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# Solution of Exercises
# Lecture Optical design with Zemax– Part 1

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## 1.1 Singlet imaging setup

Setup a system with a single lens to image an object. The wavelength should be $\lambda$=632.8 nm, the lens is made of the glass N-BK7 with radii R1 = 30 mm, R2 = -50 mm and a thickness t = 5 mm. The object distance is 50 mm. The numerical aperture in the object space is NA = 0.1.
a) Establish the system and determine the approximate image distance by three methods: 1) distance, where the marginal ray intersects the optical axis or 2) distance, where the spot of the axial object point has a minimal size or 3) determine the location in the layout, where the ray caustic has a minimal size.
b) What is the focal length of the system ? Determine the magnification and the numerical aperture in the image space. What is the reason for the differences in the direction cosines for real and paraxial raytracing ?
c) What is the relative enlargement of the spot size in the image for an object with diameter 10 mm at the edge in comparison to an object point on axis ?

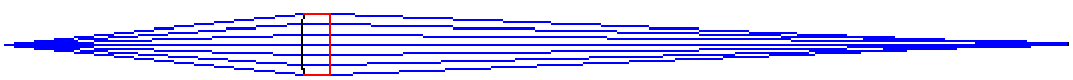
**Solution:**

a) System data:

Lens Data Editor

Edit Solves View Help

| | Surf:Type | Comment | Radius | Thickness | Glass |
|---|---|---|---|---|---|
| OBJ | Standard | | Infinity | 50.0000000 | |
| 1 | Standard | | 30.0000000 | 5.0000000 | N-BK7 |
| STO | Standard | | -50.000000 | 121.294000 | |
| IMA | Standard | | Infinity | - | |

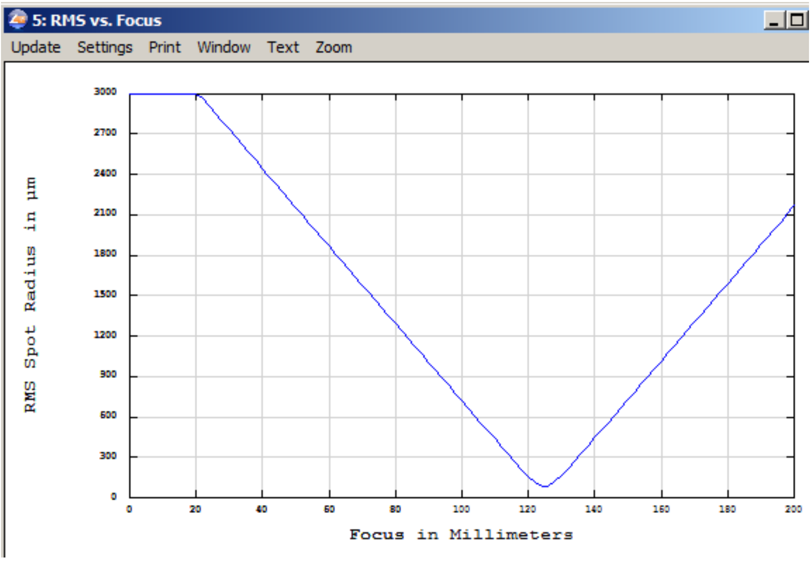


The image distance can be found by determining the distance, where is diameter of the marginal ray height is zero (in Lens Data Manager) or by calculating the marginal ray trace and deviding the height at the lens by the cosine of the ray behing the lens.

