Bifocal Optical System of the Schmidt Camera.
(Design of the Corrector Ring)

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Abstract .

In this paper we have analyzed the optical system of the AUGER Fluorescence Detector (FD) with the aim to improve the speed of the existing setup based on the Schmidt camera without corrector plate. The goal is to design suitable optical element in the shape of an annulus. This approach has been discussed several times within the FD task group.
The inclusion of the corrector ring must not deteriorate the properties of the whole optical system. The main criterion is preservation of maximum spot size in picture plane. The spot has to be contained within diameter d = 15 mm (0.5 deg in angular measure).
The issue of the correcting element boiled down to the design of the optimal shape of the first corrector ring surface. We describe possible solutions together with presentation of the corrector ring influence on the characteristics of the light spot in the picture plane. Finally we present a design of the realistic optical element as an example of the shape whose production technology will be eventually necessary to master.

1 Introduction

We shall briefly recall the technique of the optical system design generally in order to show that the final solution of the correction element under study will always have similar result regardless of the used method.
The design of any optical system has to stem from conditions imposed by the desired quality of projection, space and operation conditions and available material and technology.
The basic design is done using thin optical elements with the aim to find optimal maximum diameters of individual elements and their positions, apertures included. During this stage one has to follow reasonable optical power of individual elements, i.e. the value of relative aperture and the size of the field of view has to be kept so that the desired optical quality stays preserved.
The next step is replacement of ideal thin elements by realistic ones. The individual elements acquire now real thickness and the material of refractive elements has to be chosen. In this phase one corrects primary aberrations in the space of the 3rd order by shaping of lenses, change of thickness of the elements and distances among them or eventually by change of material of the refractive elements. Sometimes it is necessary to substitute some optical

element by two new ones so that its optical power is divided among more optical surfaces or to substitute the spherical surfaces by aspheric ones.
Then follow the trigonometric calculations of the correction state of the optical system in order to asses the necessity to change its construction parameters.
The last step of the design is the elimination of residual aberrations of higher orders by subtle change of the above mentioned parameters.

The possible subtle changes improving the quality of the optical system are:

- the change of one or more curvature radii of individual optical surfaces,
- the change of one or more distances along the optical axis (thickness of elements or their distances),
- change of the refraction index by using different material of refractive elements.

Should not such corrections lead to desired goal, i.e. improvement of the projection properties of the system, it is necessary to reconstruct the whole setup.

In the following Fig. 1 is shown the optical scheme of the current Schmidt camera with the correction plate included. In reality we suppose to use the correction plate in the shape of an annulus only. For the following discussion this is inessential.

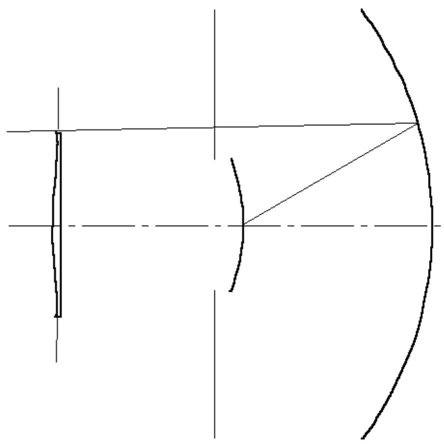

Fig. 1: Optical scheme of the Schmidt camera.

At present the design of the FD Schmidt camera optical system has passed the first two points mentioned above and it remains to do only the last step – the correction of the residual aberrations. The two preceding steps, when one can still strongly influence the optical quality of the setup have been already surpassed.

The construction parameters of the current optical system are thus already fixed and it is impossible to use them for sake of aberration corrections. Their values are as follows:

- mirror curvature radius R = 3400 mm,
- curvature radius of the PMT camera body Rc = 1743 mm,
- the distance between the mirror and the camera S = 1657 mm (3400 mm – 1743 mm),
- diaphragm position is fixed in the plane of the center of the mirror curvature.

However, these are not the only limiting parameters. Another limiting parameter in our case is given by the necessity to ensure maximum transparency of the correction element in the wavelength region cca 300 nm – 400 nm. The choice of suitable material with such spectral properties is quite restricted. The chosen material cannot have a prohibitive price. This excludes the utilization of e.g. fused silica or other suitable optical glasses. We suppose as material some optical plastics like UV Acrylite manufactured by Cyro Industries. This choice is supported also by needs of manufacture technology as the correction annulus will have one aspheric surface.
From the reasons of weight and also from the necessity of high transparency of the correction annulus follows that the thickness of this optical element has to be kept minimal. Hence even this parameter is not completely free when eliminating the optical aberrations. The change of the thickness of this element in the range of few mm has no apparent influence on the aberration state of the optical system.
Thus trying to correct aberrations of the Schmidt optical system we are basically limited to shaping the two surfaces of the correction annulus. This annulus will have the outer diameter bigger then 2000 mm and it is clear that the use of aspheric surface is a necessity. Due to the need of the most simple manufacture of this large optical element we decided to shape only the first surface (the aspheric one) and to keep the other planar.

It has to be noted that it is possible to use a double-sided correction annulus having the same profile on both sides with mirror symmetry. Maximal depth of individual aspheric surfaces would then decrease by one half and the quality of the optical system will remain the same. The choice of the single or double-sided correction annulus is limited only by the adopted production technology.

