylindrical. This made the manufacturing of the blanks easier for the glass vendors (as no specific shape machining was required), but the drawback was that the lens polisher had more material to remove, increasing the manufacturing time and risks as the blank needed more manipulations.

The market survey showed several technical limitations for manufacturing blank B1 as a cylinder. Because the lens L1 is a meniscus, this would have led to a very thick, heavy and large plano-cylindrical blank that no company was able to handle at that time. Also, the potential lens polishers were reluctant to work with a thick disk of that size as half of the material needed to be removed. The solution was to manufacture a blank using the sagging technique (also called slumping) such that the blank was pre-shaped very close to the final shape of the lens. This was also possible because the blank was made of fused silica so no melt-fit re-optimisation was required.

### 3.1.4. Homogeneity of the glass blank

The glass homogeneity of the six blanks was measured by interferometry and maps of the Optical Path Differences (OPD) showed that the required peak-to-valley (PV) variations of homogeneity in the substrate were delivered. Such OPD maps are to be used by the lens polisher to determine the required local polishing that needs to be applied on the lens surfaces.

Because of the large size of the substrates, all the blanks were tested in sub-aperture interferometry and the OPD maps were stitched together to build a full map of the refractive index homogeneity. The stitched clear aperture tested had to cover more than 90% of the blank diameter so that the clear aperture of the lens is also covered.

In the case of blank B1, as interferometry testing requires the blank to be plano-cylindrical, the measurement of homogeneity variations was performed before the sagging process. Thanks to several years of experience, the selected glass vendor was able to guaranty that the impact on the glass homogeneity by the sagging process was negligible.

As homogeneity is a function of glass thickness, it is then expected that the homogeneity of the finished lens is better than for its thicker blank. Also, as the lens thickness varies as a function of radial distance, then the homogeneity is not constant over the lens. It was then decided to use in the PFC error budget, the values of the blank homogeneity for the on-axis thickness of the lens. This then provides an upper limit and a margin for the total Transmitted Wavefront Errors (TWFE) relaxation (see 5.2.3).

### **3.2. Trade-offs for the specifications of the lenses**

#### **3.2.1. Edging of the lenses**

Due to some limitations of the optical design software used at that time, the precise modelling of the lens edges was not straightforward for the ADC lenses (because of their double-tilted surfaces), therefore, the lens edges were drawn along with the mechanical design of the lens cells.

The characteristics of the lens edges, specified in accordance with the lens polisher, include the following features:

- A reasonable chamfer, applied on both surfaces to reduce damage on the lens edge (i.e. chips, cracks, etc.).
- A flat on the concave surface, perpendicular to the lens outer cylinder within a specified tolerance, to ease the handling, supporting, alignment of the lens in its cell.

The lens polisher will not rework the outer cylinder of the blank, hence reducing the associated lens handling risks. Therefore, the lens diameter is the blank as-built diameter.

#### **3.2.2. Coating of lens L1**

It was originally envisaged to apply to lens L1 the same anti-reflective coating as that for lenses L2 to L6 (see section 5.3), but discussions with coating companies identified technical challenges that were assessed to be too risky for the project.

The first issue raised was the size of the lens. The coating chamber had to be large enough to accommodate such a large lens and ensure that coating was uniformly applied. Also, handling such a heavy lens within the coating chamber was a high-risk operation.

The second issue raised was the meniscus shape of the lens. It was not guaranteed to meet the specification of coating uniformity on such a steep lens, especially at the edge of the clear aperture.

The impact on the instrument throughput budget, of keeping lens L1 uncoated, was evaluated to be acceptable compared to the high risks, costs, and lead time that coating this lens would have generated.

#### **3.2.3. The ADC lenses**

To compensate for the atmospheric dispersion while the telescope moves in elevation, each doublet of the PFC ADC units is made of two wedged lenses acting as prisms (the direction of the lens tilt is perpendicular to the telescope elevation axis). The tilt angles of each lens surface are summarised in Table 2.

**Table 2: The wedge angles of the ADC tilted lenses. Both of the surfaces of L3 and L4 are tilted with respect to the optical axis.**

	ADC 1		ADC 2	
	Lens L2	Lens L3	Lens L4	Lens L5
Surface 1	0	-0.59 deg.	-0.03 deg.	-0.71 deg.
Surface 2	-0.59 deg.	-0.03 deg.	-0.71 deg.	0

It was envisaged to ease the manufacturing process for the lenses L3 and L4 by eliminating their small -0.03 degree tilt and letting only one surface tilted, but the image quality (star drift) was too much affected and no other parameters could have compensated this.

The doublets counter rotate in opposite direction from each other about the PFC optical axis (see Figure 2), from 0 (the nominal position of the ADC when the telescope is at zenith) up to +/- 70 degrees (corresponding to a 35-degree telescope elevation).