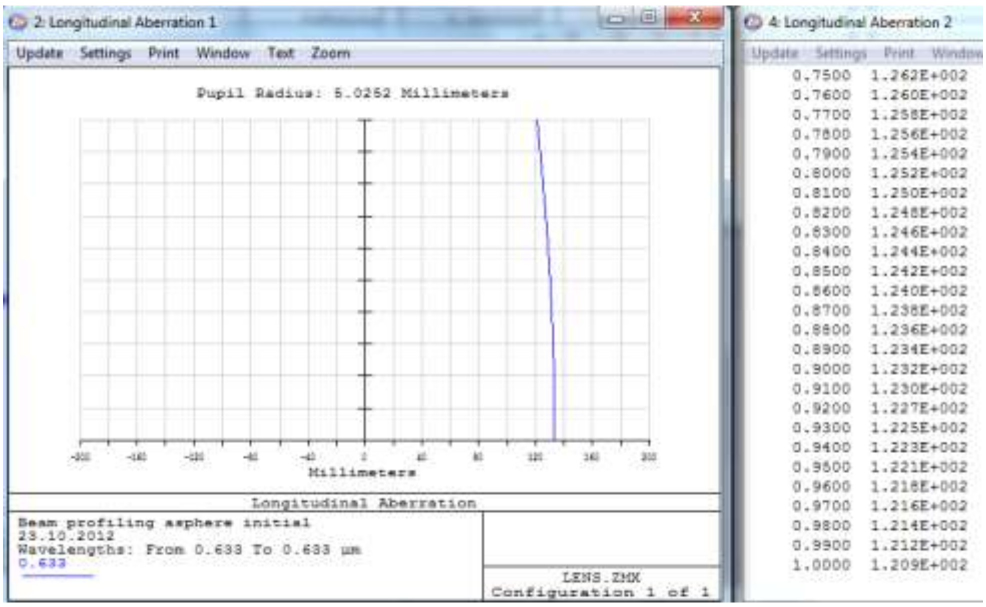
```
Real Ray Trace Data:

Surf      X-coordinate        Y-coordinate        Z-coordinate        X-cosine      Y-cosine
OBJ  0.0000000000E+000  0.0000000000E+000  0.0000000000E+000  0.0000000000  0.1000000000
  1  0.0000000000E+000  5.0685330379E+000  4.3126697263E-001  0.0000000000  0.0071634513
  2  0.0000000000E+000  5.0993940862E+000 -2.6071793890E-001  0.0000000000 -0.0420416082
  3  0.0000000000E+000 -1.5484000638E-002  0.0000000000E+000  0.0000000000 -0.0420416082
```

This gives approximately 121.3 mm. Other possibilities are minimizing the spot diameter (this gives 124.8 mm).




If the menue 'longitudinal aberration' is used for an image distance zero in the data, the exact intersection lengths of the paraxial and the marginal ray can also be taken from the text output numerically.




b) The data are found in the menue Prescription data: Focal length f = 37.19 mm. The numerical apertur is NA' = 0.0380.

2: Prescription Data

Update Settings Print Window

| | |
|---|---|
| Temperature (C) | 2.00000E+001 |
| Pressure (ATM) | 1.00000E+000 |
| Adjust Index Data To Environment | Off |
| Effective Focal Length | 37.19172 (in air at systen |
| Effective Focal Length | 37.19172 (in image space) |
| Back Focal Length | 35.08436 |
| Total Track | 129.8081 |
| Image Space F/# | 3.458545 |
| Paraxial Working F/# | 13.14791 |
| Working F/# | 11.89298 |
| Image Space NA | 0.0380014 |
| Object Space NA | 0.1 |
| Stop Radius | 5.072127 |
| Paraxial Image Height | 0 |
| Paraxial Magnification | 0 |
| Entrance Pupil Diameter | 10.75358 |
| Entrance Pupil Position | 3.49836 |
| Exit Pupil Diameter | 10.14425 |
| Exit Pupil Position | -124.8081 |
| Field Type | Object height in Millimeters |
| Maximum Radial Field | 0 |
| Primary Wavelength | 0.6328 µm |
| Lens Units | Millimeters |
| Angular Magnification | 0 |

The magnification of m=-2.64 is only seen, if a finite object height is inserted.
The image sided numerical aperture can also be seen in the raytrace data table. Due to spherical aberration, the real ray has a significantly (10%) larger numerical aperture value in the image space.