It follows from the theory of the 3rd order aberrations which primary aberrations depend on the change of the shape of the optical surface and which ones do not.
Aberrations depending on the change of the shape of the optical surface are spherical aberration, coma, astigmatism and distortion. On the other hand the longitudinal and transversal chromatic defects and the field distortion do not depend on the shape of the optical surface.
Shaping of the first surface of the corrector annulus is thus the proper way to influence the important aberrations.

2. Bifocal optical system.

The choice of the method of the corrector annulus design was our first step. To justify the insertion of corrector annulus into system we aimed at doubling the light collecting area.
The following Fig. 1 and Fig. 2 show the existing optical system of the Schmidt camera without corrector plate compared with planned optical system with corrector annulus. We shall denote them hereafter as system **I** and system **II**, respectively.
Both two figures show the schematic section through the systems with ray beams at field of view (FOV) angels 0, 10, 15 and 20 degrees.

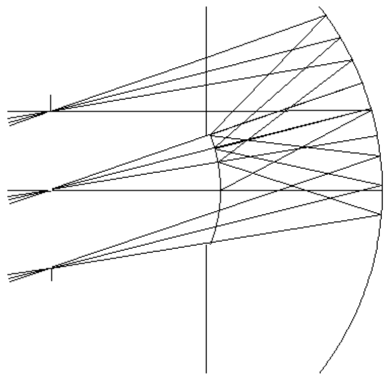

Fig. 2: Optical system I. Schmidt camera without corrector plate. Diaphragm diameter D=1700 mm, relative aperture **f**no **~ 1**. Maximal FOV is 20 degree. The mirror area is 3300 mm x 3300 mm.

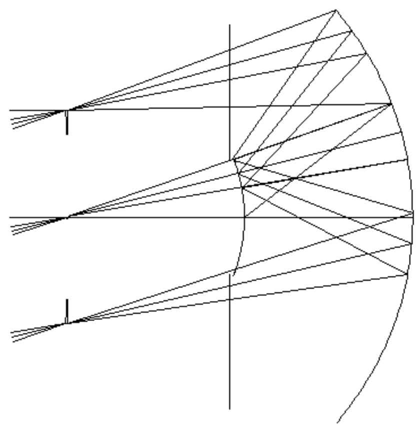

Fig. 3: Optical system II. Schmidt camera with corrector annulus of the outer diameter D=2200 mm, relative aperture **f**no **~ 0.77 .** The inner diameter of the corrector annulus is1700 mm. Maximal FOV is 20 degrees. The mirror area is about 3850 mm x 3850 mm.

By insertion of the corrector annulus with the outer diameter 2200 mm the light collecting area increases by about 104 %. However, one has to deduce this gain by losses caused by refraction and absorption in the corrector annulus.
By the notion of mirror area we understand perpendicular projection into plane tangential to the spherical surface at its apex (square of the arc length is somewhat bigger). Insertion of the corrector annulus inevitably leads to the increase of the mirror area if we want to avoid limitation of light rays coming askew (vigneting). If we look more closely at the Schmidt camera with corrector annulus it is clear that we are dealing with bifocal system composed of two subsystems. We shall decompose it back into these two parts and we shall study them independently.
The first system is shown in the Fig. 2. This system has the focal length f = 1700 mm and relative aperture approximately **1**. This is the current FD optical system without the corrector part and its properties have been analyzed already earlier (GAP-99-25).

The second system shown in the Fig. 3 has relative aperture about **0.77** and the focal length cca f = 1743 mm.

Our approach is to correct the system **II** in such a way that its spherical aberration becomes comparable with the spherical aberration of the system **I** in the whole FOV from 0^0 to 20^0 in the given picture plane. Finally we merge both two systems into one and check whether the maximum light spot stays still in the picture plane within a ring with diameter dmax = 15 mm.

In the following Fig. 4 [2] is shown the ray envelope in the vicinity of focal plane of the optical system **I**. The best picture plane is shifted from the paraxial focal plane by 42.34 mm towards the mirror of the system. The camera body with the photomultipliers will be placed in this plane and the light spot size here in ideal case has the diameter up to 15 mm.

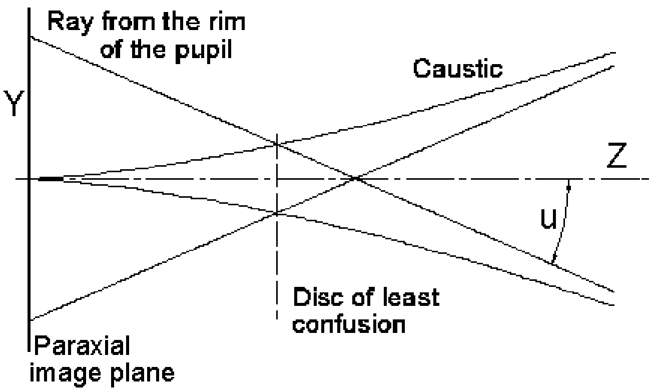

Fig. 4: The ray envelope in the vicinity of focal plane of the optical system I.

The properties of the optical system **I** are thus known and we have now to find the parameters of the optical system **II** in such a way that at first approximation its focal plane will lay in the best picture plane of the optical system **I**. Then its focal plane will acquire just the value f = 1700 + 42.34 = 1742.34 mm. This basic design uses the same method we have used earlier, which follows from the Fermat principle on light propagation of axial ray and the ray in the neutral zone which is determined by the given position of the picture plane.
We have looked for the equation of the corrector plate in the form:

$$\mathbf{Z = A\,y^2 + B\,y^4 + C\,y^6} \qquad \mathbf{(1)}$$

where Z is the depth of the profile curve,
y is the distance from the optical axis,
A,B,C are constants depending on the refraction index of the material, f-number, aperture and the position of the neutral zone.

