Version December 2022

TIE-41 Large Optical Glass Blanks

Introduction

SCHOTT has a long experience in producing and delivering large high homogeneous optical glass blanks for demanding applications. Large high homogeneous glass blanks can be found in laser fusion systems, large interferometers or stepper systems for microlithography. The scientific instruments of the upcoming extremely large telescopes require optical glasses for components with demanding requirements on the size and wavefront stability e.g. for atmospheric dispersion correction and laser guide star systems.

The most common optical glass available in large formats is SCHOTT N-BK7®. But other glass types like F2 or LLF1 can also be produced in formats up to 1000 mm and above. The production of such large homogeneous optical glass banks requires tight control of all process steps.

This technical information will address questions that arise with the production of optical glasses in large formats: Which glass types can be produced in large dimensions? What are the maximum dimensions that can be produced?

1. Production of large high homogeneity optical glass blanks

In the production of large optical glass blanks there are many parameters that influence the achievable homogeneity. Large optical glass blanks at SCHOTT are produced in continuous melting tanks. A continuous melting tank is subdivided in three separated areas: The melting area, the refining area and the mixing area. The melting area is continuously filled with raw material batches that are subsequently molten. The raw material batches are carefully composed and mixed to achieve a high stability in refractive index over time. Gas bubbles are generated as a result of the chemical reactions during melting of the raw materials. In the melting chamber these bubbles help to achieve a first homogenization of the melt. The molten glass flows into the refining chamber through an ascending pipe. In the refining area the temperature is raised to lower the viscosity of the melt and increase the buoyancy force on the bubbles. The bubbles rise to the surface of the melt, additionally supported by the help of refining agents in the composition. Next the refined glass melt is mechanically stirred in the mixing crucible to minimize striae (remaining density fluctuation / inhomogeneities) in the melt. Subsequently the glass is cast through a feeder in molds of arbitrary size and shape in the hotforming process. The molds are then slowly cooled down to room temperature in electrically heated furnaces to avoid breakage by rapid temperature changes.

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TIE-41 Large Optical Glass Blanks

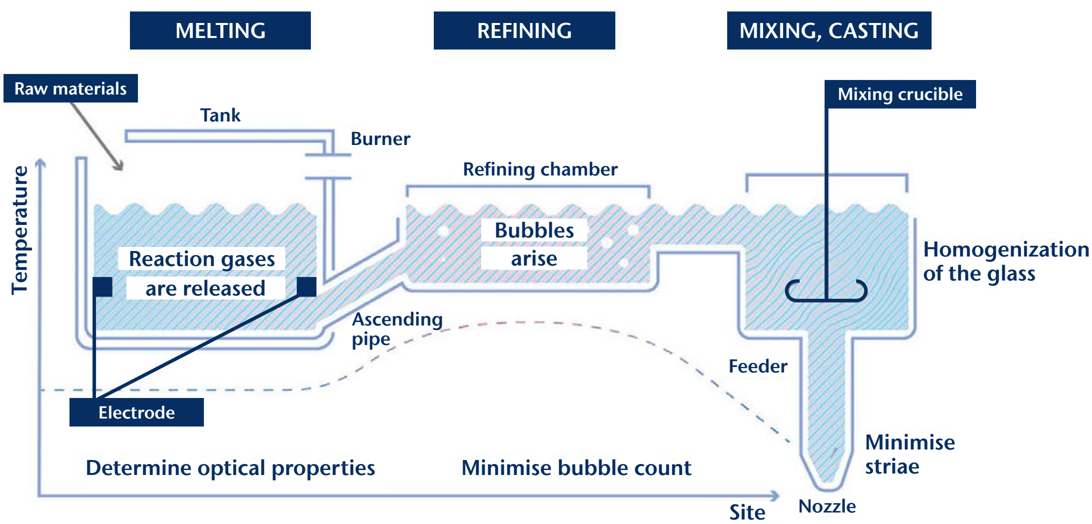


Fig. 1: Sketch of a melting tank for optical glasses including the spatial temperature profile. The over-all time consumption from the raw material melting to the casting takes several hours.

Samples are taken every two hours for tight refractive index control during the continous tank production process. Figure 2 shows a typical tank control chart. As soon as a stable process is achieved and index variation is small production of the large castings can start. Casting of large optical glass blanks in sizes up to 1500 mm diameter takes several hours. The flow of the material into the mould must be controlled very precisely. During this time the optical properties of the glass need to be as constant as possible. Changes of the refractive index in time lead to spatial refractive index distributions in the blank. Finite Element simulations of the thermodynamically behaviour of the glass during melting and casting as a function of time help to optimize the production parameters to achieve the best index homogeneity of the casting. An example is given in Figure 3. This simulations shows a color representation of the glass age spatial distribution after hot-forming in a cross section of a cylindrical mould.

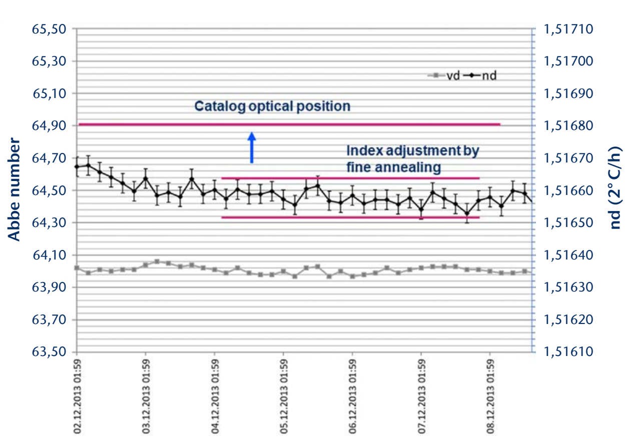


Fig. 2: Time dependent refractive index and Abbe number variations during continuous melting of SCHOTT N-BK7®.

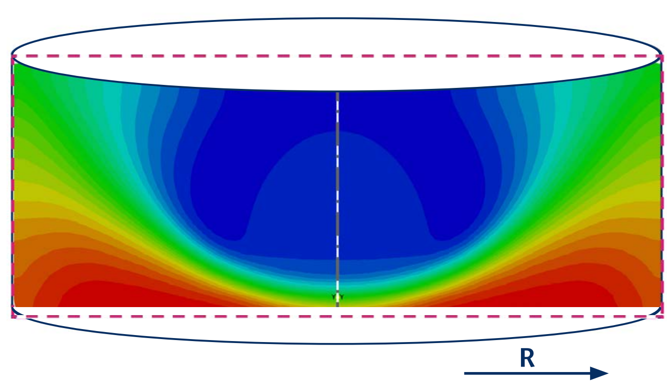


Fig. 3: Simulated cross section of glass age in hot-forming (colors represent glass age) in a cylindrical mould.

