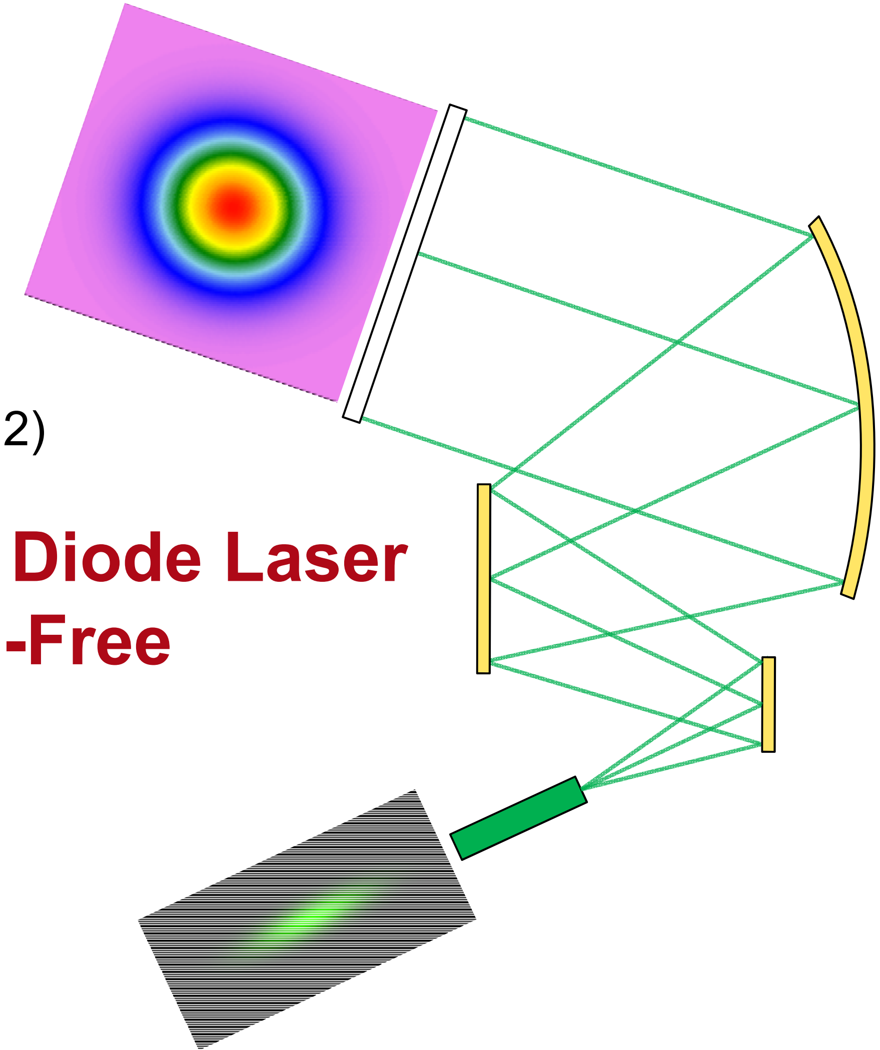
Beam Delivery Systems (BDS.0005 v1.2)

Collimation & Shaping of Diode Laser Beam Using a Dispersion-Free Off-Axis Reflective Setup



Application Example in a Nutshell

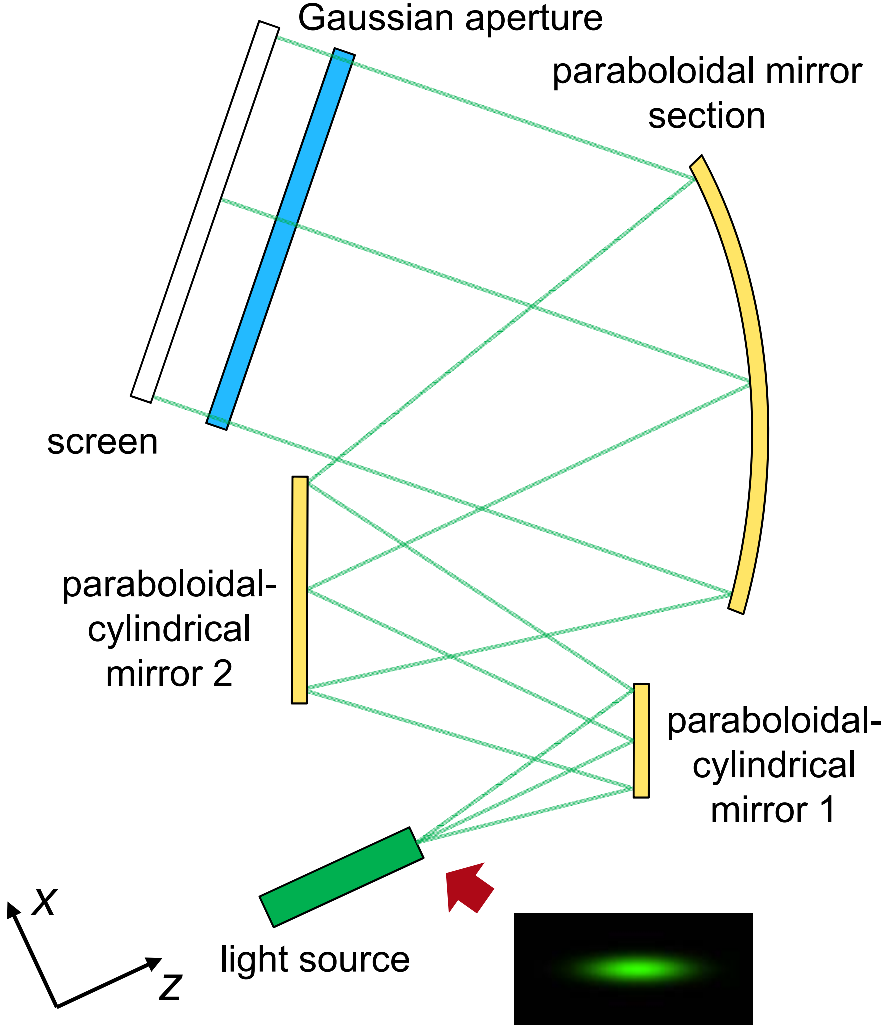
System Details

- Source
  - strong astigmatic VIS laser diode
- Components
  - reflective elements (e.g. paraboloidal-cylindrical mirrors) for beam collimation and shaping
  - aperture exhibiting a Gaussian amplitude modulation
- Detectors
  - visual check of rays (3D display)
  - wavefront error detection
  - field distribution and phase calculation
  - beam parameters (M^2-value, divergence)

  (visual check of rays, wavefront error detection: **Ray Tracing**; field distribution and phase calculation, beam parameters: **Field Tracing**)
- Modelling/Design
  - Ray Tracing: first system overview and **wavefront error calculation**
  - Geometric Field Tracing Plus (GFT+) & Classic Field Tracing (CFT):
    - ✓ **analysis and optimization of the shaped beam quality**
    - ✓ **Monte Carlo tolerancing of element orientation**

System Illustrations:

xz-plane:



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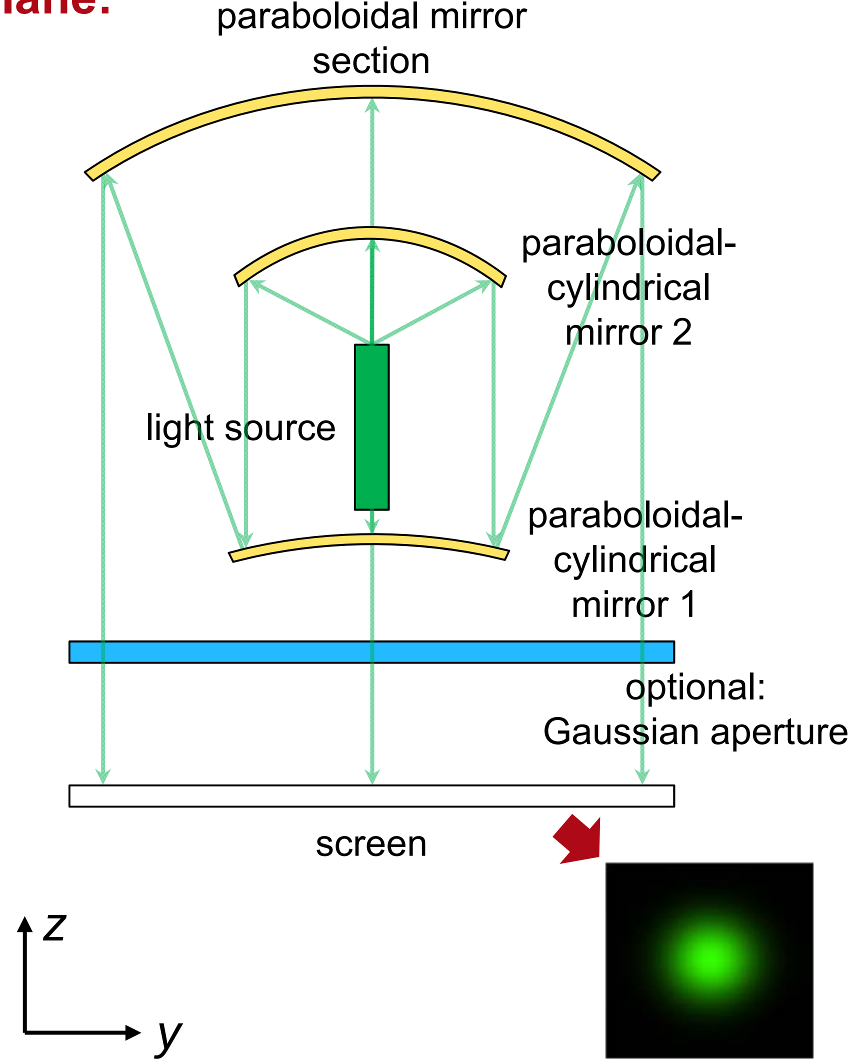
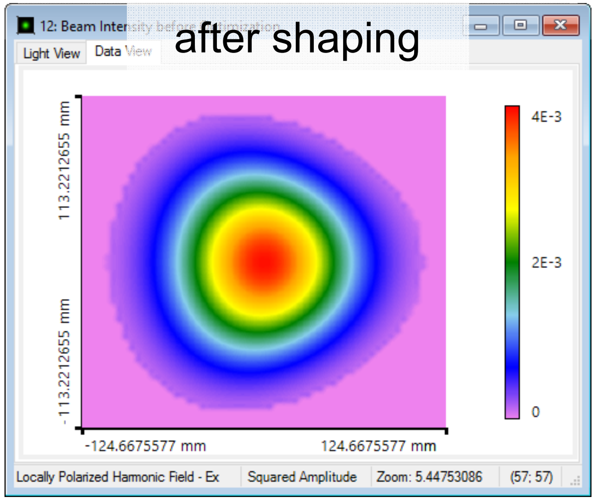
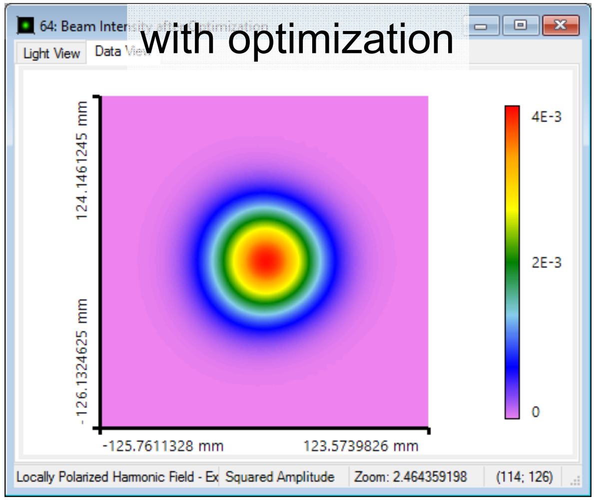


Modeling & Design Results

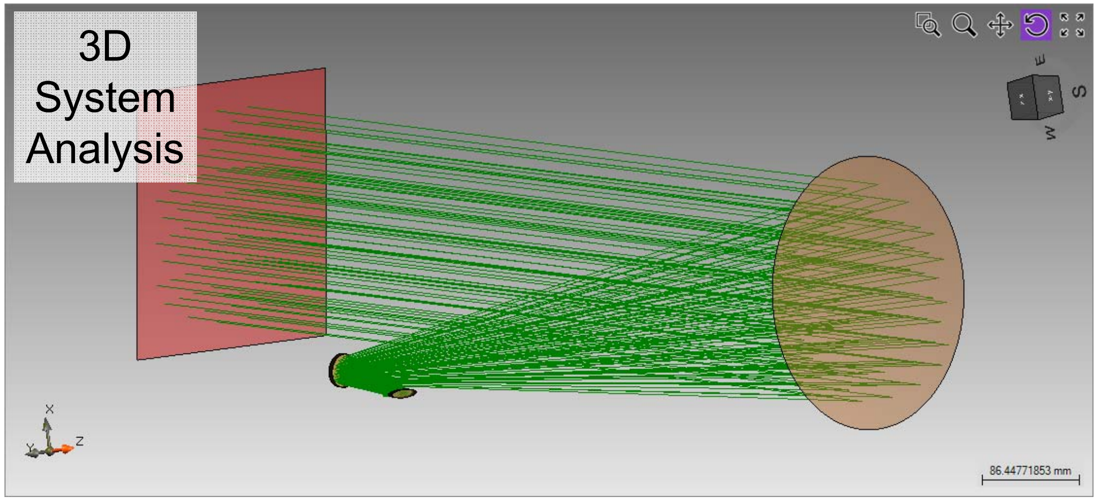
Field (Intensity) Distribution





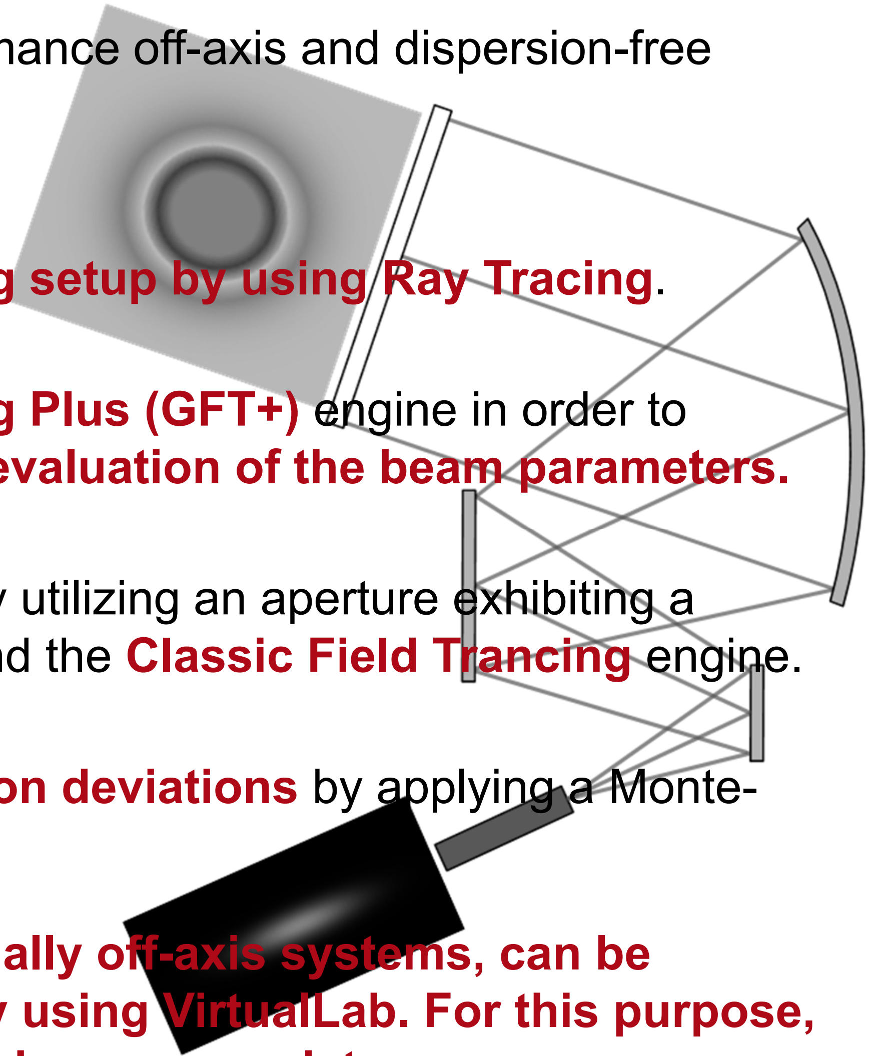
Numerical Detector Results

Quantity	Value & Unit
wavefront error (RMS)	$2.6 \cdot 10^{-5}\,\lambda$
divergence angle X × Y	3.8 μrad × 4.2 μrad
M^2 value in X × Y direction before optimization	1.67 × 1.80
M^2 value in X × Y direction after optimization	1.02 × 1.03



Summary

Realization and analysis of a high-performance off-axis and dispersion-free **reflective beam shaping setup.**



1. **Simulation**
   Verifying the **reflective beam shaping setup by using Ray Tracing**.
2. **Investigation**
   Applying the **Geometric Field Tracing Plus (GFT+)** engine in order to **calculate the field distribution and evaluation of the beam parameters.**
3. **Optimization**
   Optimization of the M^2 parameter by utilizing an aperture exhibiting a Gaussian shaped aperture function and the **Classic Field Trancing** engine.
4. **Analysis**
   Analysis of the **influence of orientation deviations** by applying a Monte-Carlo tolerancing.

Complex beam shaping setups, especially off-axis systems, can be simulated and analyzed very efficiently using VirtualLab. For this purpose, different simulation engines are applied, as appropriate.