Already in our previous paper [2] we have noted that the designed system of the FD Schmidt camera is too fast to allow us utilization of the corrector plate given by the equation with two terms only. This equation has been derived for the space of the III order (Seidel space) and outside this space it looses the precision. As the limit of validity is in the literature given the relative aperture **f / 3**. Therefore we have chosen the solution with three terms in the equation.

In case of relative aperture **f / 1** we have obtained the result with the light spot of the axial beam (FOV 0^0) nearing the 'point' size.
In the case of studied Schmidt system with the corrector plate the value of the relative aperture decreases even more to cca **f / 0.77**. This is already very fast system and one can suppose that in this case even the equation of the corrector plate with three terms will be not satisfactory. It is also apparent from the following figures 5 and 6.

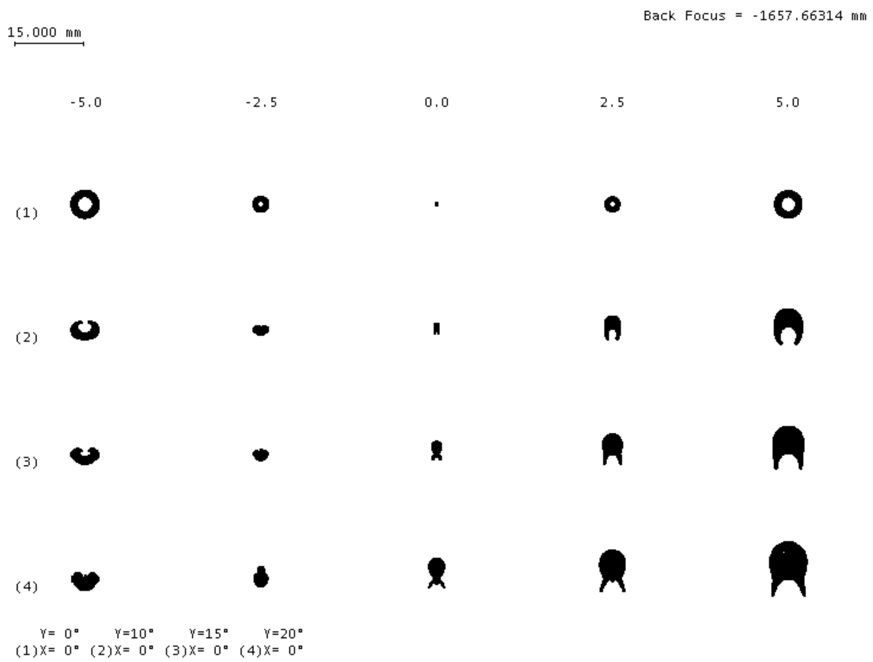

Fig. 5: Spot diagrams of the Schmidt camera with corrector plate with the diameter D = 1700 mm [2].

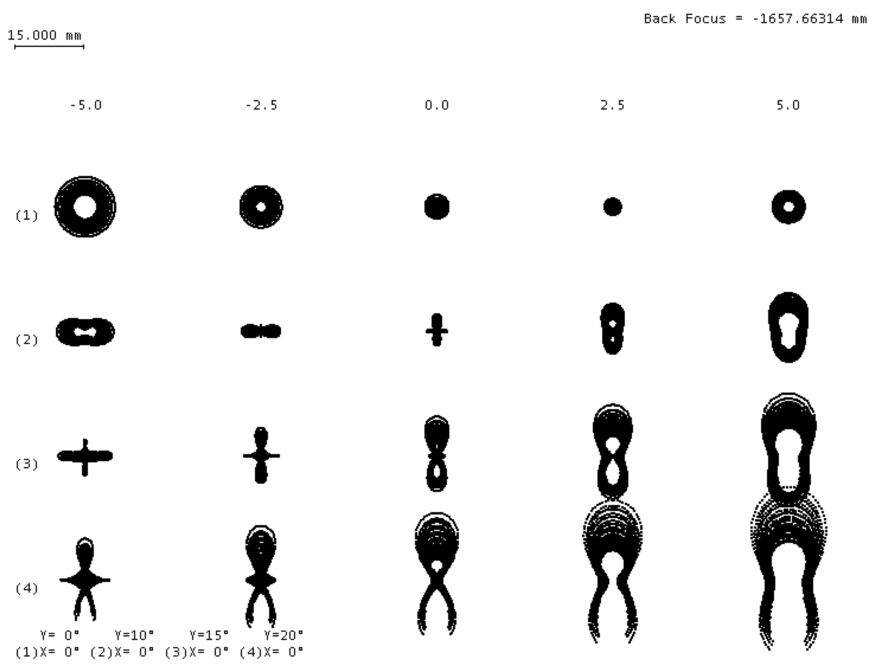

Fig. 6: Spot diagrams of the Schmidt camera with the corrector annulus (system II.)