Back to index

SCHOTT
glass made of ideas

TIE-41 Large Optical Glass Blanks

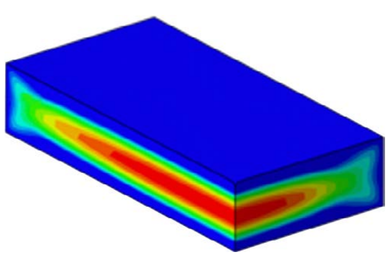
Qualitatively glass of the same feeding age settles in onion like patterns. Eldest glass ends up close to the mould bottom (red) and the side walls. Youngest glass makes up the central volume (blue). In real-world productions the structure depends on operating conditions and can change due to temperature dependent glass viscosity and density, which might even result in free convection patterns that need to be properly controlled.

The refractive index homogeneity is also influenced by the temperature distribution during fine annealing. Every casting needs to be fine annealed to adjust the refractive index to the required optical position (see pink lines for refractive index target in figure 2). During fine annealing the glass is heated up to temperatures above the glass temperature (listed as T_g in the optical glass catalog or datasheet, typically representing a glass viscosity of 10^{13} dPas). After holding time above T_g, defined by the glass volume, the glass is cooled down at a precisely defined rate between T_g and T_g-150 K to adjust the refractive index (see TIE-29). Subsequently the annealing rate can be increased for cooling down to room temperature.

Due to the fact that temperature differences scale with the square of the thickness of the glass part, the annealing rate significantly influences the final stress birefringence and therefore also the index homogeneity with increasing overall thickness. Typical annealing rates of block glass are between 0.5 K/h and 1.5 K/h leading to typical total annealing times of maximum 4 weeks. Large optical glass parts are annealed with annealing rates lower 0.5 K/h leading to total annealing times of up to 12 weeks.

Figure 4 shows the example of a Finite Element Simulation of the stress birefringence after fine annealing of a "quarter part" of a rectangular casting (symmetry conditions are enabled to ease simulation). The color code shows the stress variation between the central part and the outside for a fast and a slow annealing rate. The slow annealing rate leads to smaller differences in mechanical stress and a better refractive index homogeneity. Nevertheless, the annealing rate is only one aspect that needs to be taken into account, other aspects are the temperature homogeneity in the furnace, the furnace setup and other details.

Remaining stress after fast annealing



Remaining stress after slow annealing

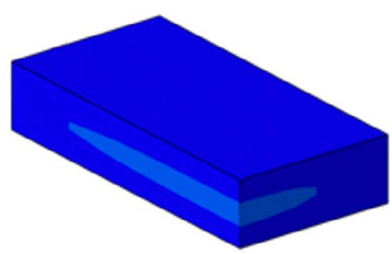


Fig. 4: Stress distribution in a rectangular SCHOTT N-BK7® blank for fast (left) and slow (right) annealing.
Only a "quarter part" of a rectangular casting depicted (symmetry conditions are enabled to ease simulation).

TIE-41 Large Optical Glass Blanks

2. Global refractive index homogeneity measurement of large optical glass blanks

SCHOTT ultilized a Zygo 24" Verifire MST at SCHOTT North America in Duryea capable of measurements with an aperture up to 600 mm (24 inch). The Zygo interferometer also exhibits a motorized 5 axis stage. SCHOTT in Mainz uses a 508 mm (20 inch) DIRECT100 Fizeau Interferometer from ZEISS for homogeneity measurement of large optical glass blanks.

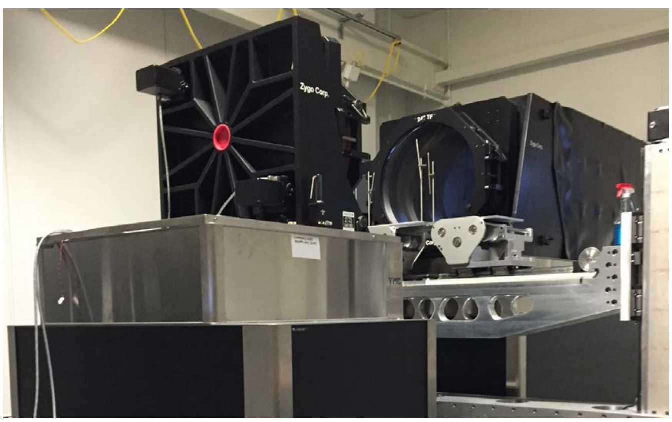


Fig. 5: 24 inch aperture Zygo Verifire MST Interferometer at SCHOTT North America in Duryea.

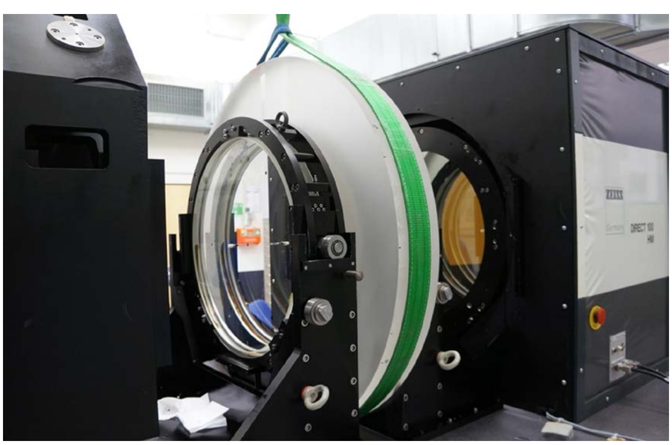


Fig. 6: 950 mm diameter SCHOTT N-BK7® prepared for oil-on-plate homogeneity measurement on the DIRECT 100 in Mainz, Germany.

The influence of the sample surfaces must be eliminated for refractive index homogeneity measurement. SCHOTT uses two methods to achieve this: The “oil-on-plates sandwich” method and the “polished sample” method.

For the “polished sample method” or PHom method (ISO 17411) the sample must be polished on front and rear surface. Additionally a small wedge of a few minutes angle must be introduced between front and rear surface. The homogeneity measurement consists of a sequence of four individual measurements. First a measurement of the empty cavity is necessary. Then three measurements of the sample are performed. The sample will be measured in transmission, in reflection from the rear surface and in reflection from the front surface. These four measurements are combined subsequently and the homogeneity distribution is evaluated.