Application Example in Detail

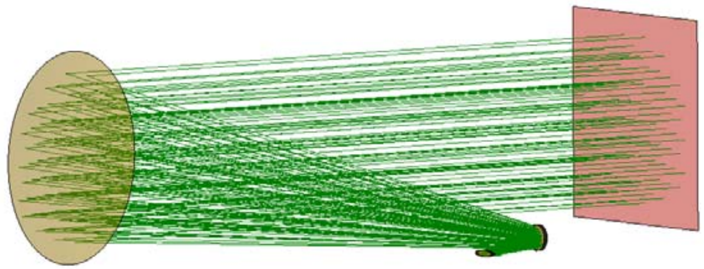
System Parameters

Context & Aim of this Application Example

In the application examples
BDS.0001, BDS.0002, BDS.0003 and BDS.0004

refractive beam delivery systems are investigated.

In contrast, the **topic of this example** is an off-axis dispersion-free high performance **reflective beam shaping** system.

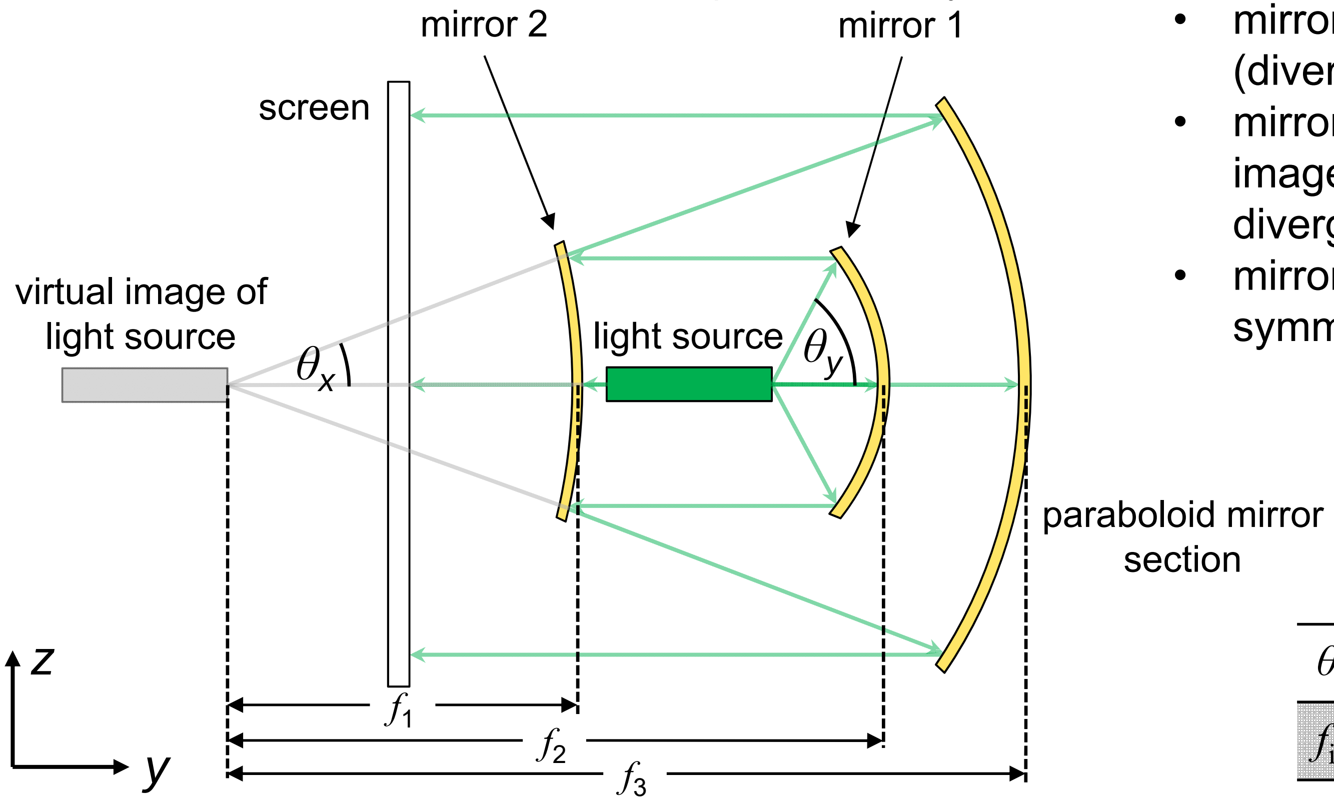


- The aim is to **collimate and symmetrize the Gaussian beam** emitted by a laser diode.
- Afterwards, the **quality of the shaped** beam is investigated and optimized.
- Further, the **influence of deviations** of mirror positions and tilts is discussed.

Simulation Task: Reflective Beam Shaping Setup

The introduced reflective beam shaping setup is based on a mirror system from [1] and consists of **two paraboloidal-cylindrical mirrors** combined with a **paraboloidal section mirror**. The focal distances and mirror positions depend on the input beam's divergence.

yz-plane:



functional principle:

- mirror 1 collimates input beam (divergence θ_y)
- mirror 2 generates a virtual image exhibiting a beam divergence equal θ_x
- mirror 3 collimates the symmetric beam

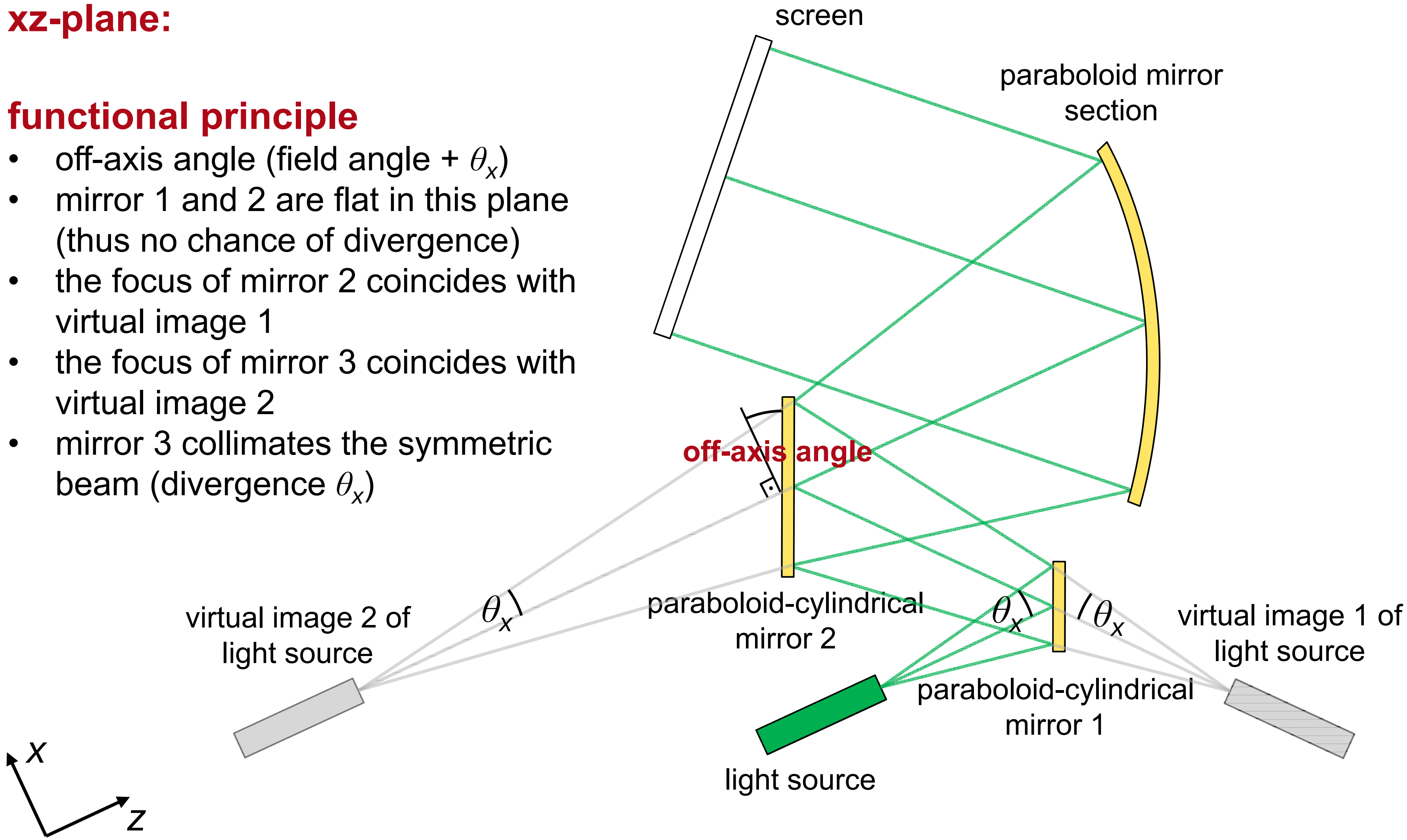
$\theta_{x,y}$	half-angle divergence
f_i	focal length of mirror i

