

# **MANUAL**

***Focal- $\pi$ Shaper\_1064\_Q-xxx***

## 1. Description

Beam shapers **Focal- $\pi$ Shaper\_1064\_Q-xxx** present optical components to convert input single mode laser beam, TEM<sub>00</sub>, to a beam with “Airy Disk” intensity distribution; focusing of the output beam by a diffraction limited lens results in spots of various intensity distributions in zone close to the lens focus, including Flat-top, Donut-like, Inverse Gaussian, etc. Thus, the **F- $\pi$ Shaper** are tools to manipulate the shape of a focused beam. Because of many same features there is applied a common denomination **F- $\pi$ Shaper**, when necessary the differences between models will be noted additionally.

Most important features and basic principles of **F- $\pi$ Shaper** are:

- refractive optical systems transforming the Gaussian to Airy Disk intensity distribution;
- flat-top, doughnut, inverse-Gauss and other profiles can be generated by the same device;
- operation with input TEM<sub>00</sub> beams, typically  $M^2 < 1.5$ ;
- operation in a certain spectral band;
- systems optimized for other wavelengths are available as well;
- integrated X/Y alignment: lateral translations,  $\pm 2$  mm range;
- easy integration in a laser system;
- any diffraction limited focusing lens can be applied;
- wide range of distances between the Focal- $\pi$ Shaper and the lens.



Fig. 1 Focal- $\pi$ Shaper\_1064\_Q-xxx.

Typical applications:

- 3D Printing (Selective Laser Melting)
- Micromachining
- Microwelding
- Cutting.

## 2. Technical Specifications:

| Common for all Focal- $\pi$ Shaper_1064_Q models: |   |      |        |       |   |       |
|---|---|------|--------|-------|---|-------|
| Type  | Beam shaper for focused laser beams, lossless transformation of a Gaussian beam to the beam creating Flat-top or Doughnut spots by focusing using a diffraction limited lens            |      |        |       |   |       |
| Input beam  | - TEM <sub>00</sub> , typically $M^2 < 1.5$<br>- Divergence within $\pm 20$ mrad range  |      |        |       |   |       |
| Spectral range, nm                                | 1020 – 1100 (other wavelengths on request)  |      |        |       |   |       |
| Transmission                                      | >99% @ 1064 nm  |      |        |       |   |       |
| Alignment   | X / Y lateral translation, $\pm 2$ mm range   |      |        |       |   |       |
| Other features                                    | - Compact design suitable for scientific and industrial applications<br>- Easy integration to an optical setup and adaptation to a laser source<br>- Any focusing lens could be applied |      |        |       |   |       |
| Features of Focal- $\pi$ Shaper_1064_Q            |   |      |        |       |   |       |
| Model   | _Q-4  | _Q-5 | _Q-7.5 | _Q-10 | _Q-17   | _Q-20 |
| Input beam $1/e^2$ diameter, mm                   | 3-5   | 4-6  | 6-9    | 8-12  | 15-20   | 18-23 |
| Max. CW power, kW                                 | 0.5   | 1    | 1.5    | 1.5   | 2   | 2     |
| Clear Aperture, mm                                | 20  |      |        |       | 38  |       |
| Diameter, mm                                      | 42  |      |        |       | 64  |       |
| Length, mm  | 29  |      |        |       | 21  |       |
| Weight, g   | 50  |      |        |       | 70  |       |
| Mounting  | <ul style="list-style-type: none"> <li>• Outer/inner threads M30x0.75</li> <li>• Other designs on request</li> </ul>  |      |        |       | <ul style="list-style-type: none"> <li>• Outer/inner threads M58x1</li> <li>• Adaptor for inner M30x0.75</li> <li>• Other designs on request</li> </ul> |       |

### 3. Features of design and operation

Outlook and general drawings of the *F- $\pi$ Shaper* are presented in Fig.2,3. There are 2 basic designs:

- with CA 20 mm and mounting outer/inner threads M30x0.75,
- with CA 38 mm and mounting outer/inner threads M58x1.