In the design, the two lenses of each doublet are air-separated by 5mm. Cementing the lenses of the doublets was also considered as a potential technical solution but was not selected due to the large sizes involved and the possible stresses that can build up. Also, the use of index matching oil between the lenses was investigated, but it proved to be too challenging to inject a uniform amount of oil between the lenses without introducing any further tilt. Having the lenses air-separated also offers the advantage of allowing the lenses to be independently aligned with respect to each other.

As the geometry of the lens surfaces is spherical, a pure tilt is equivalent to a pure decentre. In the case of lenses L3 and L4, the strategy adopted for manufacturing these double-tilted lenses was to manufacture the lens as if only one surface was tilted (using a compensated value). Then, the lens is tilted during the alignment process (see section 6) to represent the as-designed configuration. In this way, the manufacturing of the lenses can be simplified (at the expense of creating some more difficult lens - lens mount interfaces).

### 3.2.4. Aspherical surfaces

The use of aspherical lens surfaces in the optical design was minimised as this process significantly increases the manufacturing risks, costs, and delivery time. Several lens polishers were consulted, and the general opinion was that an aspherical surface is easier to be manufactured and tested on the concave side of a lens. Therefore, the optical design was such that the concave surface of lenses L5 and L6 was aspherical. Great care was taken in the way the aspherical surfaces were specified, and the maximum slope deviation was kept to an acceptable minimum.

## 4. RE-OPTIMISATION OF THE OPTICAL DESIGN

### 4.1. The as-built blanks

Due to the high-quality characteristics required for such large-dimension optics, the manufacturing process for the glass blanks would have produced refractive index and dispersion characteristics that deviated from the catalogue values. Because of this, a so-called 'melt-fit' was carried out after the manufacturing of the glass blanks. This implied that the curvatures and axial separations of the lenses had to be re-optimised after the glass material properties were known.

The glass manufacturers were required to measure the as-built refractive index for eight spectral lines specified such that the whole wavelength range of the PFC was covered. The melt-data were then used to produce the as-built set of coefficients that were updated in the glass properties of the lenses.

Since it was not expected that the manufacturing process for the two fused silica blanks B1 and B6 introduced large refractive index dispersion (see 3.1.1), the catalogue values were used in the optical design, and no melt-fit re-optimisation was carried out for these two blanks.

Two melt-fit re-optimisations were carried out, corresponding to the delivery of the two PBL1Y glass blanks (B3 and B4), and then of the B2 and B5 glass blanks (S-BSL7 and N-BK7 respectively).

After the first melt-fit process, the curvatures of the lenses L2 to L5 were re-optimised (lenses L1 and L6 were already frozen), whereas the second melt-fit re-optimised the curvatures of lenses L2 and L5 only (the curvatures of lenses L3

and L4 being frozen during the first process). The WHT/M1-L1, L1-L2, and L5-L6 axial separations were also re-optimised, while the lens central thicknesses, ADC air-space and separations as well as the back focal distance were kept constant.

The melt-fit re-optimisations were also the occasion to update the optical design in order to ease the mechanical design which was on-going in parallel with the manufacturing of the optics. For instance, the air-gap between the two lenses of an ADC unit was increased from 3mm to 5mm, the central thickness of lens L6 was reduced by 3mm, and the outer diameter of lenses L3 and L5 was increased providing more room for the assembly.

A ghost analysis was carried out and revealed that having such tilted lenses in the optical design would create an unacceptable ghost image very close to the focal plane. Using the opportunity of re-optimising the design, it was then possible to constrain the formation of ghost images to a satisfactory distance from the focal plane.

After each melt-fit re-optimisation, the design was evaluated and the impact on image quality was assessed, and each updated prescription data was reviewed. A manufacturing drawing of the final design was then produced for each lens.

#### **4.2. The as-built lenses**

The physical dimensions for each lens once manufactured will be measured on a Coordinate Measuring Machine (CMM). The as-built values of radius of curvature, central thickness, and wedge angle will be fed back into the optical design, which will be re-optimised again, such that the axial separations (WHT/M1-L1, L1-L2, and L5-L6) and the ADC rotation angles will be adjusted and frozen. Since these parameters were tolerated, the expected changes can already be predicted.

### **5. LENS POLISHING, OPTICAL TESTING AND COATING**

The manufacturing and testing of the six PFC lenses are currently in progress at KiwiStar Optics, New Zealand. Thanks to KiwiStar Optics' capabilities, up to three lenses can be manufactured in parallel. Lens L4 is already polished and tested, and is currently being coated. All the manufacturing tools (lens holders, modification of the polishing machines, etc.) and testing equipment (interferometer, Hindle spheres, test plates, etc.) were designed and procured by KiwiStar Optics.