Simulation Task: Reflective Beam Shaping Setup

xz-plane:

functional principle

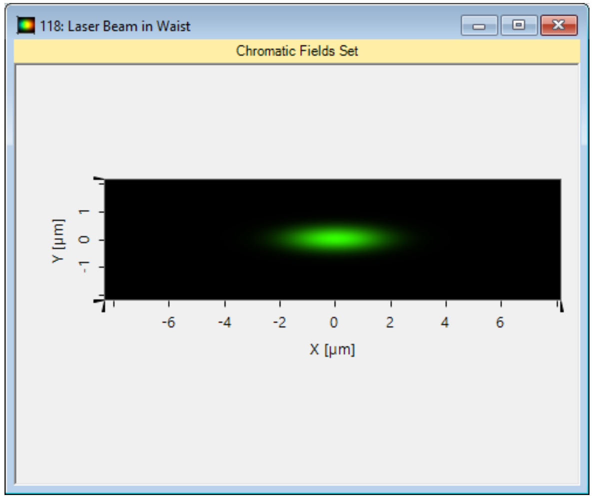
- off-axis angle (field angle + θ_x)
- mirror 1 and 2 are flat in this plane (thus no chance of divergence)
- the focus of mirror 2 coincides with virtual image 1
- the focus of mirror 3 coincides with virtual image 2
- mirror 3 collimates the symmetric beam (divergence θ_x)

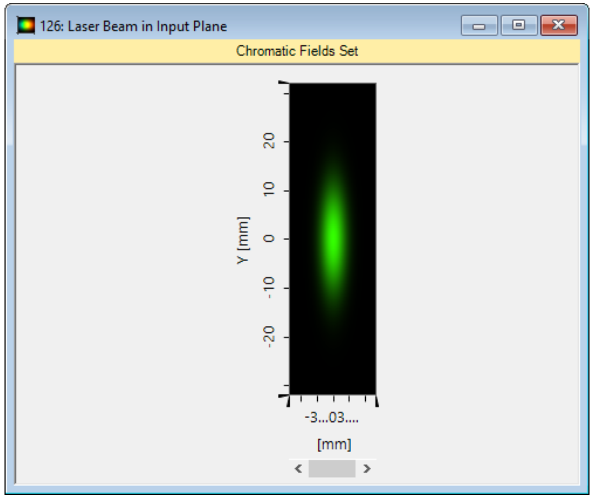


Specs: Astigmatic Laser Beam

- **strong astigmatic Gaussian beam** emitted by a laser diode
- neglecting a possible shift of emitting region in x- and y-direction

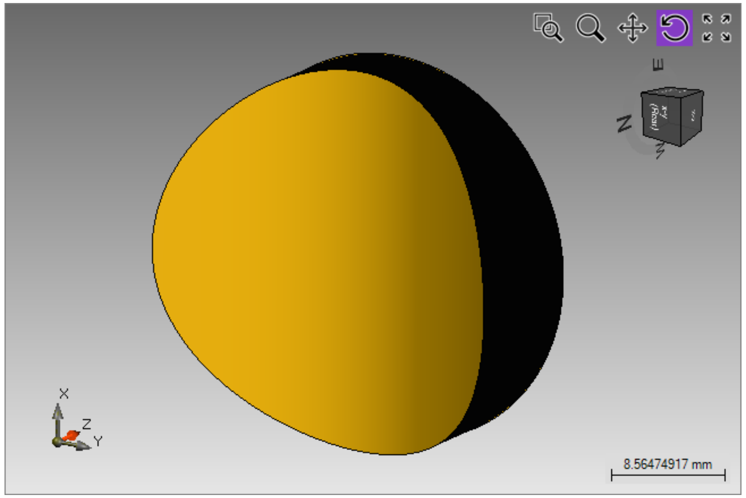
Parameter	Value & Unit
wavelength	532 nm
source type	Gaussian Beam
divergence of beam intensity	**12° x 46°** (referring to $1/e^2$ decay)
distance to input plane	24.0 mm



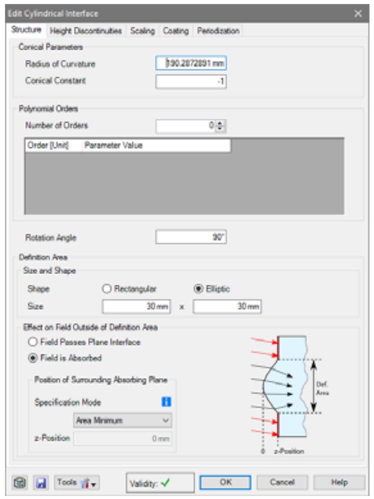


Specs: Parabolic-Cylindrical Mirrors

- cylindrical mirrors with **paraboloid curvature**
- applying the implemented **conical interface with conical const. -1**
- radius of curvature equals twice the focal distance

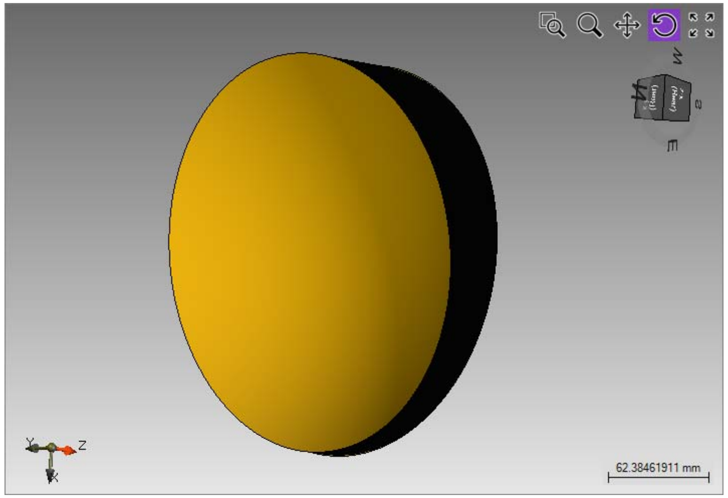


Parameter	Value & Unit
diameter mirror 1	7.43 mm × 30.0 mm
radius of curvature mirror 1	−47.12 mm
diameter mirror 2	30.0 mm × 30.0 mm
radius of curvature mirror 2	190.3 mm

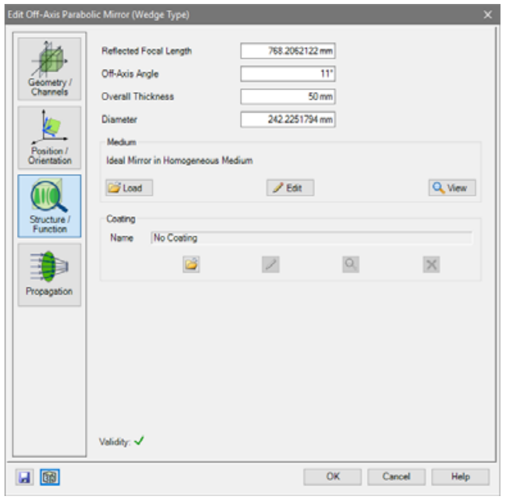


Specs: Off-Axis Paraboloid Mirror (Wedge Type)

- **section of a symmetrical paraboloid mirror** for off-axis collimation of the beam
- using the Off-Axis Parabolic Mirror (Wedge Type) from VirtualLab's component catalog
- the off-axis angle determines the sectional cut

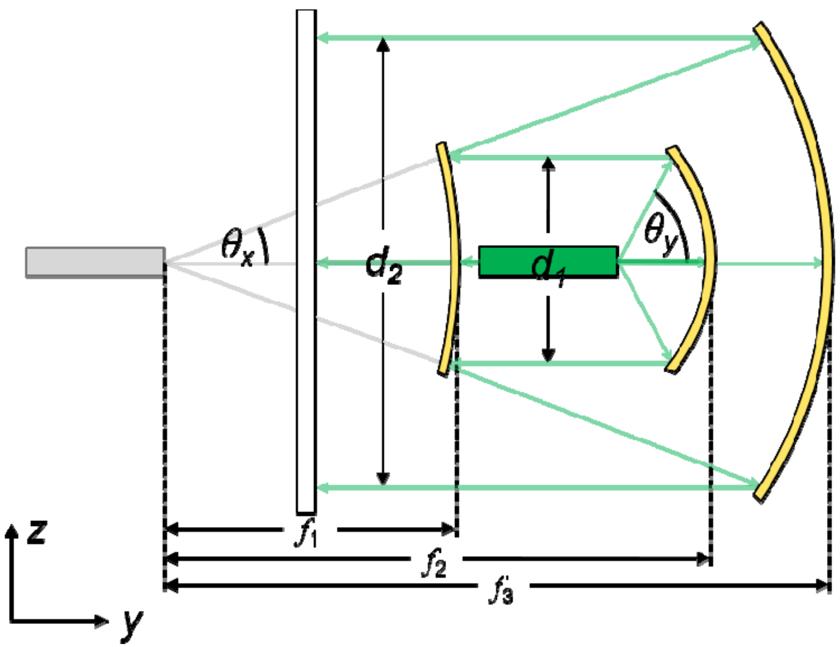


Parameter	Value & Unit
focal length	768.2 mm
off-axis angle	11°
thickness	50 mm
diameter	242.2 mm