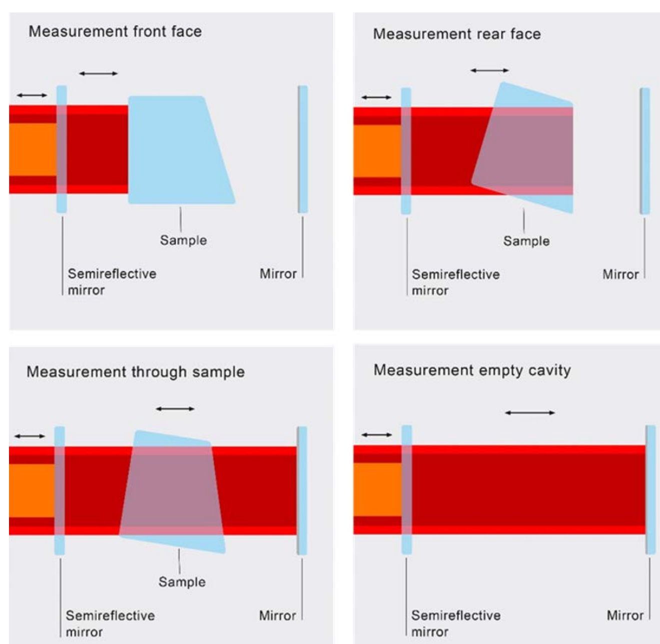


Fig. 7: Schematic representation of the 4 measurements of the PHom (ISO 17411) method for refractive index homogeneity measurement.

Back to index

TIE-41 Large Optical Glass Blanks

For the "oil-on-plates sandwich" method the sample is placed between two glass plates. These glass plates exhibit accurate polished surfaces. The glass plates are connected with the samples using immersion oil liquid that has the same refractive index as the sample. For this method the sample surfaces only need to be lapped to a good flatness, no polishing is needed. The procedure starts by measuring the oil-on-plates sandwich alone without sample attached (calibration position) and subtracting a measurement of the oil-on-plates attached to the sample (measurement position).

For the accuracy of this method, it is very important that the immersion oil matches the refractive index of the sample very precisely. To measure a wide variety of optical glasses with varying refractive indices mixtures of three immersion oils are used. Optical glasses with refractive indices from 1.473 to 1.651 can be measured using the "oil-on-plates sandwich" method.

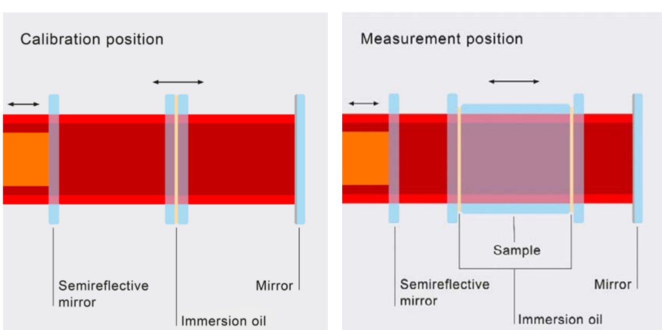


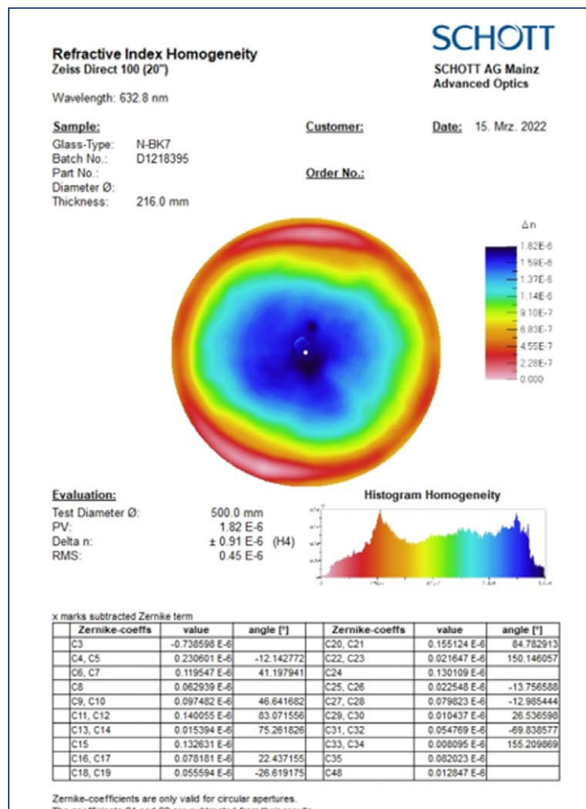
Fig. 8: Schematic representation of the 2 measurements of the "Oil-on-plate" method for refractive index homogeneity measurement.

The "oil-on-plate" method is mainly used at the DIRECT100 Fizeau Interferometer in Mainz, whereas the Zygo Verifire MST in Duryea utilizes the "polished sample method".

The measurement result is a color coded refractive index homogeneity plot of the sample as shown in Figure 9. Each color represents a refractive index difference from an arbitrary origin.

Large aperture homogeneity measurement can lead to "white spots" (areas that cannot be evaluated) in the interferogram due to either use of large oil on plates with venting holes (can be seen on the center of the color plot in Figure 9) or the implementation of stitching fiducials.

The refractive index homogeneity certificate contains all relevant homogeneity measurement results including Zernike data (if measured on circular aperture) for individual analysis of the measurement.



Refractive Index Homogeneity
Zeiss Direct 100 (20")

SCHOTT AG Mainz
Advanced Optics

Wavelength: 632.8 nm

Sample:
Glass-Type: N-BK7
Batch No.: D1218395
Part No.:
Diameter Ø:
Thickness: 216.0 mm

Customer:

Order No.:

Date: 15. Mrz. 2022

Δn
1.82E-6
1.59E-6
1.37E-6
1.14E-6
9.10E-7
6.83E-7
4.55E-7
2.28E-7
0.000

Evaluation:
Test Diameter Ø: 500.0 mm
PV: 1.82 E-6
Delta n: ± 0.91 E-6 (H4)
RMS: 0.45 E-6

Histogram Homogeneity

x marks subtracted Zernike term

	Zernike-coeffs	value	angle [°]		Zernike-coeffs	value	angle [°]
	C3	-0.738598 E-6			C20, C21	0.155124 E-6	84.782913
	C4, C5	0.230601 E-6	-12.142772		C22, C23	0.021647 E-6	150.146057
	C6, C7	0.119547 E-6	41.197941		C24	0.130109 E-6	
	C8	0.062939 E-6			C25, C26	0.022548 E-6	-13.756588
	C9, C10	0.097482 E-6	46.641682		C27, C28	0.079823 E-6	-12.985444
	C11, C12	0.140055 E-6	83.071556		C29, C30	0.010437 E-6	26.536598
	C13, C14	0.015394 E-6	75.261826		C31, C32	0.054769 E-6	-69.838577
	C15	0.132631 E-6			C33, C34	0.008095 E-6	155.209869
	C16, C17	0.078181 E-6	22.437155		C35	0.082023 E-6	
	C18, C19	0.055594 E-6	-26.619175		C48	0.012847 E-6	

Zernike-coefficients are only valid for circular apertures.
The coefficients C1 and C2 are subtracted from their results

Fig. 9: Refractive index homogeneity certificate with false color map of the refractive index distribution.