The four main steps for manufacturing the lens from a raw glass blank are as follow:

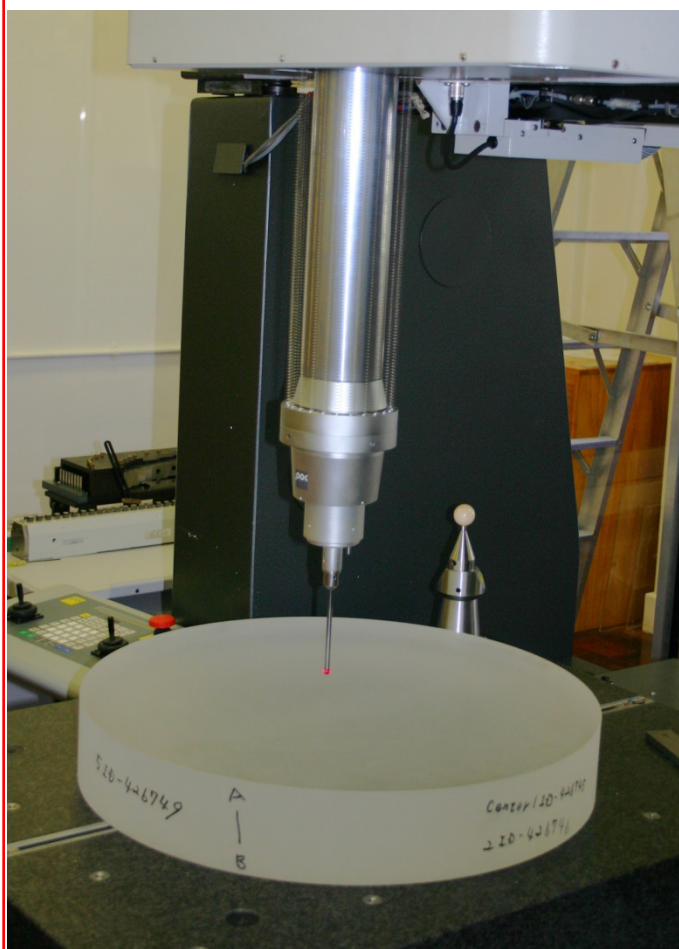
- Milling and lapping, generating the final shape of the lens
- Polishing of the two lens optical surfaces
- Optical testing of the polishing and correction of errors
- Application of the lens anti-reflection coating

The optical testing of the lenses is performed in a reasonably well temperature-controlled environment to minimise the induced OPD errors on the refractive index from any temperature gradients within the material and ensure the stability of the interferometric testing.

#### **5.1. Lens manufacturing and polishing**

The manufacturing of the lenses starts with the delivery of the blanks produced, only one blank per lens was procured, and thus, there are no spare items.

On arrival, the physical dimensions of the blank (diameter, thickness, wedge, cylindricity and perpendicularity) were checked on a Coordinate Measuring Machine (Figure 4). The CMM data are used to mill the optical surfaces plane-parallel to each other and perpendicular-cylinder to within the specified tolerance.



**Figure 3: Verification of the geometrical dimensions of the plano-cylinder blank B4 on a Coordinate Measuring Machine. The photo is courtesy of KiwiStar Optics.**

The blank is mounted on a milling machine, and the concave surface is milled first, then it is lapped with different grit sizes down to 5 $\mu$ m. The wedge, central thickness, and radius are checked on the CMM after each step. For the two aspherical lenses L5 and L6, the concave surface is lapped to the best-fit sphere before being aspherised.



**Figure 4: Verification of the geometrical dimensions of the lens concave surface on a Coordinate Measuring Machine. The blank is a 230kg meniscus of 1.1m diameter made of fused silica. The photo is courtesy of KiwiStar Optics.**

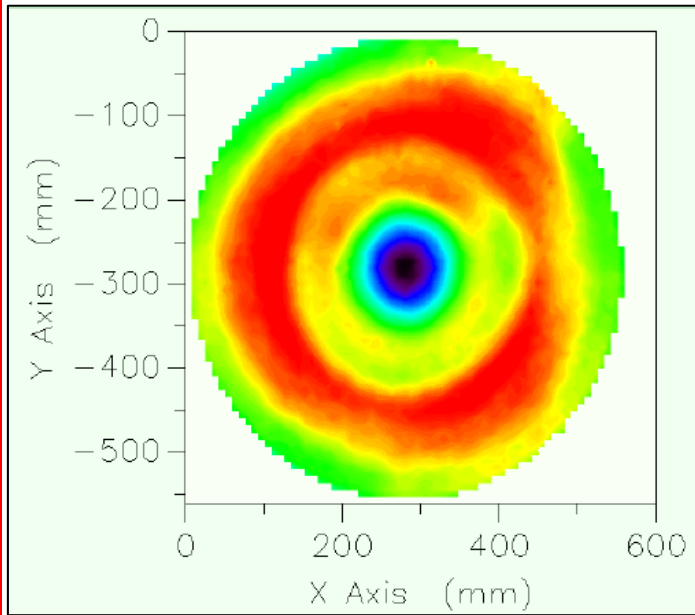
Then the lens is turned over and the convex surface is milled and lapped however during this stage the central thickness and wedge geometries are tightly controlled.