The given spot diagrams show the sizes of light spots of the Schmidt camera with the corrector plate with the diameter 1700 mm (Fig. 5) and with the corrector annulus (Fig. 6). The diagrams are calculated for the whole assumed range of wavelengths 300 nm – 400 nm.
The bar in the upper left corner shows the scale of maximum allowed spherical aberration size 15 mm. Individual columns show the shapes of the light spots in five different picture planes. The middle column corresponds to the exact picture plane and the side columns correspond to the planes shifted by step of 2.5 mm, 2.5mm and 5 mm in both two directions. The individual rows then show light spots for FOV angles 0, 10, 15 and 20 degrees (from top down).
One can see in Fig. 5 that all the spots can be circumscribed by a circle with diameter 15 mm and this setup completely satisfies the necessary condition on projection quality. The light spot of the axial beam is close to point size and even in the 20^0 limit of the FOV it is still satisfactory.
However, if we keep the equation of the corrector plate profile and increase only its diameter to the value D = 2200 mm, one can see from Fig. 6 that the correction state deteriorates considerably.
The spot diameter increases not only for FOV 0^0, which results from the imprecision of the profile equation limited to three terms only. However, the most prominent increase of the spot size is apparent for FOV more then roughly 15^0. The skew beams thus fall beyond the demanded limit 15 mm.
Naturally we could slightly change the shape of the corrector annulus profile so that we could obtain the light spot as small as possible for FOV 0^0 as shown in Fig. 5. This is the usual goal of the design of standard system of Schmidt camera.
The corrector plate of the standard Schmidt camera is calculated so that it eliminates completely the spherical aberration of the setup. The light spot then has to have size comparable with the so called diffraction limit, which is the physical limit of the optical system quality. But one can reach this correction state only for FOV 0^0. The corrector plate is a refractive element, which introduces an asymmetry into the system. In the case of skew ray beams the influence of the aberrations of higher orders is apparent. It gets bigger with the increase of the FOV angle and with the increase of system aperture. The standard Schmidt systems are thus designed to minimize aberrations of higher orders. The cameras with big aperture have limited FOV contrary to cameras with large FOV, which are designed with smaller relative aperture.
In our case both two parameters are extreme and hence the space for the aberrations corrections is quite narrow.
It is possible to decrease the large off-axis aberrations only at the price of worsening the axial aberrations. From this follows the above mentioned method of the system **II** design. The transversal size of the light spots at the optical axis and at the limit of FOV at 20^0 will be thus roughly equal.

3. Two methods for shaping of the surface of the corrector annulus profile.

We have decided in our analysis to shape the profile of the first surface of the corrector annulus so that the light spots of the system **II** could be circumscribed by the circle with the diameter 15 mm for FOV between 0^0 and 20^0. We have started from the earlier mentioned analytical solution of the corrector plate profile equation (1). To shape this initial profile we have used the two following methods:

The First Method.

Recalling the Fig. 6 one can see that in the case of the shift of the picture plane by –5 mm (the left column) the maximal transverse dimensions of light spots are comparable within the whole range of the FOV from 0^0 to 20^0. Although the spots have different shapes they all stay within circumscribed circle with diameter up to 15 mm. Of course it is impossible to unify the shapes of the spots.

Hence the needed correction state of the system **II** can be reached by slight change of the position of the focal plane of the system **II**, i.e. by the shift from the best picture plane determined by the system **I**.

We shall shift the focal plane by approximately 5 mm but this cannot be done by simple change of the distance of the picture plane. Because the corrector plate makes together with the mirror single optical system it is necessary to change slightly the profile of the corrector plate in order to reach the desired effect. We have to recalculate the coefficients of the profile equation for the new focal position. Together with the change of the surface shape also the position of the neutral zone changes, i.e. the height above the system optical axis where the tangent of the corrector plate surface is perpendicular to optical surface. In other terms it is the height where the optical rays do not change their direction after passing the corrector.

Fig. 7 shows three shapes of the first surface of the corrector plate of the system **II**. The middle curve corresponds to the profile of the initial design where the focal length of the system **II** is equal to f = 1742.34 mm. The focal plane lays in the optimal picture plane of the system **I** as shown in Fig. 4. The resulting spot diagrams are given in the Fig. 6.

The upper curve corresponds to the situation when the focal length is recalculated to the value f = 1748 mm and the lower curve corresponds to f = 1738 mm. These values have been chosen to show the change of the surface shape induced by difference 10 mm of focal plane position.

The value f = 1738 mm 'shifts' the focal plane by 5.66 mm and the result are light spots of approximately same size over the whole FOV from 0^0 to 20^0 as shown in the left column of Fig 6.

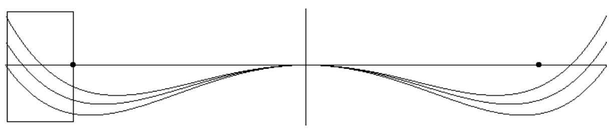

Fig. 7: Profiles of the corrector plate of the system II. The outer diameter is 2200 mm.
The two points mark the inner diameter of the annulus 1700 mm.
The scale of the profile depth is not realistic.

- upper curve   focal length f = 1748 mm (shift by -4.34 mm)
- middle curve   focal length f = 1742.34 mm (original position)
- lower curve   focal length f = 1738 mm (shift by + 5.66 mm)

The following Fig. 8 is the detail from Fig. 7 marked by the box on the left side. We present it to give better idea of how much the shape of the correction element changes after change of the focal length by 10 mm. Apparently this change is very subtle.

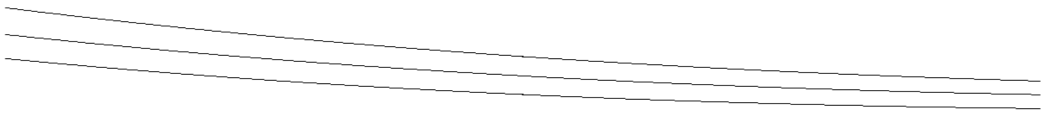

Fig. 8: Detail from Fig. 7. Profile between the radii 2200 mm and 1700 mm.