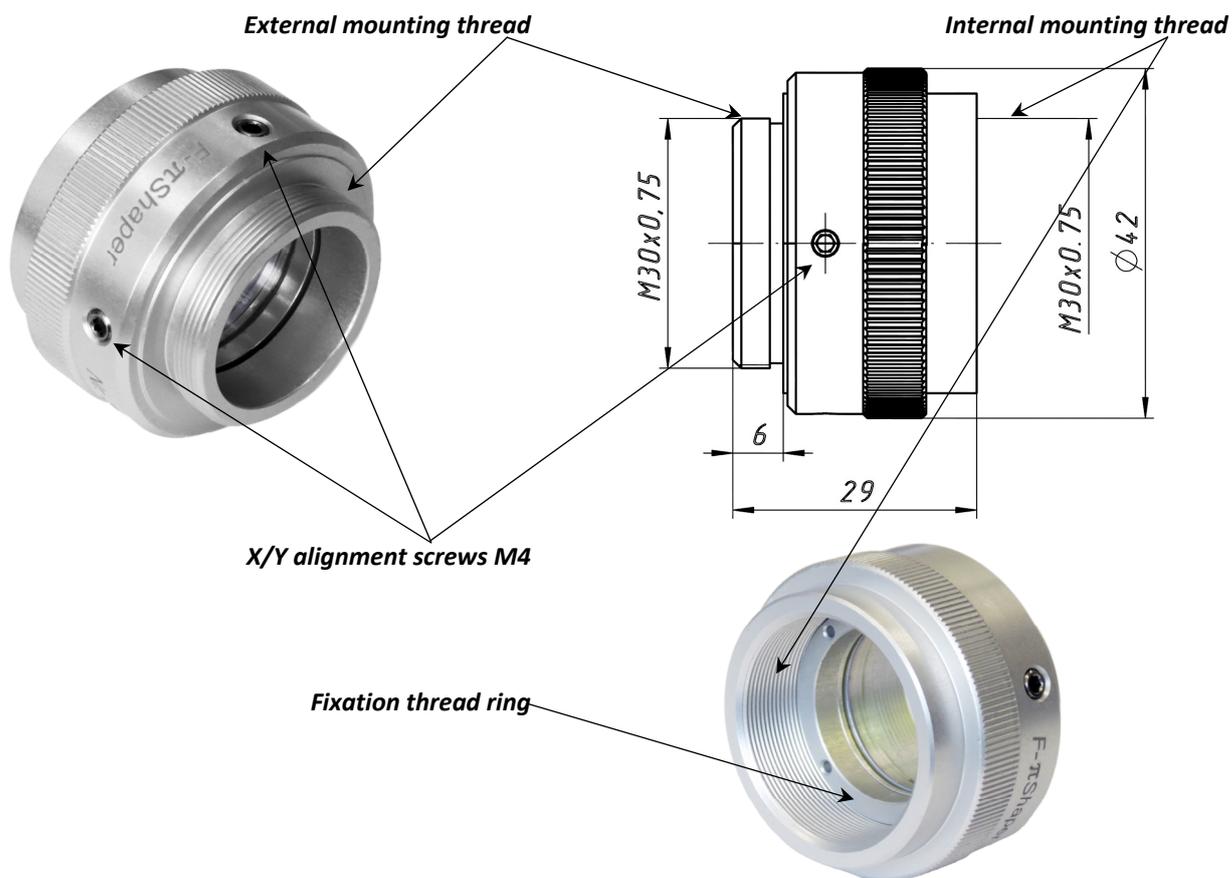


Fig. 2 *Focal- $\pi$ Shaper\_1064\_Q-xxx* of CA 20 mm with outer/inner threads M30x0.75.