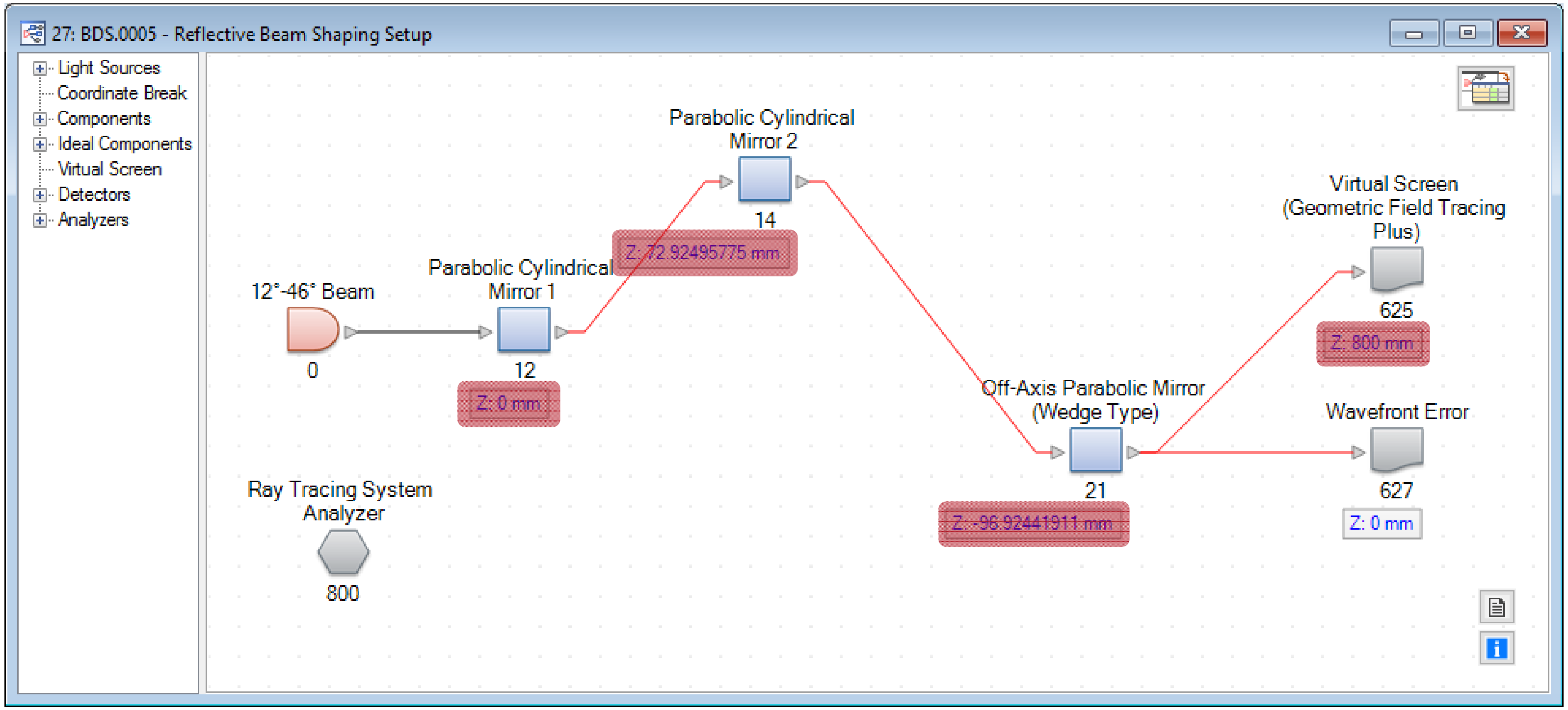


Specs: Parameter Overview (12° x 46° Beam)

Parameter	Value & Unit
field angle	5°
half-angle divergence x (θ_x)	6°
half-angle divergence y (θ_y)	23°
focal length mirror 1 (f_1)	6.0005 mm
focal length mirror 2 (f_2)	4.4892 mm
focal length mirror 3 (f_3)	1.0814 mm
beam diameter d_1	10 mm
beam diameter d_2	80 mm

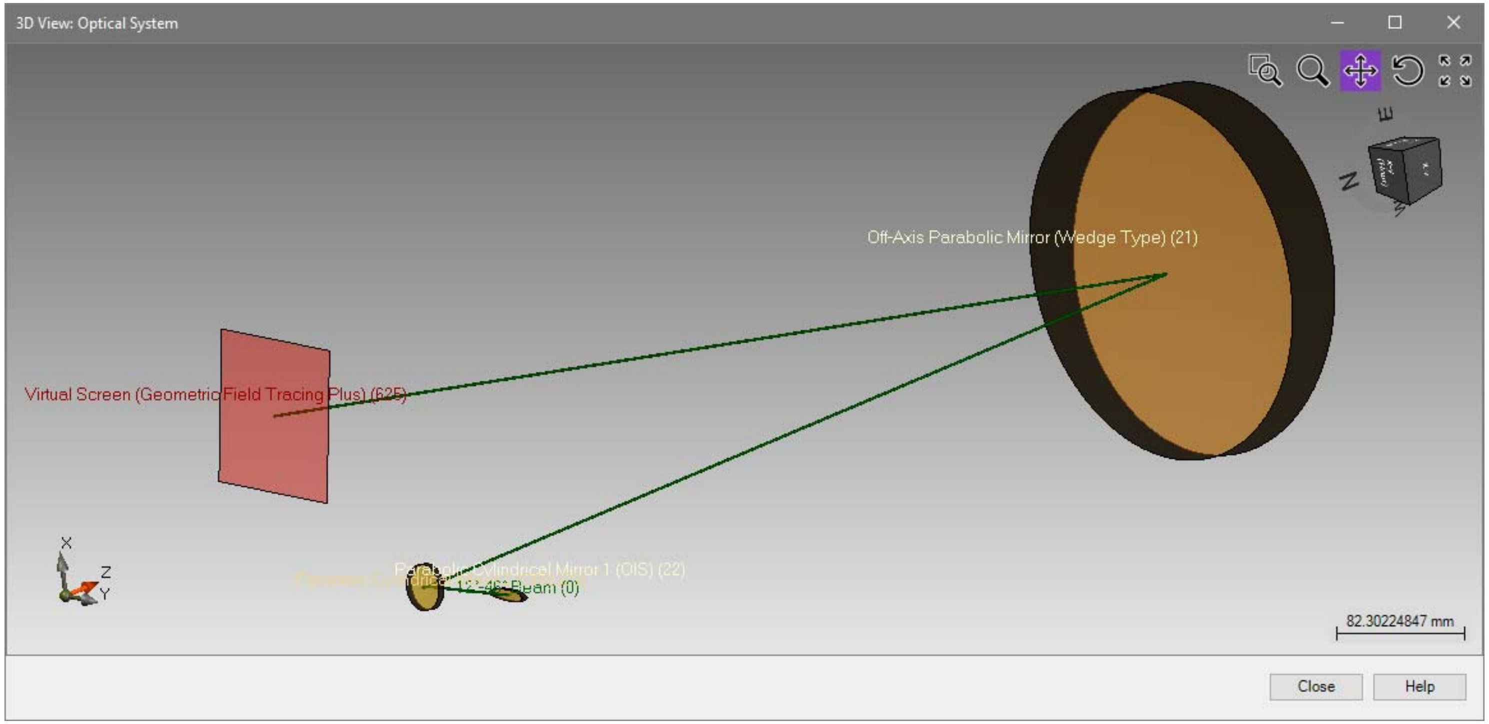


Light Path View of the Beam Shaping Setup



- Due to the relative positioning system of VirtualLab, **only the distances in z-direction have to be configured**.
- Because the positioning of the Off-Axis Parabolic Mirror is **relative to it's focus, the z-distance to mirror 2 has to be negative**.