It is possible to compare Fig. 7 with the pictures usually given in the literature which deals with Schmidt camera and the profile shapes of the corrector plate for different heights of the neutral zone, i.e. for different choices of picture plane for which the system is corrected. The method is similar.
The left column in Fig. 6 is an example of a reasonable solution where the light spots of comparable size are over the whole FOV of the system **II**. For FOV 0^0 the light spot has the annular shape while e.g. for 20^0 the shape of the spot resembles a tall human figure.

At the radiation detection it is usually desirable to have uniform illumination of the photo-sensitive area to eliminate nonlinearity. Therefore we have considered the possibility to spline the sharp edges of light spots so that their size would not change significantly.

The Second Method

The ideas about smearing the light spots led us to employment of the second method of the surface shaping of the corrector annulus. Using the first method one changes the position of the neutral zone. The second method consists of changing the optical power of the corrector plate in such a manner that we change the depth of the surface profile but the height of the neutral zone remains constant. Naturally the position of the focal plane is shifted by this change from its original state. As the starting shape we have again used the profile calculated for the optimal picture plane of the system **I**.
This procedure is schematically shown in Fig. 9.

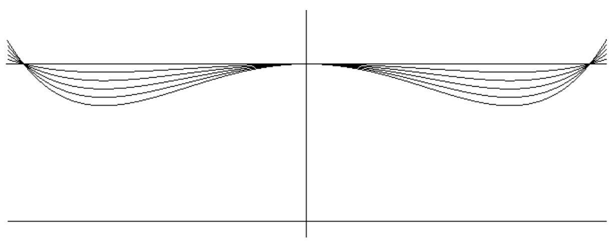

Fig. 9: The profile depth of the corrector plate changes towards planar shape.
The original shape corresponds to the middle curve in Fig. 7.

In our analysis of the system **II** we have combined both two above mentioned shaping methods in order to get the optimal profile of the corrector plate. By optimal we mean the shape which leads to system corrections and leaves the resulting light spots in picture plane within circumscribed circles with diameter 15 mm for FOV between 0^0 and 20^0.
The changes of the shape we done by changing the values of the coefficients A,B,C in the equation of the corrector plate profile (1). These changes were done 'by hand' as the search of direct analytical solution is more or less restricted to the aberration space of the 3^{rd} order (Seidl space). This space is limited by angles up to 15^0 or in other words it is relevant for optical systems with the relative aperture up to the value cca **f / 3**. The expressions for calculation of higher order aberrations become too complicated. We have found several similar solutions of the optimal shape of the first surface of the correction element and two of them are listed in the form of the spot diagrams in following Fig. 10 and Fig. 11.

The shape of the profile is described by the already listed equation :

$$\mathbf{Z = A\,y^2 + B\,y^4 + C\,y^6}$$

The two mentioned solutions have these coefficient values:

1,

$A = 1.2438489 \; 10^{-5}$
$B = -\,9.9372234 \; 10^{-12}$
$C = -\,1.5237456 \; 10^{-18}$

2,

$A = 9.9481644 \; 10^{-6}$
$B = -\,8.9382619 \; 10^{-12}$
$C = -\,1.3472051 \; 10^{-18}$

It is obvious from the following two spot diagrams that in the picture plane described by the middle column the condition of maximal size of the light spot up to 15 mm is valid. The spot of the axial beam has no longer annular shape but it is homogenized. Similarly in the case of the extreme FOV 20^0 the shape resembling human figure is thicker. This confirms the expected result of the second shaping method.

Note:

The unavoidable property of the chosen optical system is the change of the light spot shape in the picture plane with the increasing angle of FOV between 0^0 and 20^0. The choice of the set of shapes might be somewhat individual. We have chosen for the extreme FOV 20^0 the shape of human figure. However, after more detailed inspection of spot diagrams it is clear that the case where the light spot for the extreme FOV resembles e.g. a cross could be chosen as well. The changes of the shapes are induced by change of the picture plane position already by about 2 mm. This does not change significantly the shape of the corrector plate profile.