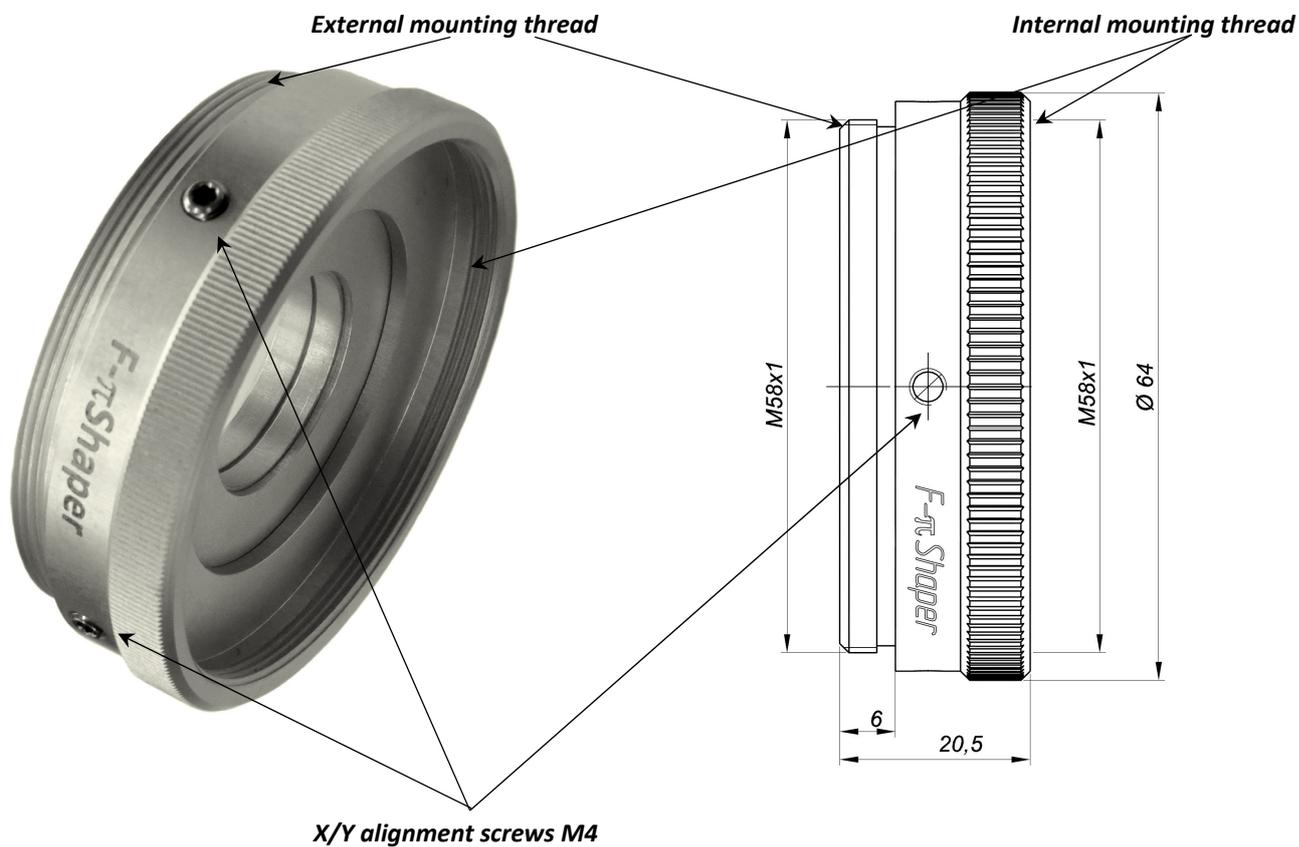


Fig. 3 *Focal- $\pi$ Shaper\_1064\_Q-xxx* of CA 38 mm with outer/inner threads M58x1.

The mounting threads are compatible with ones of widely used in industry collimators Optoskand and similar ones.

The main idea was to realize the ***F- $\pi$ Shaper*** device to be mounted at the output of a customer collimator with providing the output mounting thread of the same nominal diameter /pitch - this ease the device integration in customer equipment and doesn't require any additional adaptors.

The ***F- $\pi$ Shaper*** devices are equipped with internal means for X/Y alignment:

- ball-end thrust screws M4 for lateral translation,
- adjustment range  $\pm 2$  mm,
- it is recommended an alignment procedure with stepwise loosening and strengthening the screws
- criterion of proper alignment is symmetric fringes pattern at the ***F- $\pi$ Shaper*** output, see example in Fig.4, right.