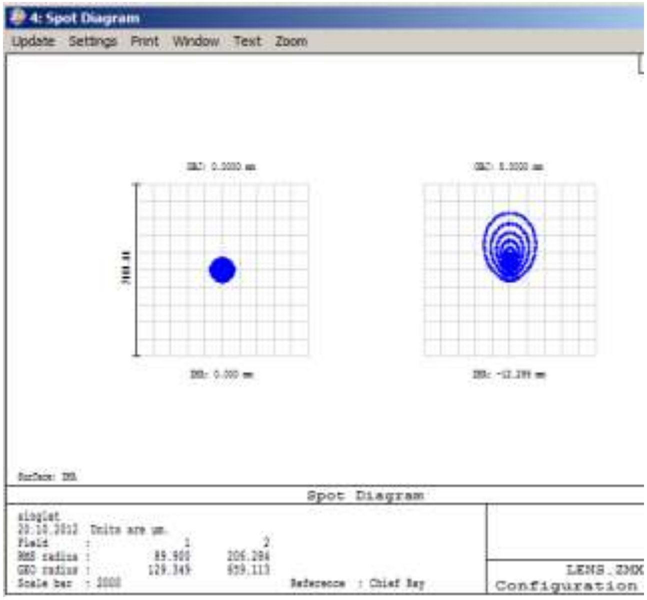
Real Ray Trace Data:

| Surf | X-coordinate | Y-coordinate | Z-coordinate | X-cosine | Y-cosine |
|---|---|---|---|---|---|
| OBJ | 0.0000000000E+000 | 0.0000000000E+000 | 0.0000000000E+000 | 0.0000000000 | 0.1000000000 |
| 1 | 0.0000000000E+000 | 5.0685330379E+000 | 4.3126697263E-001 | 0.0000000000 | 0.0071634513 |
| 2 | 0.0000000000E+000 | 5.0993940862E+000 | -2.6071793890E-001 | 0.0000000000 | -0.0420416082 |
| 3 | 0.0000000000E+000 | -1.5484000638E-002 | 0.0000000000E+000 | 0.0000000000 | -0.0420416082 |

Paraxial Ray Trace Data:

| Surf | X-coordinate | Y-coordinate | Z-coordinate | X-cosine | Y-cosine |
|---|---|---|---|---|---|
| OBJ | 0.0000000000E+000 | 0.0000000000E+000 | 0.0000000000E+000 | 0.0000000000 | 0.1000000000 |
| 1 | 0.0000000000E+000 | 5.0251890763E+000 | 0.0000000000E+000 | 0.0000000000 | 0.0093872148 |
| 2 | 0.0000000000E+000 | 5.0721272184E+000 | 0.0000000000E+000 | 0.0000000000 | -0.0380013956 |
| 3 | 0.0000000000E+000 | 4.5945413703E-001 | 0.0000000000E+000 | 0.0000000000 | -0.0380013956 |

c) If the object size is defined and the spot diagram is calculated, we get the following figure:
According to the numbers, the spot is grown by a factor of 2.2...5 depending on the criterion. Since also the shape is changed, an approximate factor of 3 seems to be reasonalbe.



## 1.2 System layout with ideal lenses

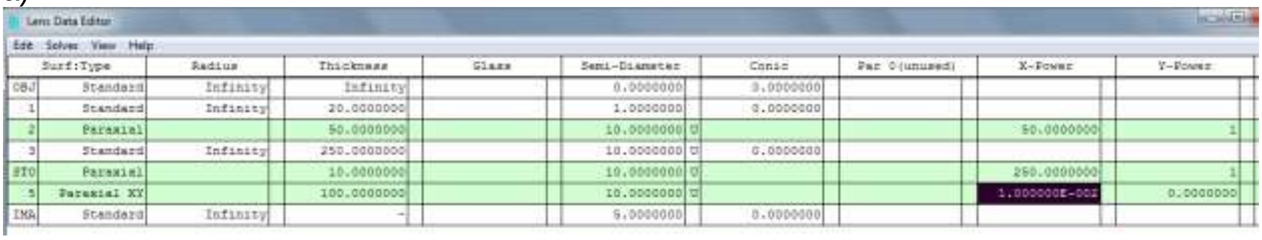
A collimated laser beam with wavelength 1.064 μm and diameter D = 2 mm should be expanded by a Kepler-type afocal telescope with a factor of 5. The enlarged beam is then focussed down by a cylindrical lens with focal length f = 100 mm to get a line focus.

a) Setup the system described above by ideal lenses

b) Show the line focus graphically

**Solution:**

a)