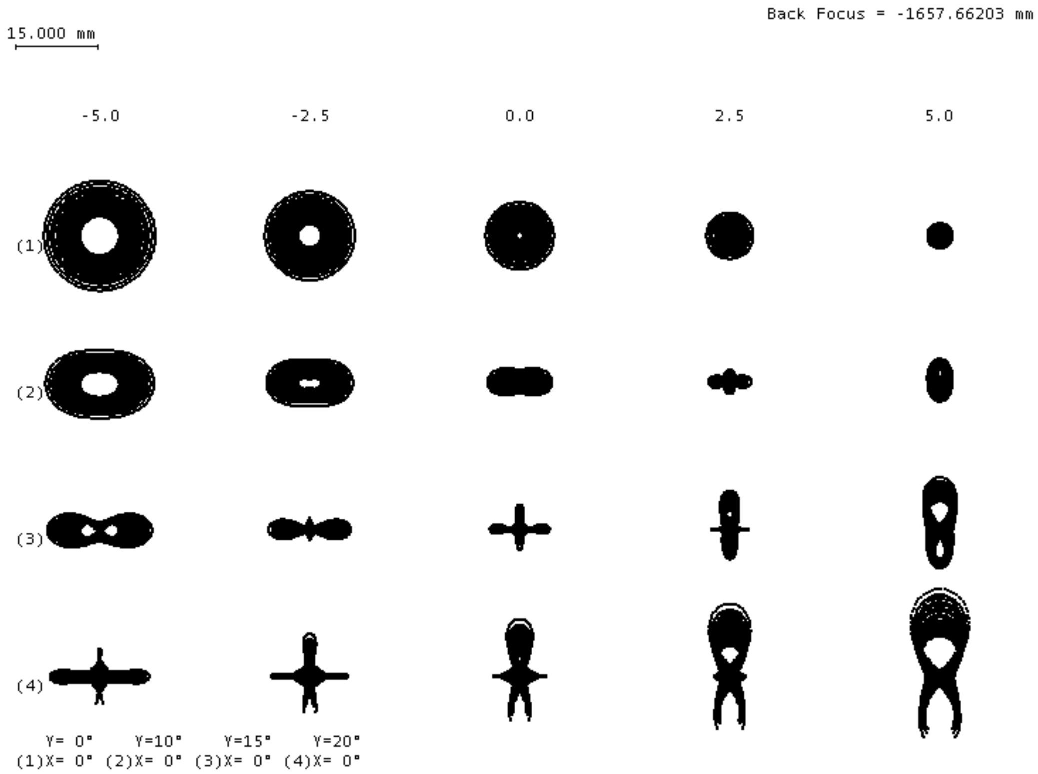

Fig. 10: Spot diagram of the system II with corrector annulus - 1st solution.

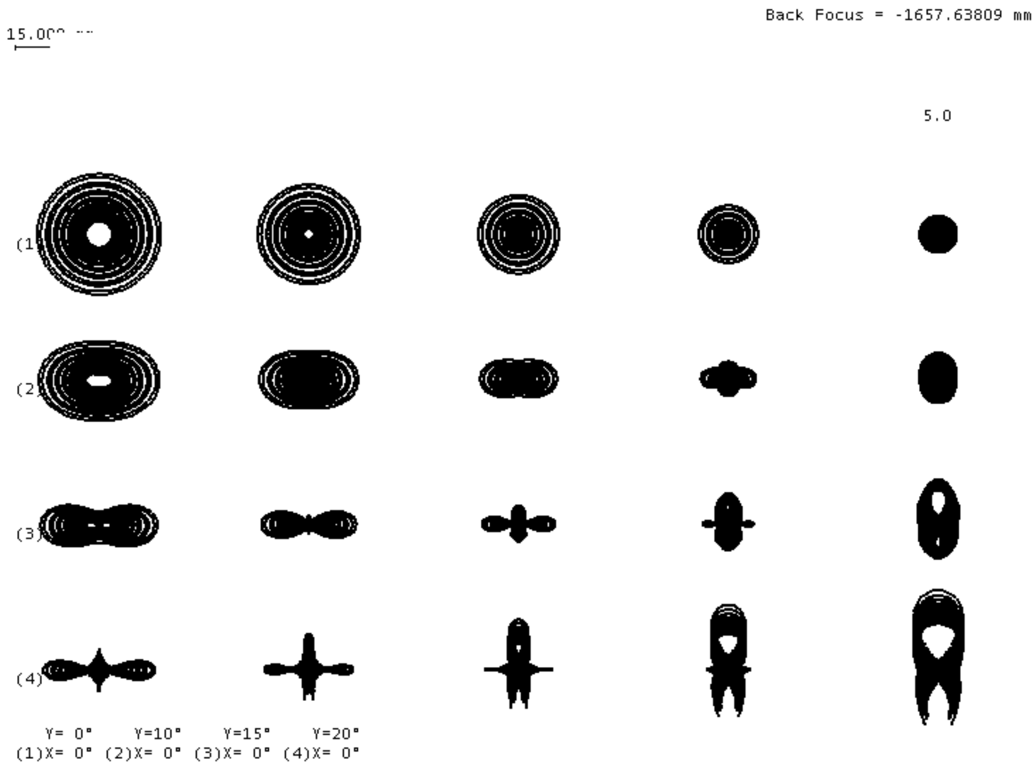

Fig. 11: Spot diagram of the system II with correction annulus - 2nd solution.

The listed two possible solutions of the corrector annulus profile are very similar. It apparent from the following series of Fig. 12, 13, 14.
The two surface shapes are sketched in Fig. 12 with exaggerated scale of profile depth. The outer diameter is 2200 mm. The inner diameter of the annulus is 1700 mm and it is marked by two points. For sake of better illustration the profile of the whole corrector plate is drawn.

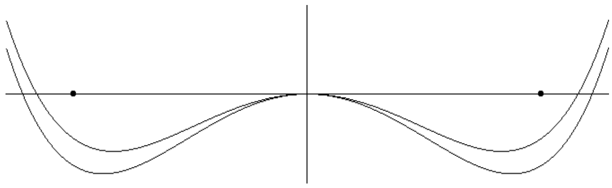

Fig. 12: Two possible solutions for the profile shape of the corrector plate.

The following picture shows the same two curves as in Fig. 12. They are both shifted so that the two end points overlap on the horizontal axis. This picture just illustrates to which extent the shapes of both two solutions coincide. It is evident that the differences are minimal - in particular in the important outer part.