The concave surface is then polished with grit size between 1 and 3  $\mu\text{m}$  depending on how hard or scratch-resistant the glass is. Then the concave surface is tested optically and protected with tape for the polishing and testing of the convex surface.

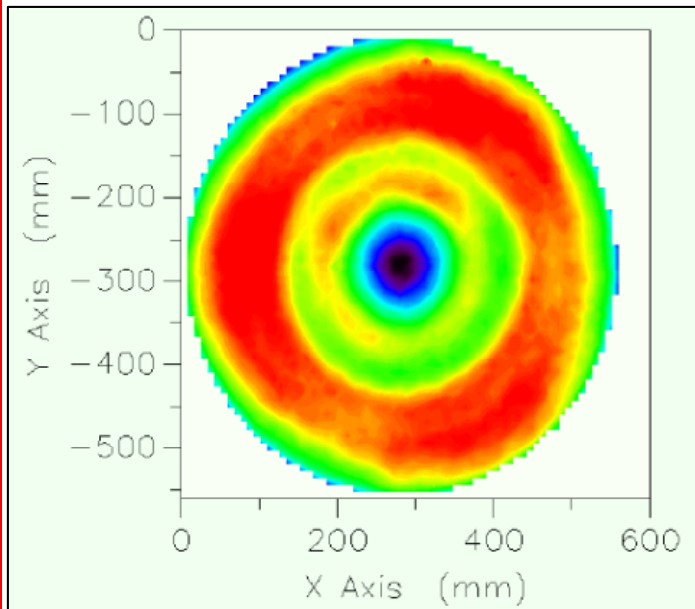
## **5.2. Lens optical testing**

Optical testing of the lenses requires measuring the residual errors of polishing specified using the standard Zernike coefficients, in a range of low (from Z5 (focus excluded) to Z11), mid (from Z12 to Z211) and high (greater than Z212) spatial frequencies (Figure 5, Figure 6, Figure 7, and Figure 8).

While in principal this decomposition of residual polishing errors allows for well-defined fabrication tolerances, high spatial frequency errors using Zernike coefficients greater than Z190 was not supported by the standard interferometric software used by KiwiStar Optics (IntelliWave from Mahr-ESDI). In practice, the residual errors from the fitted Zernike surface were used as the metric for the high spatial frequency errors.



**Figure 5:** The total surface irregularities for the lens L4 concave surface (562mm clear aperture diameter). The results have been fitted to the standard Zernike coefficients (from Z5 to Z190) with the residual fitting errors. Tilt, focus, and mount-induced astigmatism have been subtracted (residual focus is from averaging of multiple OPD files). PV = 214.8nm, RMS = 32.2nm (the colour scale runs from black to red).



**Figure 6:** The low-frequency surface errors fitted to the Z5 to Z11 standard Zernike coefficients with the residual fitting errors. PV = 174.7nm, RMS = 29.2nm (the colour scale runs from black to red).

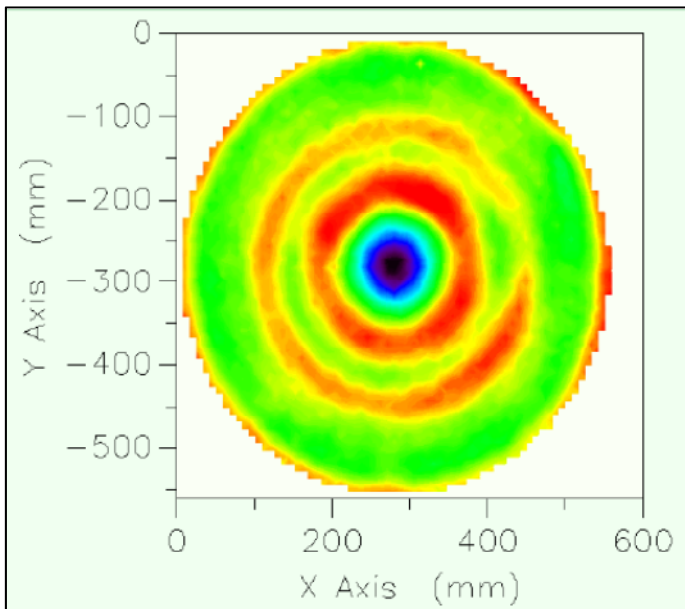


Figure 7: The mid-frequency surface errors fitted to the Z12 to Z190 standard Zernike coefficients with the residual fitting errors. PV = 143.1nm, RMS = 17.1nm (the colour scale runs from black to red).