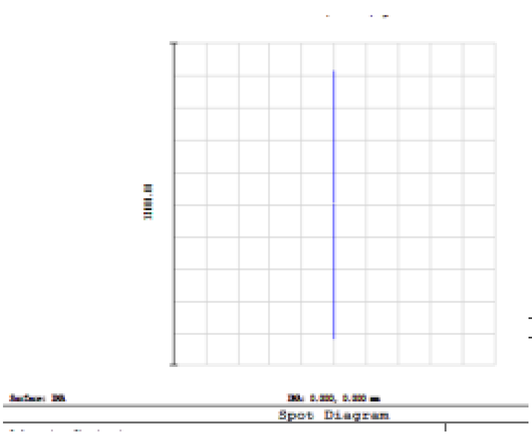
Lens Data Editor

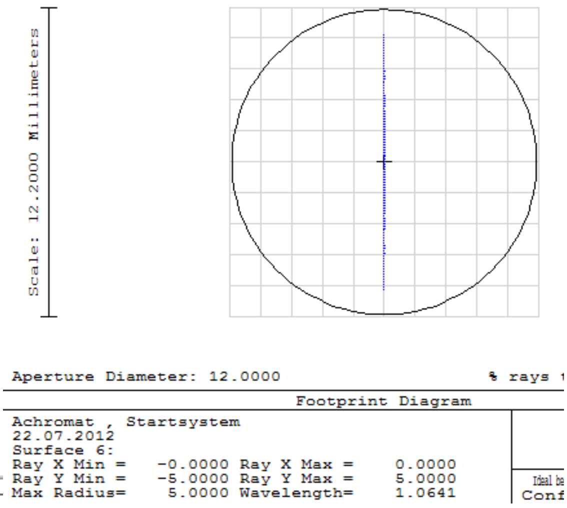
Edit Solves View Help

| | Surf:Type | Radius | Thickness | Glass | Semi-Diameter | Conic | Par 0 (unused) | X-Power | Y-Power |
|---|---|---|---|---|---|---|---|---|---|
| OBJ | Standard | Infinity | Infinity | | 0.0000000 | 0.0000000 | | | |
| 1 | Standard | Infinity | 20.0000000 | | 1.0000000 | 0.0000000 | | | |
| 2 | Paraxial | | 50.0000000 | | 10.0000000 U | | | 50.0000000 | 1 |
| 3 | Standard | Infinity | 250.0000000 | | 10.0000000 U | 0.0000000 | | | |
| STO | Paraxial | | 10.0000000 | | 10.0000000 U | | | 250.0000000 | 1 |
| 5 | Paraxial XY | | 100.0000000 | | 10.0000000 U | | | 1.000000E-002 | 0.0000000 |
| IMA | Standard | Infinity | - | | 5.0000000 | 0.0000000 | | | |

b) Spot diagram, more points, scale fixed, bad resolution

A footprint is an alternative option.




## 1.3 Symmetrical 4f-system

Setup a telecentric 4f-imaging system with two identical plano-convex lenses made of BK7 with thickness d = 10 mm and approximate focal lengths f = 100 mm. The wavelength of the system is $\lambda$ = 546.07 nm and the numerical aperture in the object space is NA = 0.2. The object has a diameter of 10 mm.

a) Determine the layout and the spot diagram of the system, if the setup is perfectly symmetrical.

b) Optimize the image location. Why is the spot size improved ?

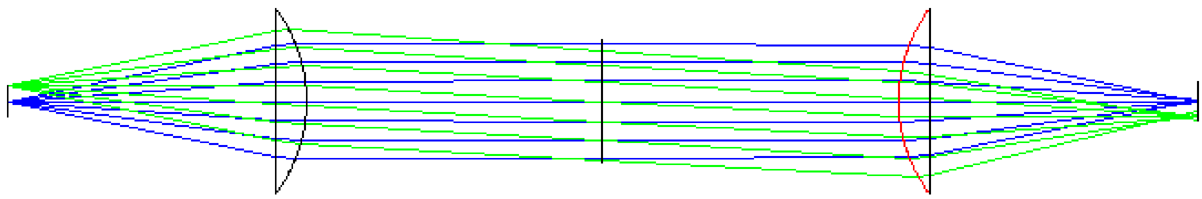
c) If the starting aperture is decreased, the system becomes more and more diffraction limited. What is the value of the NA to get a diffraction limited system on axis ? Take in mind here, that the lowered spherical aberrations needs a re-focussing, which depends on the aperture.