Back to index

TIE-41 Large Optical Glass Blanks

The homogeneity of optical glass comprises 5 classes according to ISO 10110-18:2018 and ISO 12123:2018. The homogeneity is given in maximum variation of the refractive index as shown in Figure 10. The old ISO 10110-4 definition from 1997 was reworked because the former ± notation tolerance limit implies an absolute index measurement capability that is not applicable to interferometric Fizeau measurement.

The class designation is linear from H1 to H5. The designated peak to valley limits are not linearly scaled. H5 quality has a much lower range than H1 quality as visualized in Figure 11.

SCHOTT homogeneity class indicator	NEW ISO 12123:2018 and ISO 10110-18:2018		OLD ISO 10110-4: 1997	General applicable for
	Class indicator	tolerance limits Δn [10^{-6} or ppm]	tolerance limits Δn (± notation) [10^{-6} or ppm]	
	NH100	100	±50	Common application sizes
H1	NH040	40	±20	
H2	NH010	10	±5	Partial volumes of the raw glass
H3	NH004	4	±2	
H4	NH002	2	±1	Not in all dimensions and not for all glass types
H5	NH001	1	±0.5	

Fig. 10: Homogeneity grades

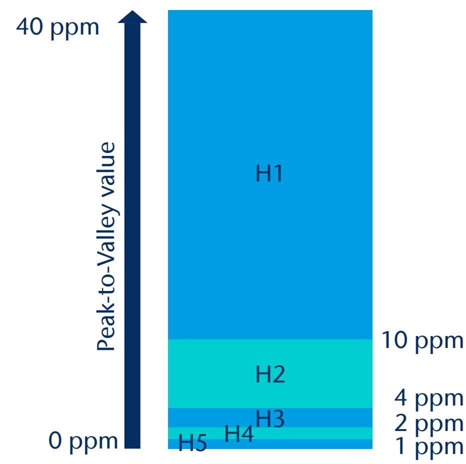


Fig. 11: Homogeneity grades are not linearly scaled

For homogeneity measurement it is standard to subtract the tilt and piston Zernike coefficients after measurement for evaluation. For large aperture homogeneity measurements additionally the focus term of the Zernike approximation is subtracted. Focus aberrations lead to a shift in the focal length that can easily be adjusted in the optical setup. An example of the focus subtraction on a Zernike reconstructed wave front from interferometer data is shown in Figure 12.

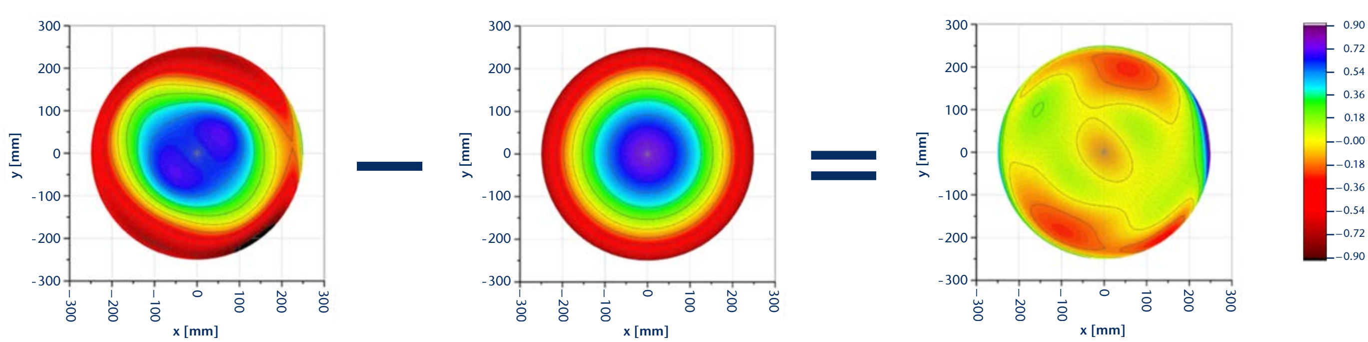


Fig. 12: Fokus subtraction from a Zernike coefficient reconstructed wavefront

Back to index

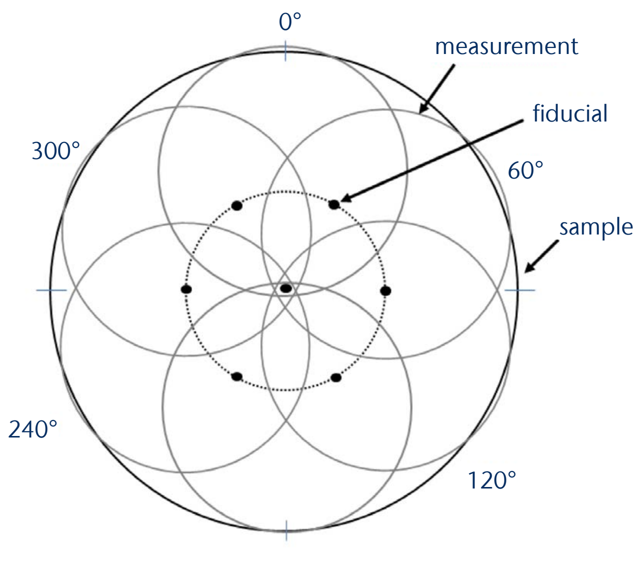
TIE-41 Large Optical Glass Blanks

3. Sub-aperture stitching

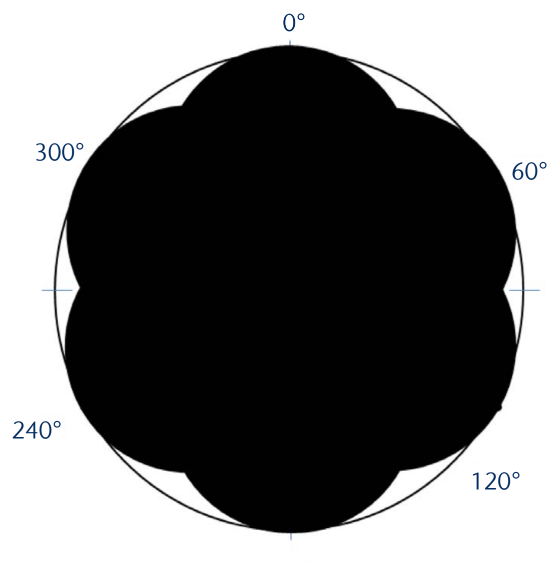
Measurements of a 1000 mm or 1500 mm diameter optical glass blanks are carried out in sub-apertures of 500 mm size. These sub-apertures are evenly spread to achieve a good area coverage. Figure 6 shows the 500 mm oil-on-plates being attached to a 950 mm diameter and 100 mm thick SCHOTT N-BK7® blank on the DIRECT 100 interferometer. The blank was fine ground to achieve a reasonable flatness for the oil-on-plates method.