3D View of the Reflective Beam Shaping System



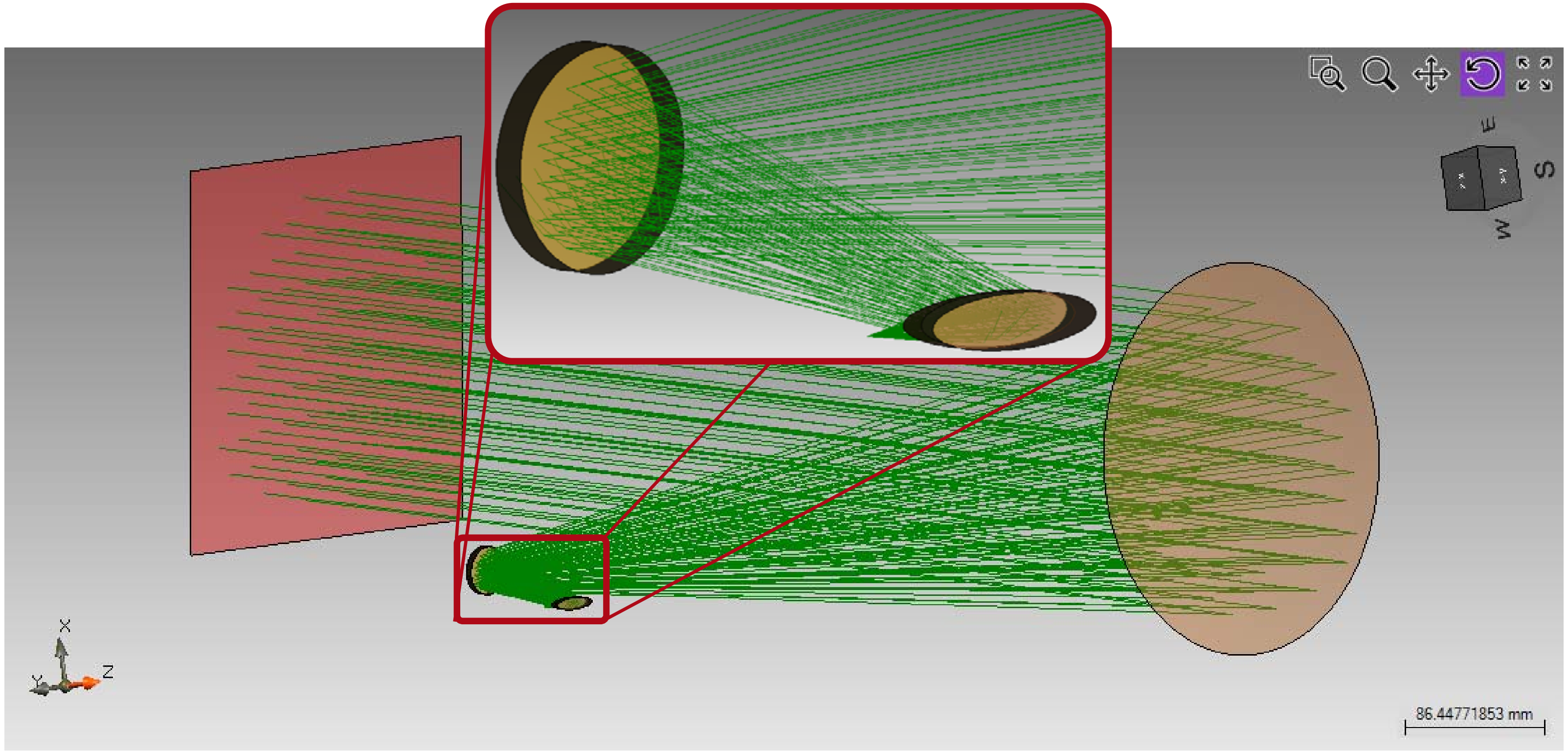
- The positioning of the optical elements can be displayed by the use of the **3D System View**.
- The green line depicts the resulting **optical axis, generated by the basal positioning strategy** of VirtualLab (only z-distances and tilts are set).

Application Example in Detail

Simulations & Results

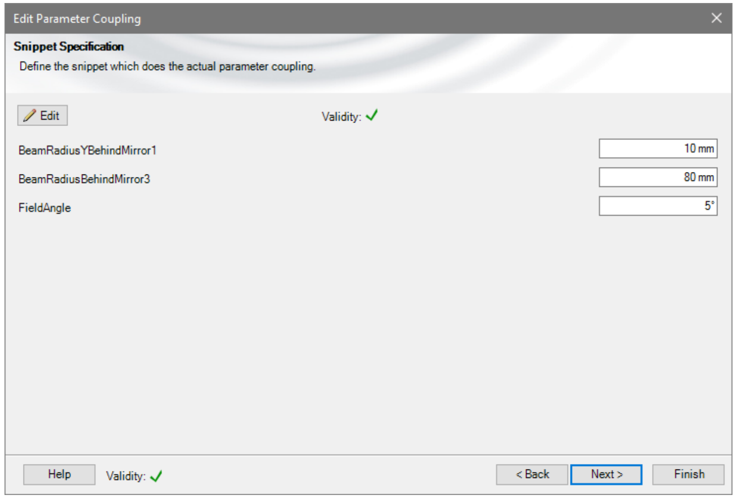
Result: 3D System Ray Tracing Analysis

- First, **Ray Tracing** is applied to investigate the light propagation through the optical setup.
- For the analysis, the **Ray Tracing System Analyzer** is used.



Using Parameter Coupling to Set Up the System

- Due to the functional principle, **all system parameters** (distances, foci, diameters) **can be calculated** from the beam parameters analytically.
- For this calculation, the **embedded Parameter Coupling feature is applied**.



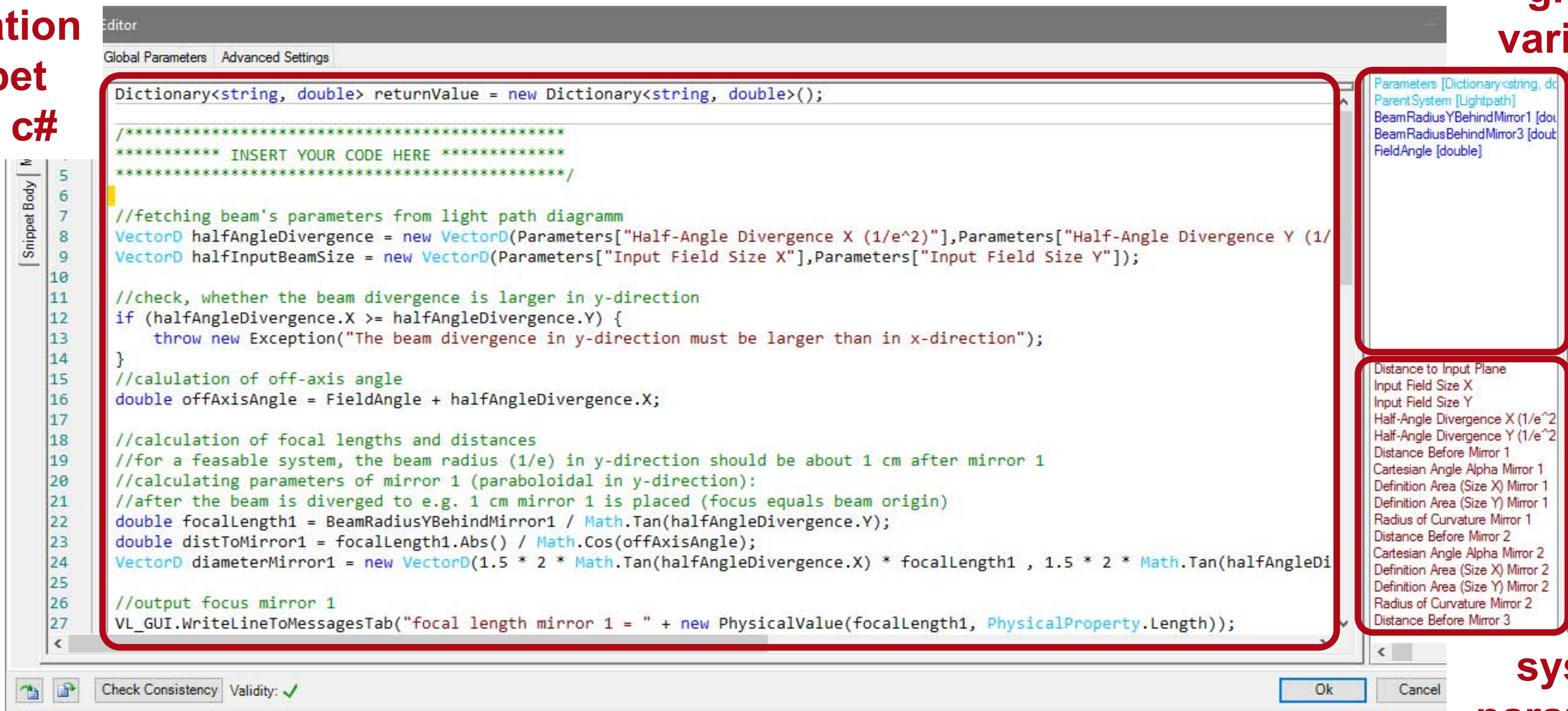
The following **parameters are independent of the beam parameters** and **allow simple system variations**:

- beam radius (y-direction) behind mirror 1
- beam radius behind mirror 2
- field angle, which determines the off-axis orientation

I.e. the used Parameter Coupling snippet code ensures that in case of a changed field angle the whole system will be adjusted appropriately.