**Note: By working with beam shapers it is strongly recommended to apply beam profilers!**

**Alignment procedure can be done with using camera-based beam profilers.**

- by choosing optimum alignment the position of the holder of optical component to be fixed using the Fixation thread ring.

#### 4. Conditions of operation:

The ***F- $\pi$ Shaper*** developed to operate with variety of lasers: TEM<sub>00</sub> Nd:YAG lasers, Fiber Laser, other solid-state lasers of working spectral band.

Applying the ***F- $\pi$ Shaper*** out of optimum spectrum will effect increasing of losses and reduction of the performance. Input side, left at the picture, has a clear diameter 16 mm, and “smaller” size of mechanical cabinet.

#### Recommended maximum power specifications

| Model                          | Material* | 5 ns pulses      |                             |                                | CW       |
|--------------------------------|-----------|------------------|-----------------------------|--------------------------------|----------|
|                                |           | Pulse energy, mJ | Fluence, mJ/cm <sup>2</sup> | Peak Power, MW/cm <sup>2</sup> | Power, W |
| Focal- $\pi$ Shaper 1064_Q-xxx | FS        | 50               | 200                         | 50                             | 200      |

#### 4.1 Input beam

***F- $\pi$ Shaper*** is a field mapping beam shaper where

***Variation of input beam diameter results in variation of the spot intensity distribution.***

This is illustrated by calculations of resulting profile near the focal plane presented in p. 4.2 “Influence of input beam size on resulting profile”.

The input beam to be collimated, full angle divergence within  $\pm 20$  mrad range.

Only TEM<sub>00</sub> beam can be applied,  $M^2 < 1.5$ .

The optical design of ***F- $\pi$ Shaper*** presumes the total input beam has diameter smaller than 20 mm, for example in case of TEM<sub>00</sub> the waist diameter  $2\omega$  (at  $1/e^2$  intensity level) should be less than 12 mm, this case the clear diameter is about 1,67 times bigger than  $2\omega$ , hence theoretically more than 99% of Gauss beam is inputted.

Optimum waist diameters  $2\omega$  (at  $1/e^2$ ) for particular ***F- $\pi$ Shaper*** models are presented in the table in chapter 2.

On the stage of alignment (see corresponding chapter below) it is recommended to provide maximum input beam of  $1/e^2$  diameter, then beam shaping effect is most pronounced.

On the late stage of the adjustment procedure the input beam diameter has to be tuned using an external zoom beam expander or other means, please, see the p.4.3 of the paper in Appendix 2.

**Note: By of working with beam shapers it is strongly recommended to apply beam profilers! Alignment procedure can be done with using camera-based beam profilers.**

**Note: To analyze the final spots of several tens of microns, it is recommended to use beam profiling instruments dedicated for focused laser beams, like Focus Monitor.**

## 4.2 Influence of input beam size on resulting profile

Features of transformation of the spot intensity distribution is described in details in Fig.6 and in p.4.2 of the paper in Appendix 2. Shortly, it is recommended to consider use following spot profiles

- “big flat-top”,
- “donut”,
- “small flat-top” and
- flat-top in focal plane of a focusing lens (not in waist!).

The beam waist appears between the “small flat-top” and focal plane of a focusing lens.

Variation of input beam diameter results in variation of spot intensity distributions. Results of calculations using the optical design software demonstrate this effect, please, see example in below table.

Conditions:

- Focal- $\pi$ Shaper\_1064\_Q-5;
- input beam size variable,  $2\omega = 5\dots 7$  mm ( $1/e^2$ );
- the “small flat-top” working plane.