For stitching typically 4 to 6 sub-apertures are measured and combined in a stitching software. The ZEISS DIRECT 100 interferometer does not employ an automatic stage for positioning the blank, therefore fiducial marks have to be employed during measurement for the software to find the correct position of each sub-aperture measurement to each other.

Figure 13 left shows the sub-aperture arrangement for stitching of a 950 mm diameter SCHOTT N-BK7® blank. In total 6 sub-apertures were used to achieve a ~89 % area coverage of the 950 mm diameter blank area. The 500 mm diameter apertures are adjusted in such a way, that they touch the edge of the physical blank. On a diameter 400 mm in the center 6 fiducial markings have been placed by engraving shallow circular marks of several millimeters in size. An additional fiducial marking was placed in the center. The overlap between each two sub-apertures contains two shared fiducials. Each fiducial is registered properly in the software. The software itself moves the sub-apertures to find the best match between the fiducials.



6 measurements (0°, 60°, 120°, 180°, 240°, 300°)
and 6 fiducials for positioning



area coverage after stitching

Fig. 13: Stitching arrangement for a 950 mm diameter blank with 6 subapertures and fiducials (left) and corresponding area coverage (right)

Back to index

SCHOTT
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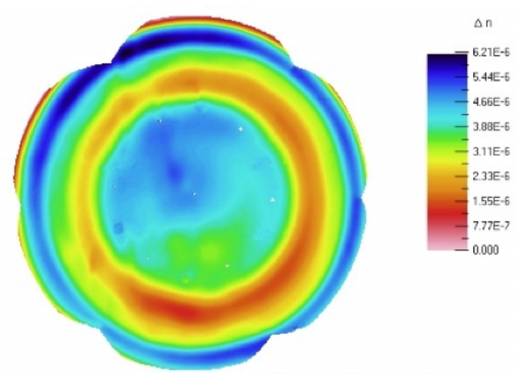
TIE-41 Large Optical Glass Blanks

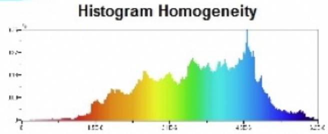
Figure 14 shows the measurement result of the stitching in a colored refractive index homogeneity map. The choice of 6 sub-apertures results in the typical flower. Also the 7 fiducials are visible as white dots. The peak to valley homogeneity after focus subtraction is 6.2 ppm on an aperture of 900 mm. The Zernike coefficients can be displayed on the certificate for the given aperture.

Stitching Interferometry is actually commonplace for the measurement of large optics (X-ray mirrors, Telescope mirrors, etc.). But implementation of this technique is not straightforward. More precisely, because stitching interferometry involves multiple overlapping measurements, errors usually irrelevant, or just simply ignored, in standard measurements, now show up as overlap error.



Evaluation:

Test Diameter Ø: 899.2 mm
PV: 6.21 E-6
Delta n: ± 3.11 E-6 (H2)
RMS: 1.08 E-6



x marks subtracted Zernike term

	Zernike-coeffs	abs. value	angle [°]		Zernike-coeffs	abs. value	angle [°]
x	C3	6.356961 E-6			C20, C21	0.332177 E-6	-60.542973
	C4, C5	0.274795 E-6	-57.092022		C22, C23	1.619213 E-6	123.250778
	C6, C7	1.422577 E-6	126.526306		C24	1.691265 E-6	
	C8	1.148929 E-6			C25, C26	0.765559 E-6	-24.008448
	C9, C10	0.507214 E-6	6.652820		C27, C28	0.478036 E-6	20.128992
	C11, C12	0.472163 E-6	-33.383049		C29, C30	0.468402 E-6	17.122158
	C13, C14	1.677076 E-6	135.138824		C31, C32	0.247809 E-6	78.112213
	C15	1.001621 E-6			C33, C34	0.316289 E-6	-6.895075
	C16, C17	0.504862 E-6	23.716408		C35	0.108776 E-6	
	C18, C19	0.510711 E-6	5.057528		C48	0.479701 E-6	

Zernike-coefficients are only valid for circular apertures.
The coefficients C1 and C2 are subtracted from their results

Fig. 14: Refractive index homogeneity and Zernike coefficients after subtracting of focus on SCHOTT N-BK7® with a test diameter of 900 mm.

Blending the data into a smooth final figure – which is a simple operation – does not eliminate the existence of these overlap errors, which have to be analysed and processed to obtain the final real figure, because each error type generates a different overall error.

As an illustration of the practical difficulties of stitching, a few typical error sources, ubiquitous in stitching measurements, are listed below:

Calibration: Calibration of overall figure is required so that the second order terms (i.e., "power", "astigmatism") do not propagate across the whole component: These actually stitch with no overlap error, and are therefore impossible to detect by simple analysis of the stitched data.

Vibration: Inherent sensitivity of phase shifting to vibration requires good vibration control: Fringe print-through will generate visible overlap errors, but also some slight random deformation with the appearance of a low amplitude patchwork. One method to reduce the latter is to use large overlap values.

Thermal drift: Probably the worst enemy of stitching: Because manipulation of large blanks is a lengthy operation, thermal drift can creep in and create slight mismatch between overlapping sub-apertures. This, in turn, will generate, as above, a low amplitude patchwork, but without the smaller scale fringe print-through effects.

Back to index

TIE-41 Large Optical Glass Blanks

4. Temperature dependence of homogeneity measurement results

During measurement of large high homogeneous blanks it is very important to properly control temperature differences in large glass blanks. Temperature differences lead to refractive index changes. The temperature coefficient of refractive index for SCHOTT N-BK7® is about 2.7 ppm/K in the temperature range from 20 °C to 30 °C for a wavelength of 632.8 nm. Table 2 gives an indication of the effect of temperature differences on the refractive index homogeneity in SCHOTT N-BK7® blanks. A temperature difference of about 1 K in SCHOTT N-BK7® leads to an inhomogeneity of 2.7 ppm that is equivalent to H3 homogeneity grade.

ΔT [K] =>	Δ*n* peak to valley [ppm]	Homogeneity grade
14.7	40	H1
3.7	10	H2
1.5	4	H3
0.7	2	H4
0.4	1	H5

Tab. 1: A temperature difference of about 1 K in SCHOTT N-BK7® leads to an inhomogeneity 2.7 ppm (H3)

Figure 15 shows the expected temperature difference within a 1000 mm diameter and 100 mm thick SCHOTT N-BK7® blank after change from a temperature environment of 17 °C to 22 °C. The temperature difference between the center and edge of the parts needs at least 17.1 hours to drop below 0.05 K.