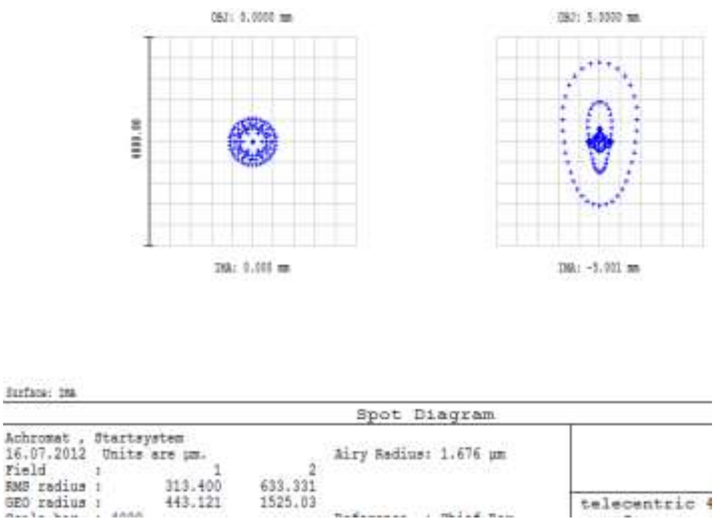
**Solution:**

Lens Data Editor

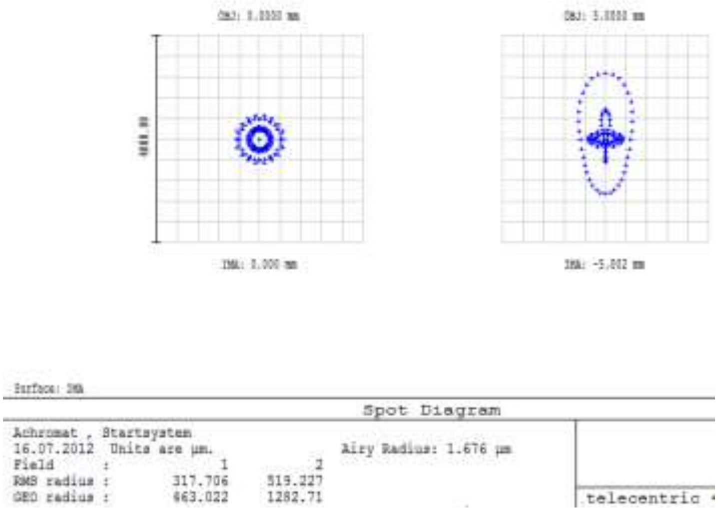
Edit Solves View Help

| | | Comment | Radius | | Thickness | | Glass | | Semi-Diameter | |
|---|---|---|---|---|---|---|---|---|---|---|
| * | Standard | | Infinity | | 87.0000000 | | | | 5.0000000 | |
| 1* | Standard | | Infinity | | 10.0000000 | | BK7 | | 30.0000000 | U |
| * | Standard | | -50.0000000 | | 96.0000000 | | | | 30.0000000 | U |
| 3 | Standard | | Infinity | | 96.0000000 | P | | | 20.0000000 | U |
| 4* | Standard | | 50.0000000 | P | 10.0000000 | P | BK7 | P | 30.0000000 | P |
| 5* | Standard | | Infinity | | 87.0000000 | P | | | 30.0000000 | P |
| * | Standard | | Infinity | | - | | | | 6.2237698 | |

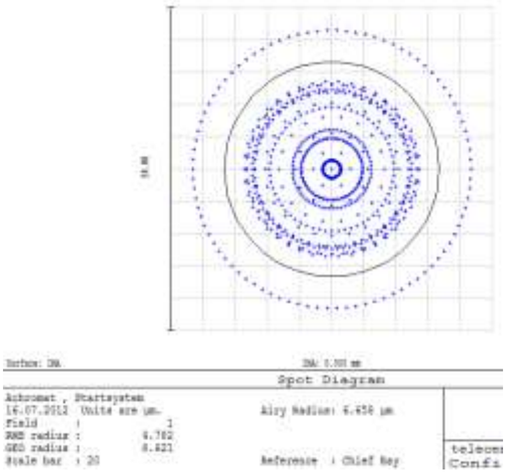





The best image location is approximately 1 mm nearer to the system with a considerably smaler size due to the spherical aberration of the system.