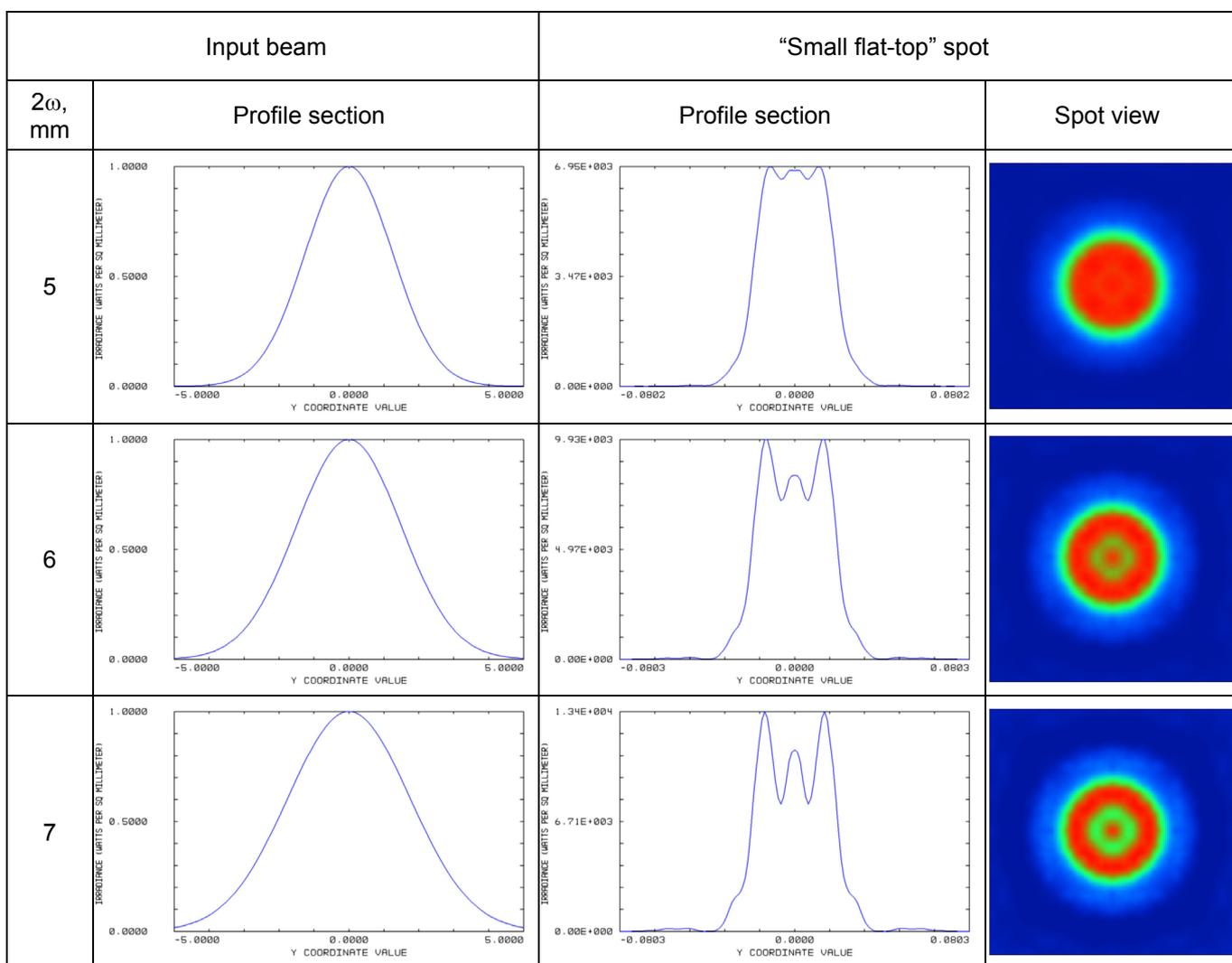


Fig. 4 Change of resulting spot profile by variation of input beam size.

Increasing the input beam diameter results in stronger modulation of resulting spot profile, therefore optimum input beam diameter to be defined experimentally. See also p.4.4.

### 4.3 Output beam

According to principle of operation of the *F- $\pi$ Shaper* the output beam has intensity distribution optimized to provide various intensity distributions in the area close to the focal plane of a focusing lens. Some examples of beam profiles after the *F- $\pi$ Shaper* are presented in p.4.2 of the paper in Appendix 2.