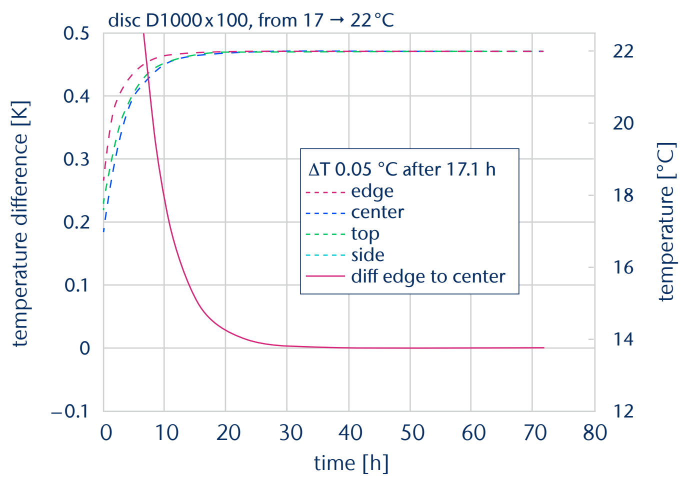


Fig. 15: Required temperature conditioning time for a 1000 mm diameter and 100 mm thick SCHOTT N-BK7® blank.

5. Maximum production size of optical glasses

The useful maximum size of optical glass is connected to the process parameters and geometries required to keep the homogeneity as stable as possible. Therefore the typical maximum casting diameter is about 1200 mm and the thickness to between 200 and 300 mm depending on the diameter. Figure 16 shows still liquid SCHOTT N-BK7® glass in a mould of 1500 mm in diameter.

There are several limiting factors in the production of large optical glass formats with respect to the glass itself. The specific chemical composition of the glass not only influences its optical properties but also, for example, the thermo-mechanical properties like viscosity, the reactivity of the melt with the

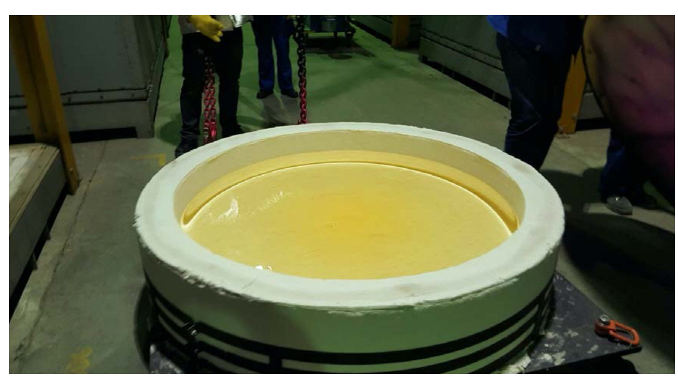


Fig. 16: Mould with a 1500 mm diameter SCHOTT N-BK7® casting.

Back to index

SCHOTT
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TIE-41 Large Optical Glass Blanks

tank materials, the tendency of crystallization and the necessary sensitivity to handle the melting and casting process. Different optical glasses have different viscosity behavior. The viscosity of the glass limits the glass flow rate but also influences the achievable homogeneity. The glass flow rate must be limited to ensure a continuous isotropic flow into the mould to prevent striae. This leads to long casting times which can range from several hours to almost one day. During this time all technical and environmental parameters have to be kept as stable as possible.

Typical production formats of optical glasses with the continuous melting technique are strip glass, blocks and round disks. Most optical glasses can be fabricated as strip glass with cross section of 160 x 38 mm. Some glasses are restricted to smaller thickness because of their tendency to crystallize. A very special large production format for SCHOTT N-BK7® are big rectangular strips of about 900 mm x 450 mm x 100 mm³ volume. An example SCHOTT N-BK7® strip glass with a cross section of 450 mm x 100 mm is shown in Figure 17. The length of the strip, in principle, is only limited by the available fine annealing and cutting equipment.

Fig. 17: SCHOTT N-BK7® strip glass with about 450 x 100 mm cross section

The most common production format out of a continuous melting process, other than strip glass, is block glass. The size of a typical block glass format is 200 x 200 x 180 mm. Glasses that can be produced in block format, for example, include LF5, LLF1, N-BAK, SCHOTT N-BK7®, N-F2, N-FK5, some SK, F and SF glasses. Upon special request, disk-shaped glass formats can also be produced from a continuous melting tank. In the past, disk-shaped glass formats have been produced from 280 mm diameter up to about 1500 mm. Maximum achievable standard formats and homogeneities are shown in the pocket catalog in table 1.6.

Classical borosilicate crown, barium crown, dense crown, flour crown glasses, and lead silicate flint glasses have the highest chance to be produced in large dimensions. Many other glass types especially those with outstanding optical properties like very low dispersion or special partial dispersion cannot be made in large sizes due to their crystallization tendency.

Table 2 gives an overview of the possible optical glass sizes and preferred glass types for most common glass families.

The most common optical glasses that can be produced in large dimensions of up to 1200 mm are SCHOTT N-BK7® and F2. With a large continuous melting tank providing the best chances of achieving high optical homogeneity, the maximum achievable dimensions for BK glasses are 1500 mm diameter and 500 mm thickness, corresponding to 2.2 tons of SCHOTT N-BK7®.

Flint glasses have been produced as radiation shielding glass blocks with dimensions up to 1500 x 1000 x 200 mm.

The glasses FK5HTi, LLF1HTi and LF5HTi were optimized for the lithography industry, to cope with the demand on extremely high quality glass. They can be found in microlithography equipment with sizes up to 300 mm in diameter.

In addition, SF-type glasses with refractive index of up to 1.8 are also possible to be produced in large formats. SF1 has been produced in diameters of up to 500 mm in the past, and SF6 can be produced in diameters equal to or larger than 1000 mm.

LLF, LF, F and SF glasses, in principle, can be produced in formats up to 1000 mm diameter and 300 mm thickness with present capabilities in big continuous tanks. The maximum achievable dimensions with additional development effort are 1500 mm diameter and 500 mm thickness or other dimensions with equivalent volume. The dimensions are mainly restricted by casting time and striae quality.

Back to index

SCHOTT
glass made of ideas

TIE-41 Large Optical Glass Blanks

Some of the SF glasses can also be ordered as lead-free N-types. These N-type glasses exhibit nearly the same refractive index and Abbe number but often behave totally different in melting and casting. In principle, all N-type SF glasses are restricted to strip glass formats with maximum diameters of 160 mm.

Lanthanum (LAK, LAF and LASF), phosphate (PSK, PK) and fluorine (FK) glasses tend to crystallize during the casting and cooling processes. These glasses have extreme positions in the Abbe diagram. To prevent uncontrolled crystallization, it is necessary to cross the critical temperature range of crystallization as quickly as possible in a very controlled way. This becomes more and more difficult with increasing sizes of the mould. Therefore many glasses cannot be produced in large formats.