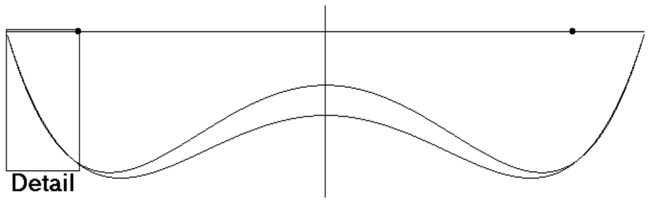

Fig. 13: The curves from Fig. 12 shifted vertically.

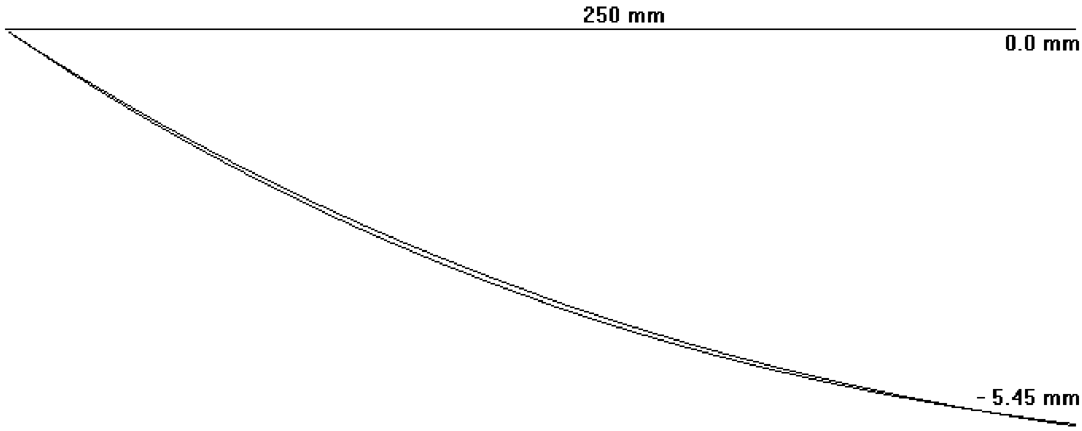

Fig. 14: The detail from Fig. 13. The scale is apparent from the numbers in mm.

The comparison of the two possible annulus profile solutions is in enlarged detail in Fig. 14. The maximum depth of the profile is between the outer diameter of the annulus 2200 mm and its inner diameter 1700 mm. Hence the width of the annular part is 250 mm as marked in the upper middle part of the picture. The maximum depth of the profile is about 5.5 mm (in case of the chosen material – Acrylite).

Thus we have found the solution of the possible shape of the first corrector annulus surface and we have shown that it complies with the condition on maximum spot size in the picture plane of the camera.

The next step is verification of this solution of the system **II** in such a way that we shall calculate the spot diagrams of the bifocal system of the Schmidt camera as a whole, i.e. the system **I** together with the system **II**.
Let us first recall the original design of the optical system of the Schmidt camera without correction element and with the radius of the aperture diaphragm 1700 mm. The corresponding spot diagram is in Fig. 15

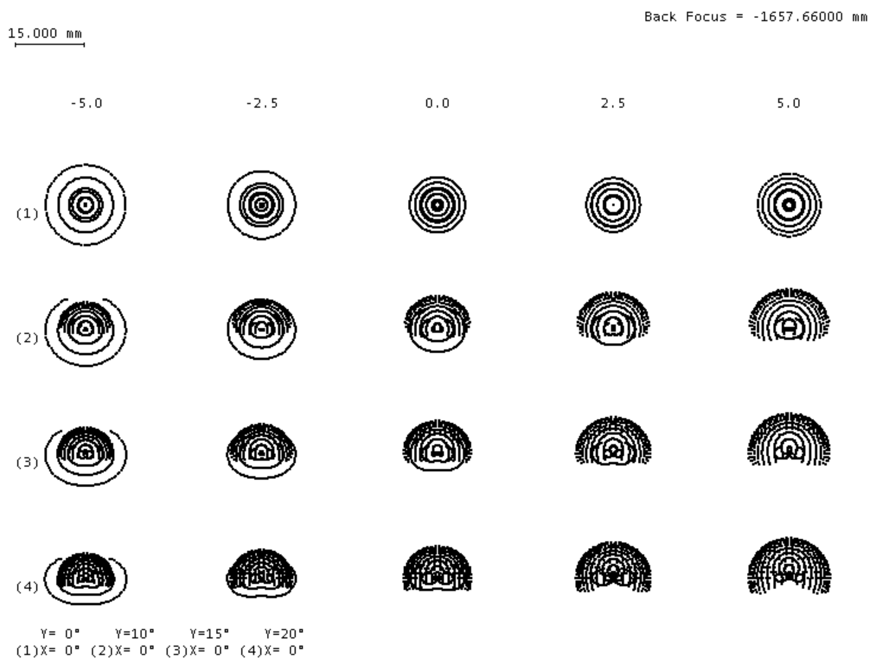

Fig. 15: Spot diagram of the Schmidt camera without corrector ring with the aperture diaphragm of the diameter 1700 mm (GAP-99-025)

Spot diagram of the Schmidt camera without the corrector plate shows that in the optimal picture plane (the middle column) one can circumscribe all the light spots with a circle of diameter 15 mm.
The shapes of the spots change with the increasing FOV angel as a result of the shadowing by the photomultiplier camera body. Without this shadowing all the spots would be the same. Looking at the middle column evidently bigger amount of energy is deposed in the middle of the spot at FOV angel 0^o. This effect has been discussed in GAP-99-025. This is also the reason why we have tried to smear the energy of the axial ray of the system **II** using the second shaping method.
To simulate the whole bifocal system we have chosen the first from the two above mentioned solutions of the system II. Corresponding spot diagram is shown in Fig. 16.