Using Parameter Coupling to Set Up the System

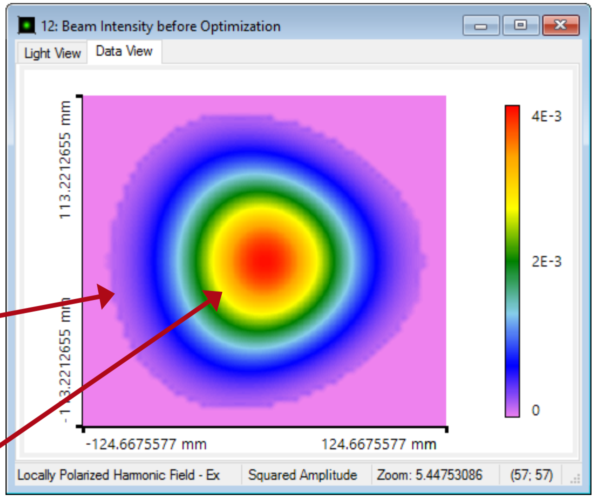
- **Based on the beam divergence** and diameter (x- and y-direction) the foci, diameters and z-distances of the mirrors are calculated and set.
- In case of this example **20 parameters are evaluated** and returned to the light path diagram (LPD).

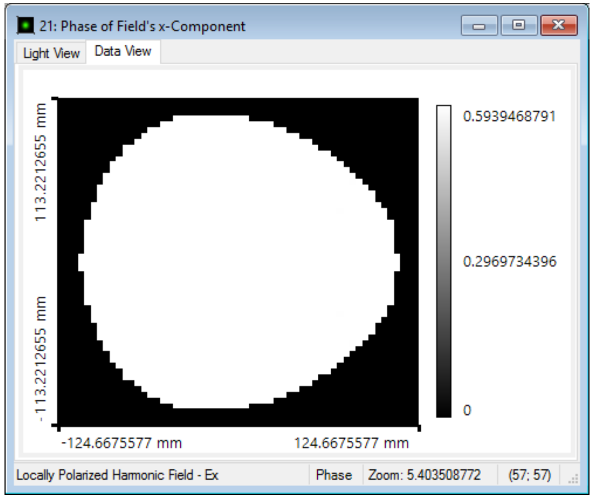


Result: Beam Shaping using GFT+

- Now, **computing the resulting beam profile** by utilizing Geometric Field Tracing Plus.
- Due to the off-axis setup, the **ray distribution** exhibits a **slightly asymmetric** shape.
- Nevertheless, the **field distribution is almost symmetrical** (better to be seen using false colors)
- The resulting **phase is perfectly flat**, yielding a wavefront error of:

Sub-Detector	Result
RMS [λ] of Wavefront Error for 532 nm	2.636798295E-05

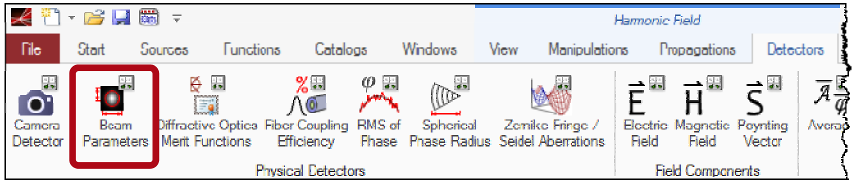




 file used: BDS.0005_Reflective_BeamShaper_01_RT.lpd

Result: Evaluation of Beam Parameters

- From the resulting field distribution of the shaped beam the **beam parameters can be evaluated**.
- This can be done directly via the interface using the ***Detectors*** ribbon.
- In this example, we are interested in the beam's **radius, divergence and M² value**.



Sub - Detector	Result
Radius X	76.05140768 mm
Radius Y	73.84830208 mm
Divergence Angle X	0.0002136121563°
Divergence Angle Y	0.0002363281438°
M^2-Parameter in x-Direction	1.674359956
M^2-Parameter in y-Direction	1.798753145

- The shaped beam exhibits an almost **identical radius in x and y**.
- The **divergence is about 4µrad**.
- The M² value is distinctly above

(the higher M² value is caused by a deviation of the beam parameters compared to an ideal Gaussian beam)

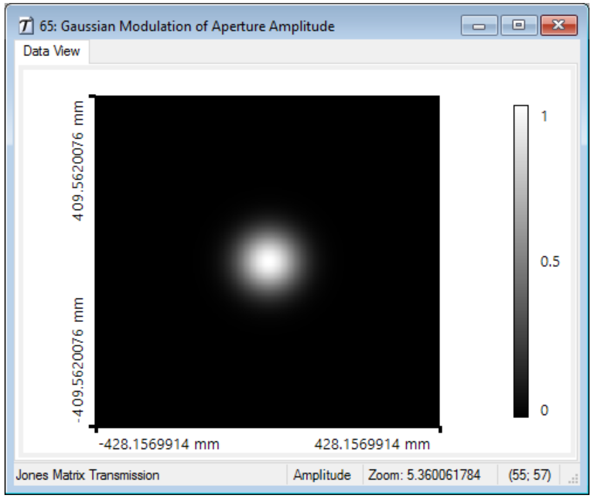
Optimization of Beam Quality

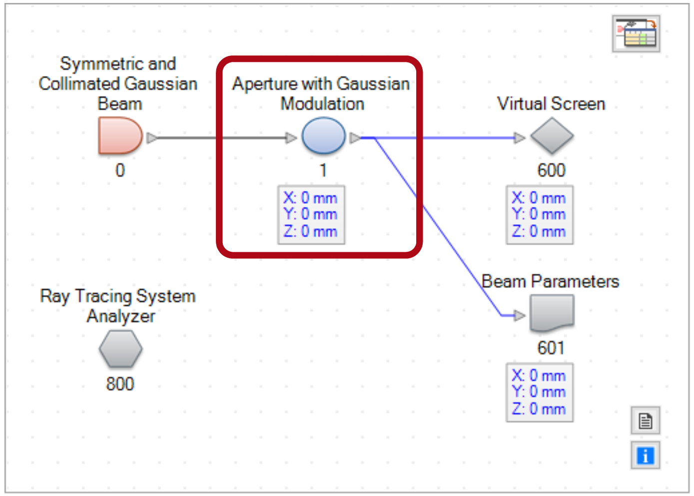
- Usually, apertures with an appropriate Gaussian modulation are used to optimize the M^2 value.

- Thus, we generate a Gaussian beam by using the measured **radius as waist radius** (vanishing divergence).

- Afterwards, convert the received field in a transmission function.

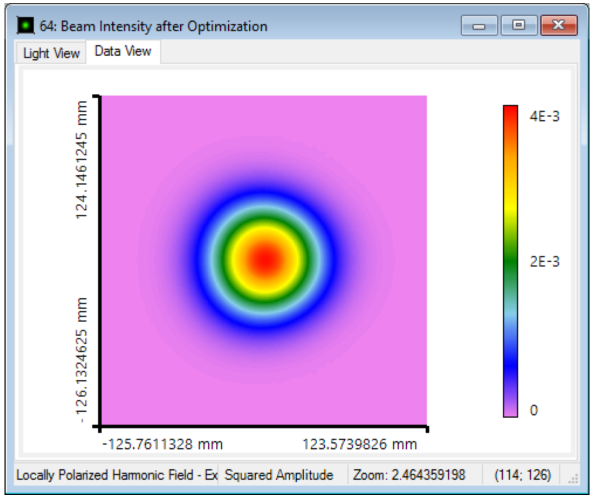
- This **transmission function is used as aperture** (in a Transmission Function component).





Result: Optimization of Beam Quality

- Due to the propagation through the Gaussian aperture the beam exhibits an **ideal Gaussian shape**.
- Thus, the **M² value is almost 1** for both directions.



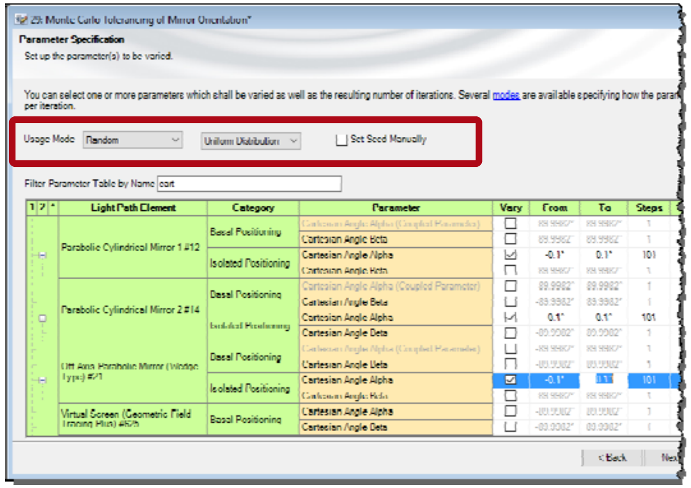
- However, the beam **radius is reduced** slightly.