If the numerical aperture is reduced to a value of NA = 0.05, the system approximately is diffraction limited, as can be seen on the spot diagram on axis and the corresponding Airy diameter.




## 1.4 Conic surface

A system with an ellipsoidal mirror should be installed. For this task, the following steps should be performed:

a) A source with wavelength $\lambda$ = 1.064 $\mu$m and numerical aperture NA = 0.1 is imaged by a spherical mirror in a 1:1 setup with a mirror radius of 20 mm

b) The image distance is enlarged to 40 mm. The radius of the mirror and the conical constant is optimized for this geometry

c) The coordinate system is rotated by 60° directly after the object. For a proper layout, the subaperture of the mirror which is used should be explicitly defined. Make a shaded model layout with this setup.
What is the bending angle of the central ray at the mirror ? Determine the shape and the approximate x/y-aspect ratio of the illuminated area on the mirror.

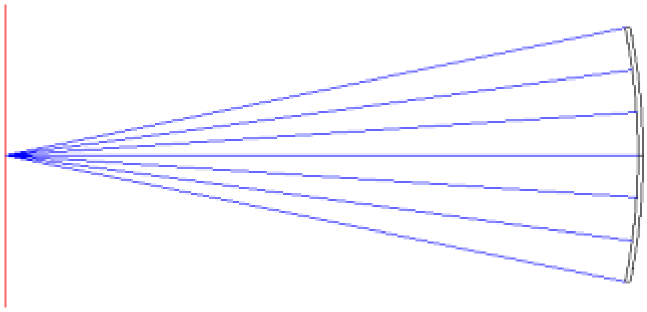
**Solution:**

a) spherical mirror with radius 20 mm

Lens Data Editor

Edit Solves View Help

| | Surf:Type | Comment | Radius | | Thickness | | Glass | | Semi-Diameter | | Conic | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * | Standard | | Infinity | | 20.0000000 | | | | 0.0000000 | | 0.0000000 | |
| * | Standard | | -20.0000000 | | -20.0000000 | | MIRROR | | 4.0000000 | | 0.0000000 | |
| * | Standard | | Infinity | | - | | | | 6.0000000 | U | 0.0000000 | |



b) Image distance doubled and a simple merit function (default) is used to optimize the radius r and conic constant

Lens Data Editor

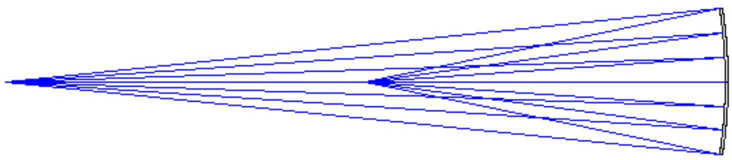
Edit Solves View Help

| | Surf:Type | Comment | Radius | | Thickness | | Glass | | Semi-Diameter | | Conic | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * | Standard | | Infinity | | 20.0000000 | | | | 0.0000000 | | 0.0000000 | |
| * | Standard | | -26.6666667 | V | -40.0000000 | | MIRROR | | 4.0283067 | | -0.1111111 | V |
| * | Standard | | Infinity | | - | | | | 6.705836E-011 | | 0.0000000 | |

Merit Function Editor: 1.126763E-010

Edit Tools View Help

| Oper # | Type | | | | | |
|---|---|---|---|---|---|---|
| 1: DMFS | DMFS | | | | | |
| 2: BLNK | BLNK | Default merit function: RMS spot radius centroid GQ 3 rings 6 arms | | | | |
| 3: BLNK | BLNK | No default air thickness boundary constraints. | | | | |
| 4: BLNK | BLNK | No default glass thickness boundary constraints. | | | | |
| 5: BLNK | BLNK | Operands for field 1. | | | | |
| 6: TRAC | TRAC | | 1 | 0.0000000 | 0.0000000 | |
| 7: TRAC | TRAC | | 1 | 0.0000000 | 0.0000000 | |
| 8: TRAC | TRAC | | 1 | 0.0000000 | 0.0000000 | |