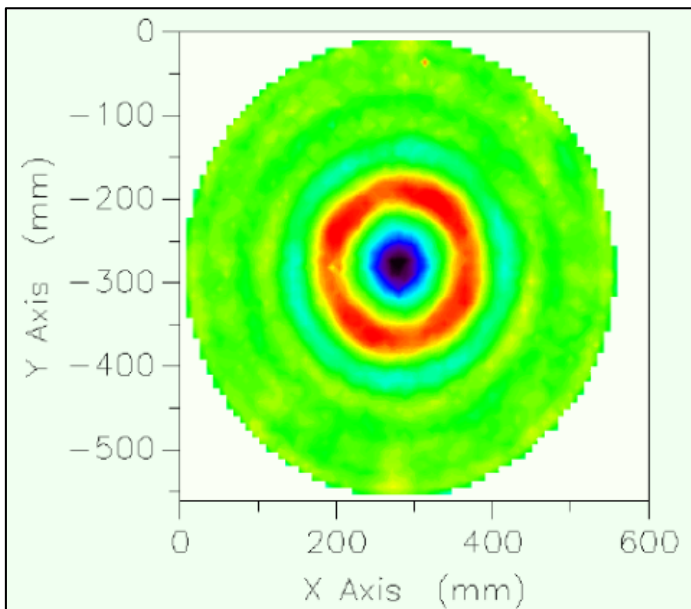


Figure 8: The residual fitting errors. PV = 107.5nm, RMS = 11.3nm (the colour scale runs from black to red).

### 5.2.1. The lens test set-up

KiwiStar Optics have developed a dedicated test tower to measure the optical surface form errors from the concave surfaces and the transmitted wavefront of each lens. Testing is carried out having the lens optical axis in a vertical orientation (as if the telescope were at zenith) for the following reasons:

- It eases the alignment of the Hindle sphere for the sub-aperture tests when required.
- The mount and self-weight deflection errors are reduced (particularly important for the 230kg lens L1) but conversely requires a custom mounting ring for each optic.
- It reduces the risk of handling errors of the large optical elements.

The opto-mechanical test set-up, as showed in Figure 9 and Figure 10, consists of:

- A test tower made of large aluminium rails
- A Mahr-ESDI interferometer and its auxiliary optics
- A large flat mirror folding the beam down to the lens
- A lens holder fitted with the required degrees of freedom (X and Y translations, tip and tilt rotations, and collimation)
- Hindle spheres (acting as a return mirror) lying underneath the lens being tested. Prior to lens testing, the adequate Hindle sphere is aligned with respect to the interferometer optical axis.

Some of the more challenging aspects of the measuring the PFC lenses results from the ADC lenses with large amounts of wedge. The testing of the ADC lenses in most cases requires tilting and decentring of a sub-aperture Hindle sphere to the local axis of the lens and then rotating the tilted and decentred Hindle sphere about a tilted plane.

The mount-induced errors (determined by rotating the lens at four angles), as well as the surface form errors (SFE) of the fold mirror and auxiliary optics, are measured separately and errors are taken out from the global SFE of the lens surface.

Due to the size and geometry of lenses L1 and L4, a full aperture interferometric test would have required the procurement of a large and/or cumbersome Hindle sphere. Therefore, lenses L1 and L4 are to be tested in sub-aperture whereas the testing of lenses L3 and L5 will be performed in full-aperture. For each lens tested in sub-aperture, several OPD maps are generated (4 maps typically), and then stitched together to create an overall OPD map of the lens.

### 5.2.2. SFE of the concave surfaces

The Surface Form Errors (SFE) of all the concave surfaces are measured in full-aperture interferometry (see Figure 9). The lens is positioned concave side up, with the optical axis vertical, in a holder that was specially designed to guarantee minimum lens deformation, in most cases low order astigmatism and trefoil. Multiple tests are performed to remove the mount-induced errors from the mount and self-weight deflection.