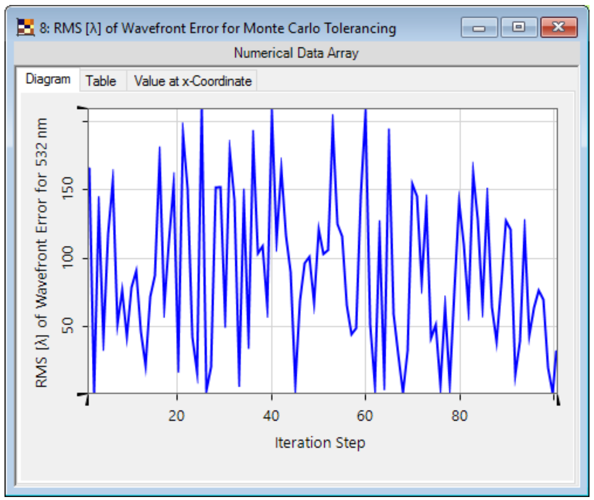
Sub - Detector	Result
Radius X (Classic Field Tracing)	55.12684003 mm
Radius Y (Classic Field Tracing)	54.04568743 mm
Divergence Angle X (Classic Field Tracing)	0.0001794946269°
Divergence Angle Y (Classic Field Tracing)	0.0001846118193°
M^2-Parameter in x-Direction (Classic Field Tracing)	1.019835579
M^2-Parameter in y-Direction (Classic Field Tracing)	1.028338641

(The beam radius shown on the last slide is the reason for the deviation from an ideal Gaussian.)

Monte Carlo Tolerancing of Mirror Orientation

- For Tolerancing we use the **Parameter Run feature in Random mode**.
- This means a **normal distribution** of the variated parameters.
- Thus, the **influence of the combination of deviations** can be investigated.





- For this example an **angular deviation of ±0.1°** for each mirror is assumed (isolated orientation).
- Due to this deviations, the wavefront error of the shaped beam is noticeable increased.

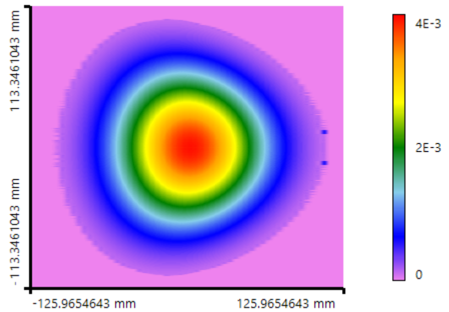
This means, that the wavefront is very sensitive to alignment errors.

 file used: BDS.0005_Reflective_BeamShaper_04_Tolerancing.run

Monte Carlo Tolerancing of Mirror Orientation

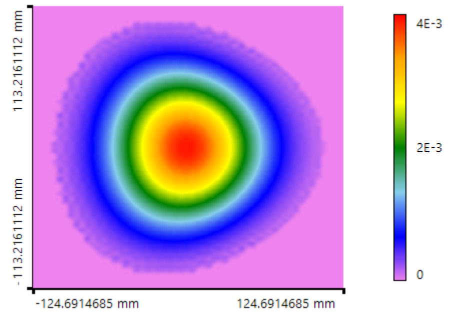
Exemplary intensity distributions for the first random tolerancing steps:
(corresponding RMS wavefront errors: 1.08λ, 40.4λ, 140λ)

1.08λ



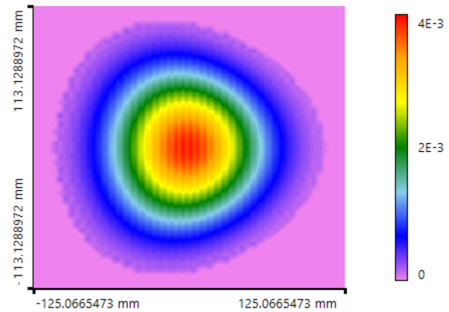
M²: 1.98 × 14.8

40.4λ



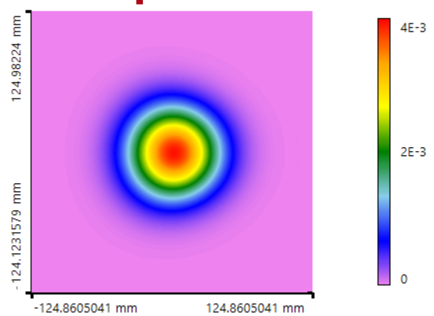
M²: 349 × 1.87

137λ

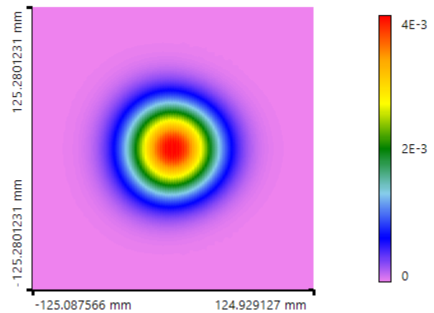


M²: 1183 × 1.84

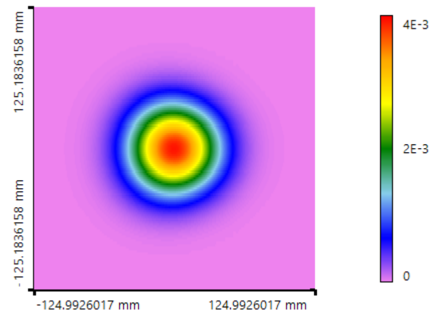
after optimization:



M²: 1.30 × 2.37



M²: 252 × 1.04



M²: 858 × 1.03

The M² value is distinctly increased for larger wavefront errors and therefore alignment deviations. It can be reduced by using the Gaussian aperture.

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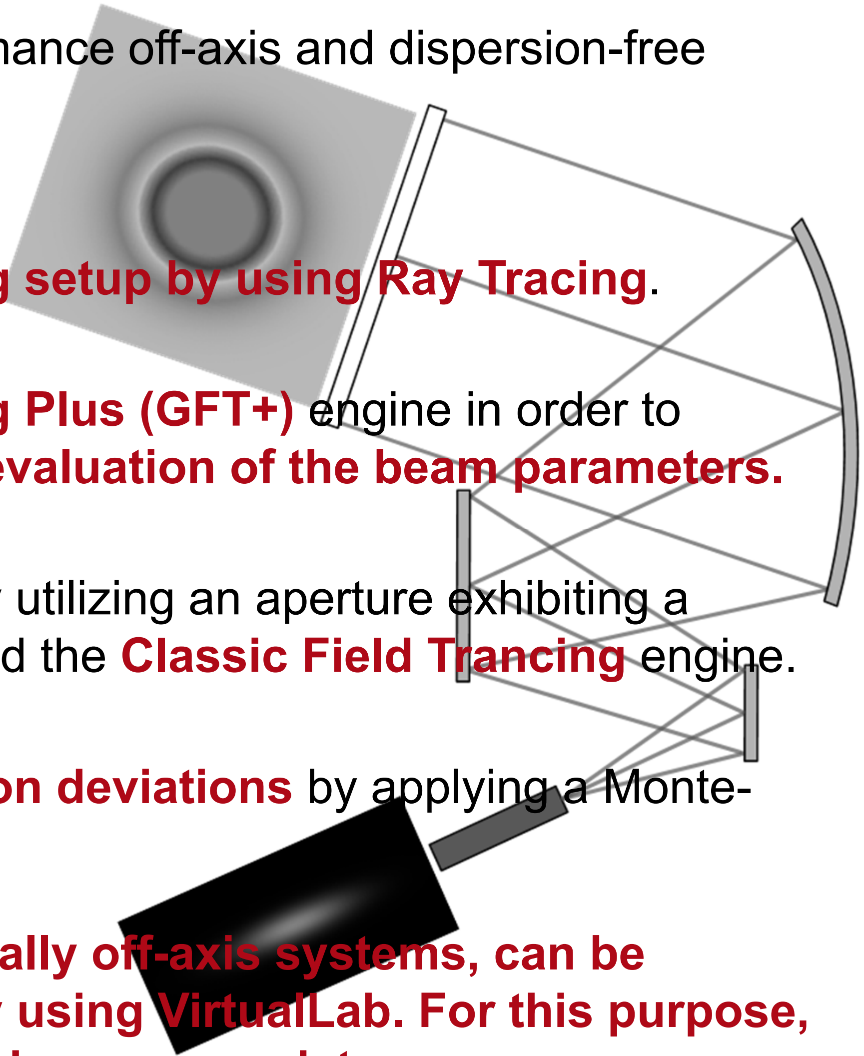

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References

[1] M. Serkan, H. Kirkici, and H. Cetinkaya, “Off-axis mirror based optical system design for circularization, collimation, and expansion of elliptical laser beams”, Appl. Optics 46, No. 22, 5489-5499 (2007).

Further Readings

Further Readings

- Get Started Videos
  - Introduction to the Light Path Diagram
  - Introduction to the Parameter Run

- Documents Related with This Application Example
  - BDS.0001: Collimation of Diode Laser Beam by Objective Lens
  - BDS.0002: Focus Investigation behind Aspherical Lens
  - BDS.0003: Optimization of a Lens Doublet for Laser Beam Focusing
  - BDS.0004: Focal Beam Size Reduction by Generating a Bessel Beam using Axicon Pair