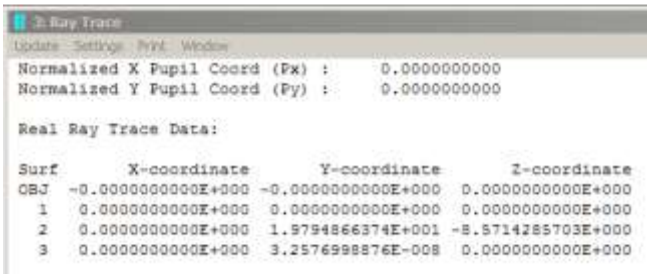
c) An additional surface is introduced after the object and a coordinate break is defined with 60°tilt around the x-axis.

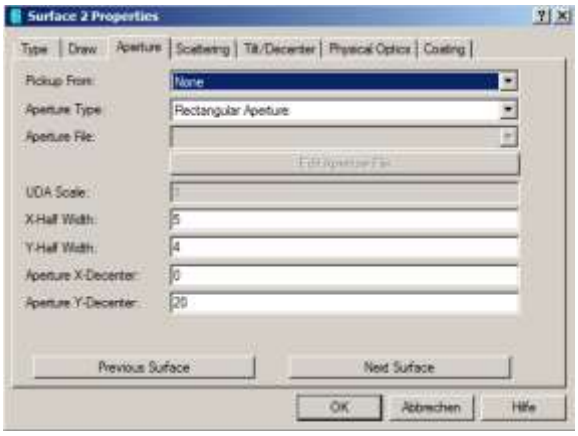
Lens Data Editor

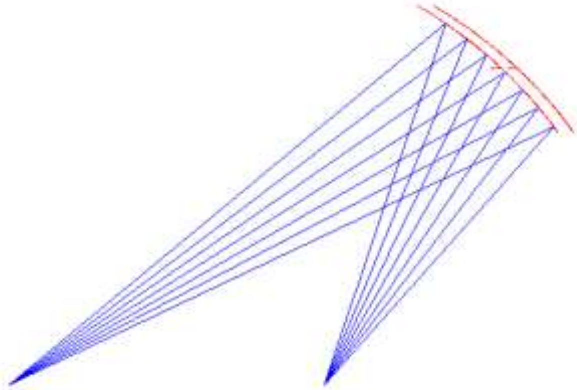
Edit Solves View Help

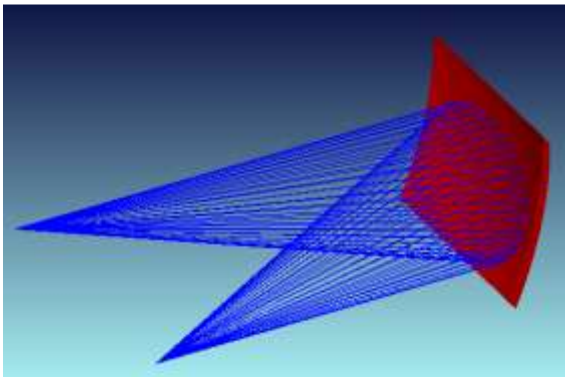
| | Surf:Type | Comment | Radius | | Thickness | Glass | Semi-Diameter | | Conic | | Par 0(unused) | Par 1(unused) | Par 2(unused) | Par 3(unused) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * | Standard | | Infinity | | 0.0000000 | | 0.0000000 | | 0.0000000 | | | | | |
| 1 | Coordinate B.. | | | | 20.0000000 | - | 0.0000000 | | | | | 0.0000000 | 0.0000000 | 60.0000000 |
| * | Standard | | -26.6666667 | V | -40.0000000 | MIRROR | 25.0000000 | U | -0.1111111 | V | | | | |
| * | Standard | | Infinity | | - | | 5.710031E-008 | | 0.0000000 | | | | | |

A raytrace shows, that in the y-z-plane the y-values of the aperture cone are 16.3...19.8...22.9 mm. Therefore a rectangular aperture with y-shift 20 mm and half diameters of 4 and 5 mm are defined.





If the ray trace is calculated for the central ray, we get the incidence angle 13.90°. Therefore the bending of the central ray is 27.8°.

A footprint on the mirror looks nearly elliptical with an aspect ratio of 0.712