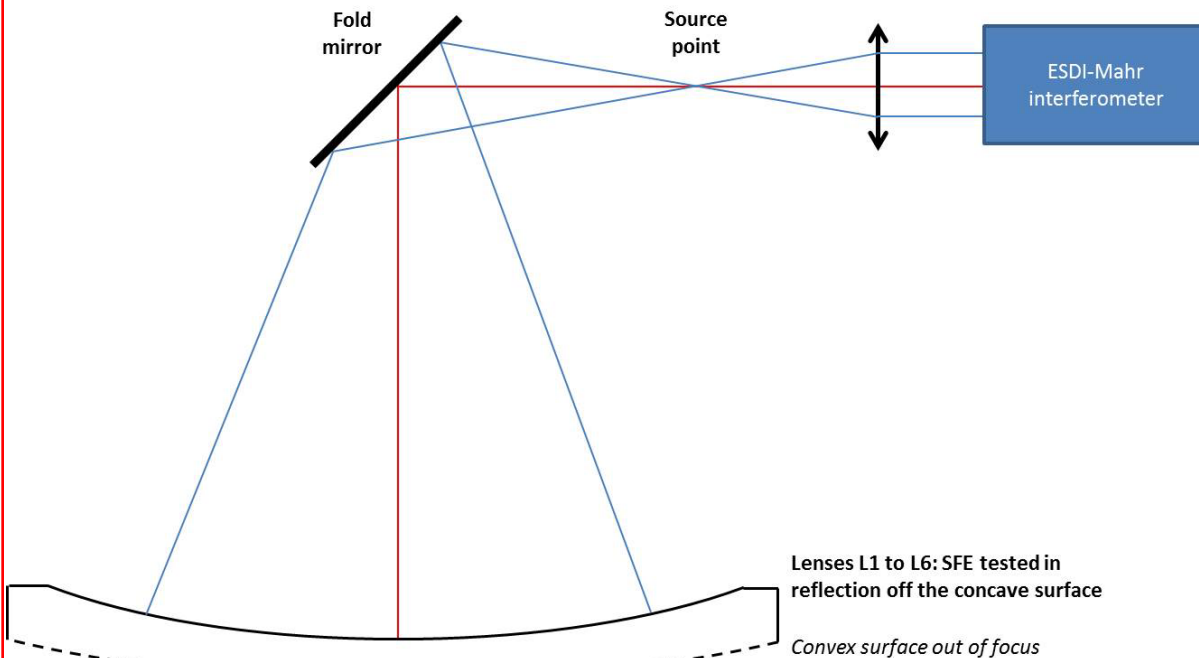


Figure 9: The optical layout for the testing of the Surface Form Errors of the concave surfaces of lenses L1 to L6.

### 5.2.3. Lens transmitted WFE

The specification for the total transmitted wavefront errors was calculated for each lens as the square root of the following sum-squared contributors:

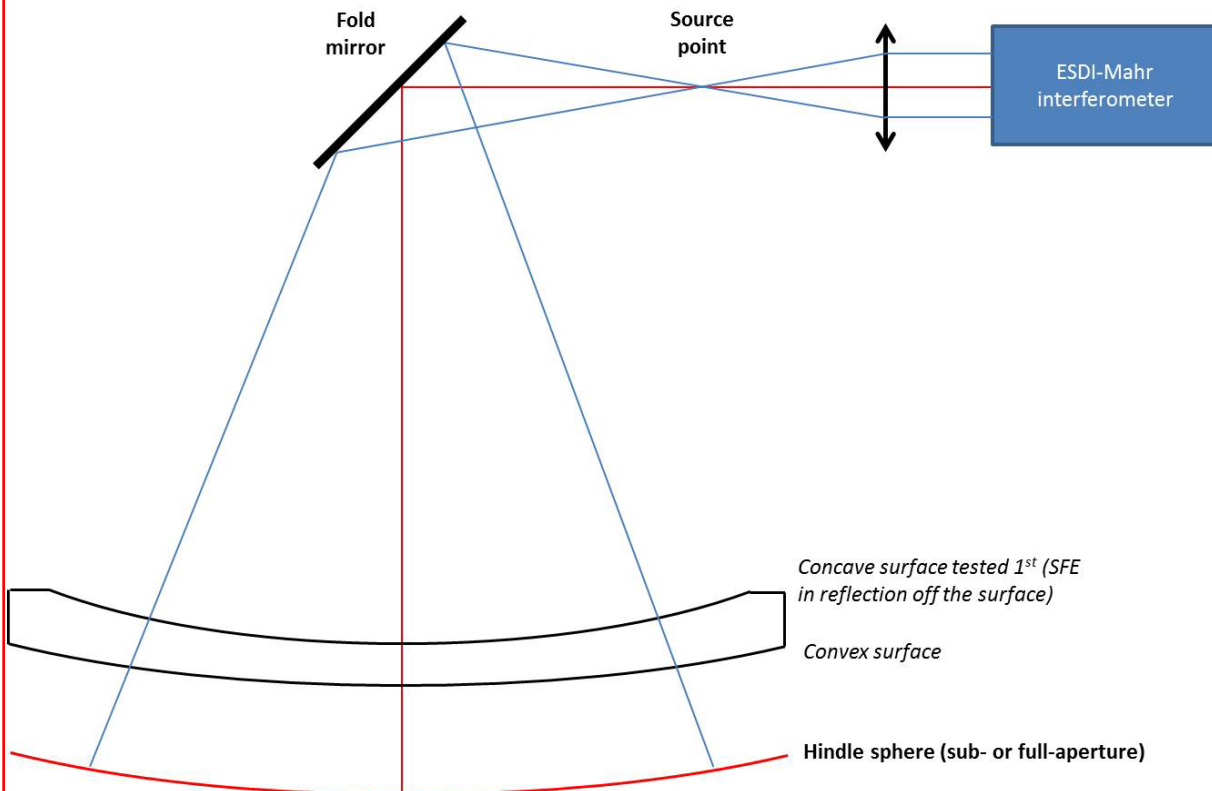
- WFE arising from concave and convex surface irregularities due to the polishing errors
- Internal variations of homogeneity in the thick lens substrate
- Internal quality of the glass blank such as stress-induced birefringence and striae