LAK, LAF and also KZFS glasses can be produced in long, wide strip formats with relative low thickness. Therefore lenses with diameters up to 160 mm and 43 mm thickness are currently possible. Dimensions of 280 x 280 x 80 mm might be realizable with additional development efforts.

FK and PK glass types can be produced up to diameters of 300 mm and 80 mm thickness with additional development effort.

Larger diameters with some pre-forming of curvatures may be achieved with the slumping method. The glass will be reheated until it becomes soft enough to flow under its own weight. Standing in a mould with larger diameters and a curved bottom will help it acquire the new desired shape when sufficient total volume is available. In general, this process does not affect the quality of the glass.

Figure 18 is showing a 2200 mm diameter SCHOTT N-BK7® blank after slumping in the mould. It was possible to completely fill the mould. This is the largest ever produced SCHOTT N-BK7® blank. The edge thickness is about 60 mm.

Fig. 18: 2200 mm diameter SCHOTT N-BK7® blank after slumping

Material/Glass Type Family	Max Dim current Capabilities [GD in mm]	Max Dim with Development [GD in mm]	Restricted by	Preferred Glass Types
BK	∅ 1200 x 300	∅ 1500 x 500 or equiv. Vol	CT, CS, ES	SCHOTT N-BK7®
LLF, LF, F, SF, *(FK)*	∅ 1200 x 300	∅ 1500 x 500 or equiv. Vol	CT, CS, ES	LLF1/LLF1HTi, LF5HTi, F2, SF6, *(N-FK5)*
FK, PK	∅ 160 x 40	∅ 300 x 80	Cryst, VS	N-FK51A
LAK, LAF,	300 x 160 x 43	280 x 280 x 80	Cryst, VS	N-LAK8, N-LAK9
KZFS	300 x 160 x 43	360 x 280 x 80	Cryst, VS	N-KZFS4

CT: Casting Time
CS: Center-Striae
ES: Edge-Striae
VS: Volume Striae
Cryst: Crystallization
GD: Gross diameter

Tab. 2: Glass types and their associated production information

Back to index

SCHOTT
glass made of ideas

TIE-41 Large Optical Glass Blanks

6. Homogeneity of large SCHOTT N-BK7® and LLF1 cylindrical blanks

Figure 19 shows the result of the homogeneity measurement of an 1150 mm diameter SCHOTT N-BK7® blank with 100 mm thickness on an aperture of 870 mm diameter. The focal aberration Zernike term is subtracted. The peak to valley homogeneity is about 3.9 ppm equivalent to H3 homogeneity. The small white spots in the color map result from the stitching fiducials of 6 individual measurements.

It is important to recognize that the homogeneity of optical glass is usually much better on smaller apertures. A systematic evaluation of the whole blank on sub-apertures of 100 mm is shown in Figure 20. Most of the apertures show a homogeneity of H5 (< 1 ppm peak to valley, green color) all other apertures have a homogeneity of H4 (< 2 ppm peak to valley, yellow color) after piston and tilt subtraction.

Homogeneity on 100 x 100 sub-apertures (piston and tilt removed)

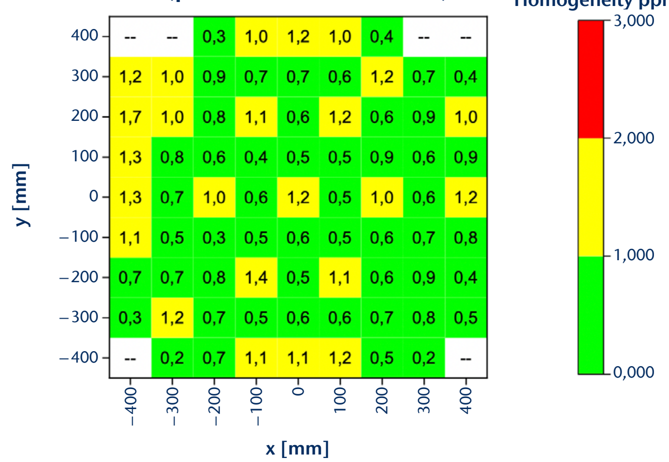

Fig. 20: The same blank yields H4 to H5 quality on all 100 x 100 mm sub-apertures (after piston and tilt subtraction)! The number in each square shows the peak-to-valley refractive index variation.

Homogeneity on 870 mm diameter aperture (piston, tilt and focus removed)

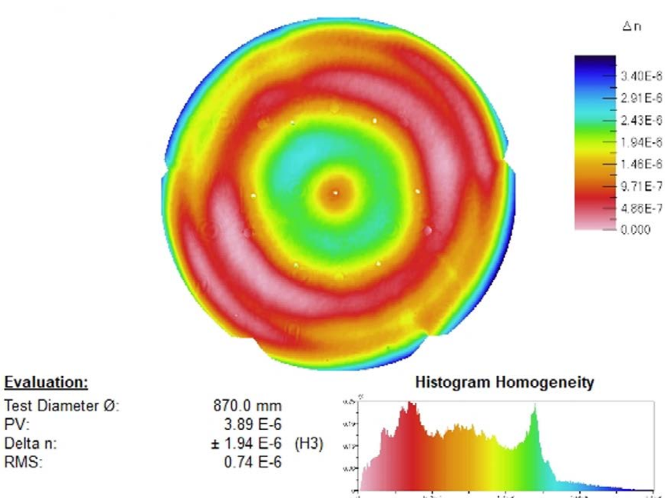

Fig. 19: 1150 mm diameter SCHOTT N-BK7® blank measured on 870 mm aperture yields H3 (after piston, tilt and focus subtraction).

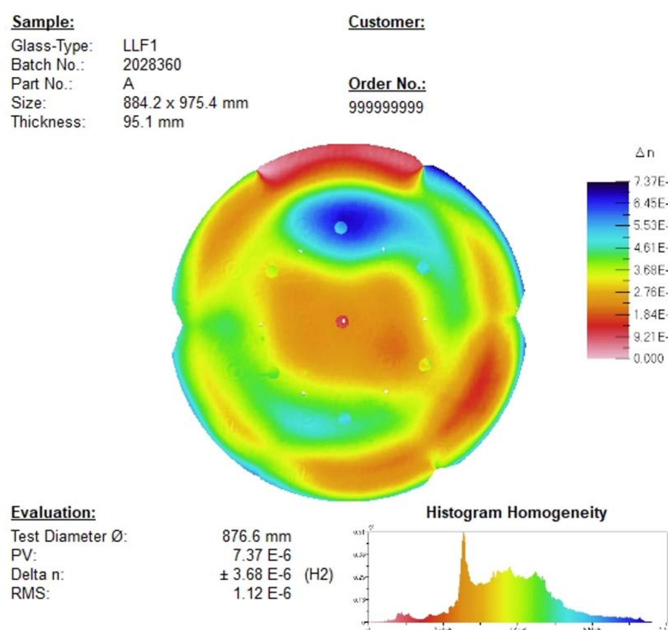

Fig. 21: 900 mm diameter LLF1 in H2 quality!