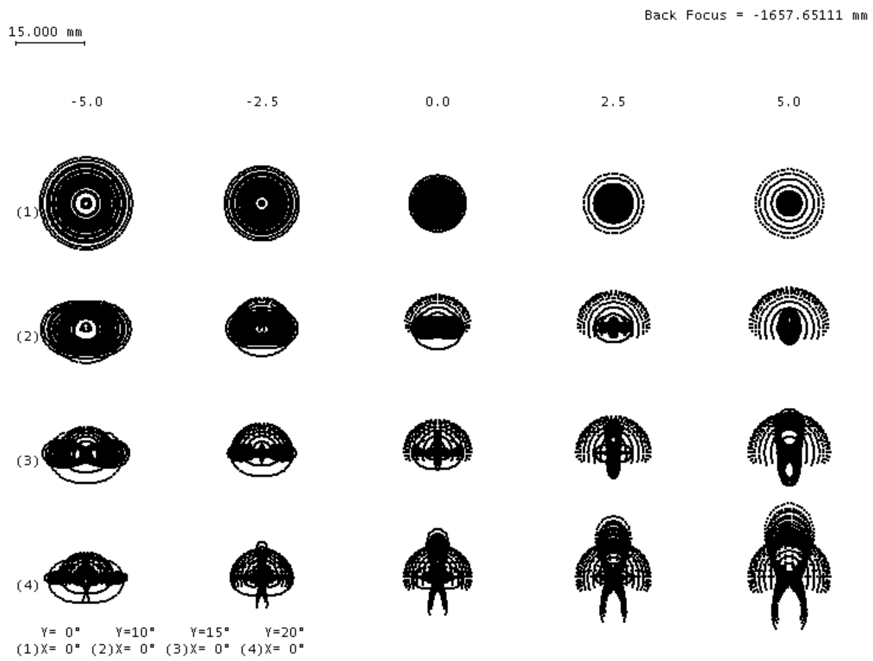

Fig. 16: Spot diagram of the whole bifocal system of the Schmidt camera with the corrector annulus with the outer diameter 2200 mm.

It is evident from the given picture that in the optimal picture plane the imposed condition on the spot size within 15 mm circle is fulfilled. This simultaneously corroborates the validity of the chosen design method, i.e. the division of the solution into two systems and their consecutive merging.

The energy distribution inside light spots is relatively homogenous within the whole range of the FOV from 0^0 to 20^0, which was our goal.

It can be also seen from the picture, that slight defocusation of the whole system in units of mm does not deteriorate significantly its quality.

Conclusions

The given results depend also on the choice of the corrector annulus material. We have supposed the use of acrylate, which is transparent in the ultraviolet part of the spectrum. The other materials seem to us expensive and even more difficult to machine in the case of supposed aspheric surface. Unfortunately we were not able to find exact values of the refraction index of the available material. Hence we have used the values given in the material database of the optical program KIDGER

These values were as follows:

wavelength	refraction index
300 nm	1.53294
350 nm	1.517036
400 nm	1.50731

We have calculated the optical aberrations for all listed wavelengths, i.e. for the whole supposed spectral region. It turned out that the chromatic aberrations do not play in the studied system any significant role.
We have supposed in our calculations the maximum width of the correction element 15 mm but this element can be made thinner – up to the theoretical limit. The changes of the corrector plate thickness do not influence the quality of the system. By theoretical limit we mean the state when the thinner side changes to sharp edge.

The presented calculations have been made without consideration of imprecision of the optical surfaces. We shall proceed in this direction during investigations of possibilities to manufacture the correction element. The final design of the surface shape will be possible only after the exact refraction index of perspective material will be given directly by manufacturer.

Concerning the production of the corrector annulus one has to bear in mind its size and therefore we stick to the accepted solution to divide the annulus into trapezoidal segments. An example of such division is given in Fig. 17.

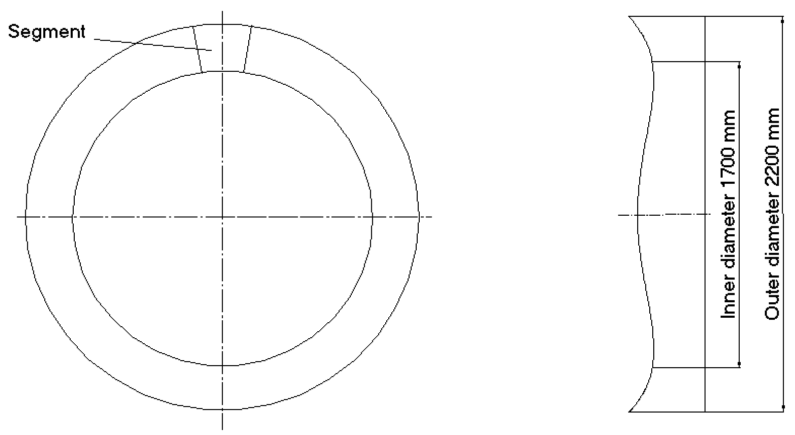

Fig. 17: An example of the corrector annulus segmentation.

Remark:

Part of this note is an individual page (file) with possible shape of one segment section in the scale 1 : 1. The thickness of this element is chosen just for orientation purpose and it depends on the necessary stiffness of the element and on the technology of its production. Theoretically one side can be reduced to sharp edge.

References:

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