The formula used for specifying the lens Transmitted Wavefront Errors (TWFE), in the case of a single-pass lens interferometric testing, is

$$TWFE = \sqrt{WFE_{irreg}^2 + WFE_{homo}^2 + WFE_{stress}^2 + WFE_{striae}^2} \quad (1)$$

Due to the thickness of the glass, the tolerance analysis of the optical system showed that glass homogeneity is the most important contributor to the WFE. Thus, it became crucial to the performance of the system that the variation in homogeneity of the glass blanks was controlled to less than 10 ppm peak-to-valley (PV) or +/- 5x1E-6 PV. In all cases, glass vendors delivered optical blanks of better quality than required.

The testing of the TWFE consists in a double-pass through-lens interferometric testing in reflection off a large spherical return mirror, as showed in Figure 10.



**Figure 10: Optical layout for the testing of the lens Transmitted Wavefront Errors (double-pass through lens interferometric testing).**

Even if OPD maps of homogeneity variations were provided by the glass vendors for each blank produced, transmitted wavefront testing is also required of the polished lens to confirm the total OPD errors from the homogeneity and surface form errors. In this way, local homogeneity errors can be compensated with limited corrective polishing.

### 5.3. Lens coating

In order to maximise the overall throughput of the instrument, an anti-reflective coating will be applied to both surfaces of all the PFC lenses, with the exception of lens L1 as explained in section 3.2.2.

The coating is specified as follow:

*“All coated surfaces must have an average reflectivity less than or equal to 1% over the [370-1000]nm wavelength bandpass. Furthermore, any peaks over 1% should stay below 1.5%.”*

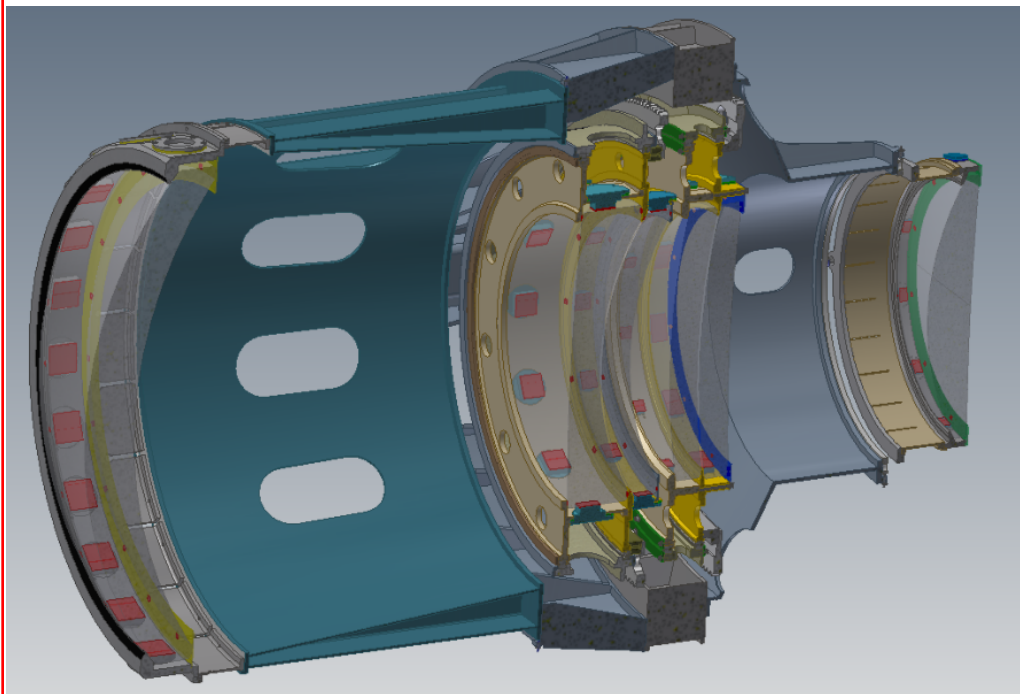
An annulus mask is to be placed at the outer edge of the concave surface of the lenses in order to delimit the coated area (specified as to be 2mm larger than the polished clear aperture diameter). A maximum coated diameter was specified for the convex surface of the lenses ensuring a clear region for the gluing of the RTV mounting pads.