Back to index

SCHOTT
glass made of ideas

TIE-41 Large Optical Glass Blanks

Figure 21 shows the results of the homogeneity measurement certificate of a 900 mm LLF1 blank on a measurement aperture of 876 mm and 95 mm thickness. The measurement was taken on the 500 mm aperture Direct 100 interferometer. The peak to valley refractive index homogeneity is 7.4 ppm equivalent to H2 quality after focus subtraction.

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7. Homogeneity of large SCHOTT N-BK7® strip glass

Another production format for large SCHOTT N-BK7® applications are large strips that can be produced continuously (see Figure 22). The homogeneity of these parts with typical size 900 x 450 x 100 mm³ is better than 4 ppm peak to valley (H3) over almost the full aperture. The stress birefringence is typically very low (< 5 nm/cm) with no short range variations like striae or ripples.

Figure 23 shows the homogeneity results of such a strip glass on a measurement aperture of 800 x 400 mm². The measurement was done on the Zygo 24" Verifire MST in Duryea. The peak to valley variation of the refractive index is 2 ppm equivalent to H4 quality according ISO 10110-18. No short range refractive index variations are visible.

Fig. 22: 900 x 450 x 100 mm³ continuously produced SCHOTT N-BK7® strip!

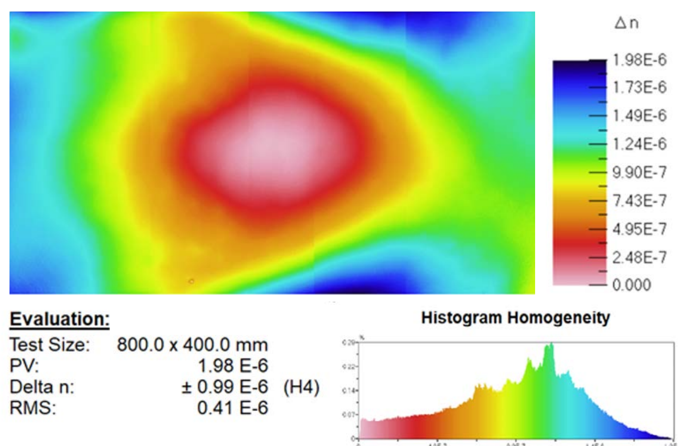

Fig. 23: 800 mm x 400 mm SCHOTT N-BK7® strip in H4 quality!

Back to index

TIE-41 Large Optical Glass Blanks

8. Production Sequence

The total production cycle for a slumped large blank easily extends to one year. Table 3 shows a list of the different production steps and the corresponding time required in weeks. The preparation process and the melting, refining and casting process steps of a blank with 1500 mm diameter blank would take about 7 weeks in total.

With today's continuous tanks it is not possible to produce glass for just a single large blank. The need for high homogeneity requires casting over a time range, where the refractive index has to be very constant. Normal variations at the start of a new tank melt have to be eliminated before casting may begin. Only after one or two days of production can the first casting begin. Therefore if only one blank is needed, the price of the blank has to cover the total costs of all the glass, which has to be produced along with that blank. The remaining glass may possibly not be sold due to restricted demand and special optical positioning with respect to the refractive index and dispersion. This is especially so with lead containing glass types, which are not used in consumer optics anymore.

Directly after the casting process, the still viscous melt has to be taken to a coarse annealing furnace. The hot glass melt will be cooled down to room temperature in special coarse annealing ovens for about 6 weeks. The time required depends on the size and the type of glass involved and needs to be done slowly in order to preserve the blanks from breakage due to internal stress. During coarse annealing, the temperature field around the mould must be kept as stable as possible.

Production step	**Weeks**
1. Production of large moulds	16
2. Melting, refining, casting	1
3. Coarse annealing and first inspection	6
4. Fine annealing	17
5. Pre-machining for inspection (polished faces with moderate flatness specification for striae and inclusion inspection, fine lapping for interferometric measurements), cutting samples for the measurement of optical properties (refractive index, Abbe number, internal transmittance)	4
6. Inspection of internal quality (striae, bubbles and inclusions, stress birefringence)	1
7. Homogeneity measurement with Fizeau interferometer	1
8. Final machining to requested blank shape – Geometrical inspection	2
Total time optimum when all resources are available in time	48

Table 3: Production sequence of large optical glass blanks. The typical production times needed per step are given in weeks. The total production of a large slumped glass blank will take more than 1 year.

After a first inspection for striae, bubbles and inclusions, the glass blank will be fineannealed. This is the most time-consuming process in the production of large optical glass blanks. The fineannealing process determines the final refractive index, the optical homogeneity and the stress birefringence. The refractive index of a piece of glass is given by its chemical composition only in the range of 10^{-3}. The final values down to the 6^{th} or 7^{th} decimal place will be fixed by the fine annealing.

Back to index

TIE-41 Large Optical Glass Blanks

During cooling down over this temperature range, one must keep the temperature differences in a large piece of glass as small as possible. The differences induced in a volume of a poor thermal conductor are not linear with its dimensions. They are proportional to the square of the thickness of a plate. So even if larger and hence thicker blanks could be cast, the annealing times necessary to achieve high homogeneity would become extremely long – too long to be practical.

After fine-annealing, the glass goes through internal quality inspection and homogeneity measurement.

9. Recommendations

The availability of large optical components depends on several factors as discussed above. Here are some concluding recommendations:

- Keep dimensions of the transmissive optical elements as small as possible. This holds especially true for the thickness of large lenses. The thickness determines the thermal inertia of the lens, which is the cause for many problems in production and in operation of the optical element. Due to the quadratic influence on temperature differences in the volume even small thickness reductions will help.

- Large lenses will be unique and sensitive pieces. They play a key role in the optical system and require very long periods of time in order to replace them during cases of accidents. Therefore it is recommended to apply special risk management procedures to the entire production process, right from the very start until the final mounting of the lenses in the structure of the telescope.

- Most of the internal imperfections like striae or inclusions will lead to stray light or deflected light. They may also become visible if they are close to an intermediate image plane. Simulation calculations should be considered to assess the effects of these imperfections to prevent overspecification and to find restrictions early enough to look for remedial solutions. The same holds for the temperature gradient induced inhomogeneity. The most promising ways of minimizing it, is the thermal stabilization and its inclusion in the adaptive optics correction feedback loop.

SCHOTT is confident of producing large glass blanks. With existing methods, it offers products that can be manufactured on a best-effort basis. If required combinations of glass type and dimensions development projects are not realizable upfront, development projects can be taken into account. Nevertheless, development times and production cycles usually take long periods of time and should therefore be initiated early on.

TIE-41 Large Optical Glass Blanks

10. Literature

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Back to index

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