In order to monitor the lifetime instrument throughput, two witness samples will be procured, made of the same glass material to that of the component to be coated. These will be placed in the coating chamber along with the lens to be coated, and will be monitored over time at the telescope location.

No optical testing is to be performed after a lens is coated, as coating stress-induced errors are expected to be negligible on such large and thick lenses.

## 6. LENS MOUNTING & ALIGNMENT PHILOSOPHY

The mechanical design foresees that each lens is secured into a cell using a number of discrete RTV mounting pads. These pads are used to support radially on the lens cylindrical edge and axially on the lens convex surface and provide an athermal mounting arrangement. The RTV pads are initially cast and then glued in place following a technique which involves rotating the lens on a rotatory table and looking at the back reflection of an alignment laser. The number, size and location of these RTV pads depend on the size of the lens and relative coefficient of thermal expansion of the lens, lens cell and RTV pads.



**Figure 11: A cross sectional view of the PFC lenses supported by discrete RTV pads.**

The mechanical design of the lens cells is mostly driven by the fact that the ADC lens surfaces are decentred or tilted with respect to the PFC optical axis. The general alignment philosophy requires that the cylindrical edge of a manufactured lens is concentrically aligned with the bore of its cell. Therefore to attain the correct alignment for the ADC lenses, the cell of L3 is manufactured with a bore decentred with respect to the cell of L2 and the bore of cell L4 is tilted with respect to the cell of L5. Subsequently, the outer diameters of all the lens cells are aligned to be concentric with the PFC optical axis by means of lasers, targets, and alignment markers. For this, each lens cell is fitted with the

required degrees of freedom (X and Y centration, tip/tilt rotations, and collimation) and the physical position of each lens is measured against the specified tolerance budget.

As a final end-to-end test, the flexure of the aligned PFC will be measured as a function of elevation angle using an adequate mount that reproduces the telescope movement. Finally, the aligned PFC will be shipped to the observatory where it will be integrated into the WEAVE top-end (see Figure 1), and then the whole assembly will be aligned onto the WHT optical axis.

## 7. CONCLUSION

The manufacturing process for the WEAVE Prime Focus Corrector optics is a great technical challenge due to the large size, demanding high quality optical performance, and specific characteristics of the six lenses. Thanks to a flexible and well-controlled budgeted optical design, it is possible to account for the as-built data of the blanks and lenses, optimising further parameters. Various discussions with the glass vendors and lens polisher were necessary to understand the compromises that had to be done to ensure the manufacturability of the PFC within acceptable time, risks, and costs while achieving the best image quality. The results of polishing errors for the first lens already tested are well within specifications and the quality of the lenses to be produced is promising.

## 8. REFERENCES

- [1] Dalton, G., et al., "WEAVE: the next generation fibre spectroscopy facility for the William Herschel Telescope: project overview and update on the final design stage," Proceedings of the SPIE, Volume 9147 (2014).
- [2] Dalton, G., et al., "WEAVE: the next generation wide-field spectroscopy facility for the William Herschel Telescope," Proceedings of the SPIE, Volume 8446 (2012).
- [3] Balcells, M., et al., "The WEAVE spectrograph on the WHT: plans for radial velocity and chemistry surveys of the northern and equatorial Milky Way," EAS Publications Series, Volume 67-68 (2014).
- [4] Balcells, M., et al., "Design drivers for a wide-field multi-object spectrograph for the William Herschel Telescope," Proceedings of the SPIE, Volume 7735 (2010).
- [5] Agócs, T., et al., "Final optical design for the WEAVE two-degree prime focus corrector," Proceedings of the SPIE, Volume 9147 (2014).
- [6] Agócs, T., et al., "Preliminary optical design for the WEAVE two-degree prime focus corrector," Proceedings of the SPIE, Volume 8444 (2012).
- [7] Agócs, T., et al., "Two-degree FOV prime focus corrector and ADC concepts for the 4.2m WHT," Proceedings of the SPIE, Volume 7735 (2010).
- [8] Abrams, D.C., et al., "The Mechanical Design for the WEAVE Prime Focus Corrector System," Proceedings of the SPIE, Volume 9147 (2014).