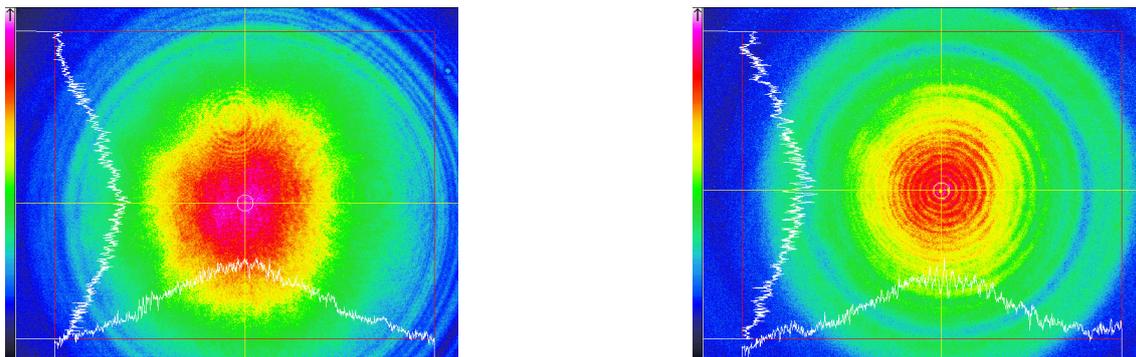


Fig. 5 Examples of beam profiles right after the *Focal- $\pi$ Shaper\_1064\_Q-xxx*.

When focusing the beam after the *F- $\pi$ Shaper* by a diffraction limited lens there are created various beam profiles in area of focal plane of that lens. Examples of spot profiles are presented in the below picture.

Features of transformation of the spot intensity distribution is described in details in Fig.6 and in p.4.2 of the paper in Appendix 2.

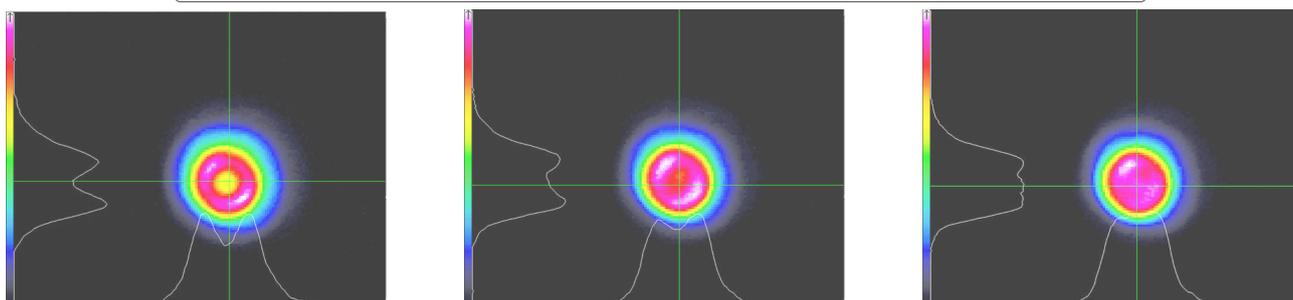
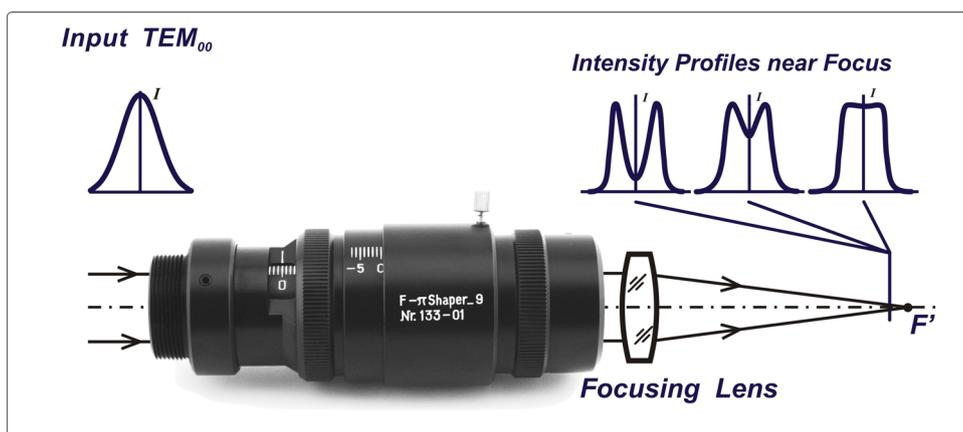
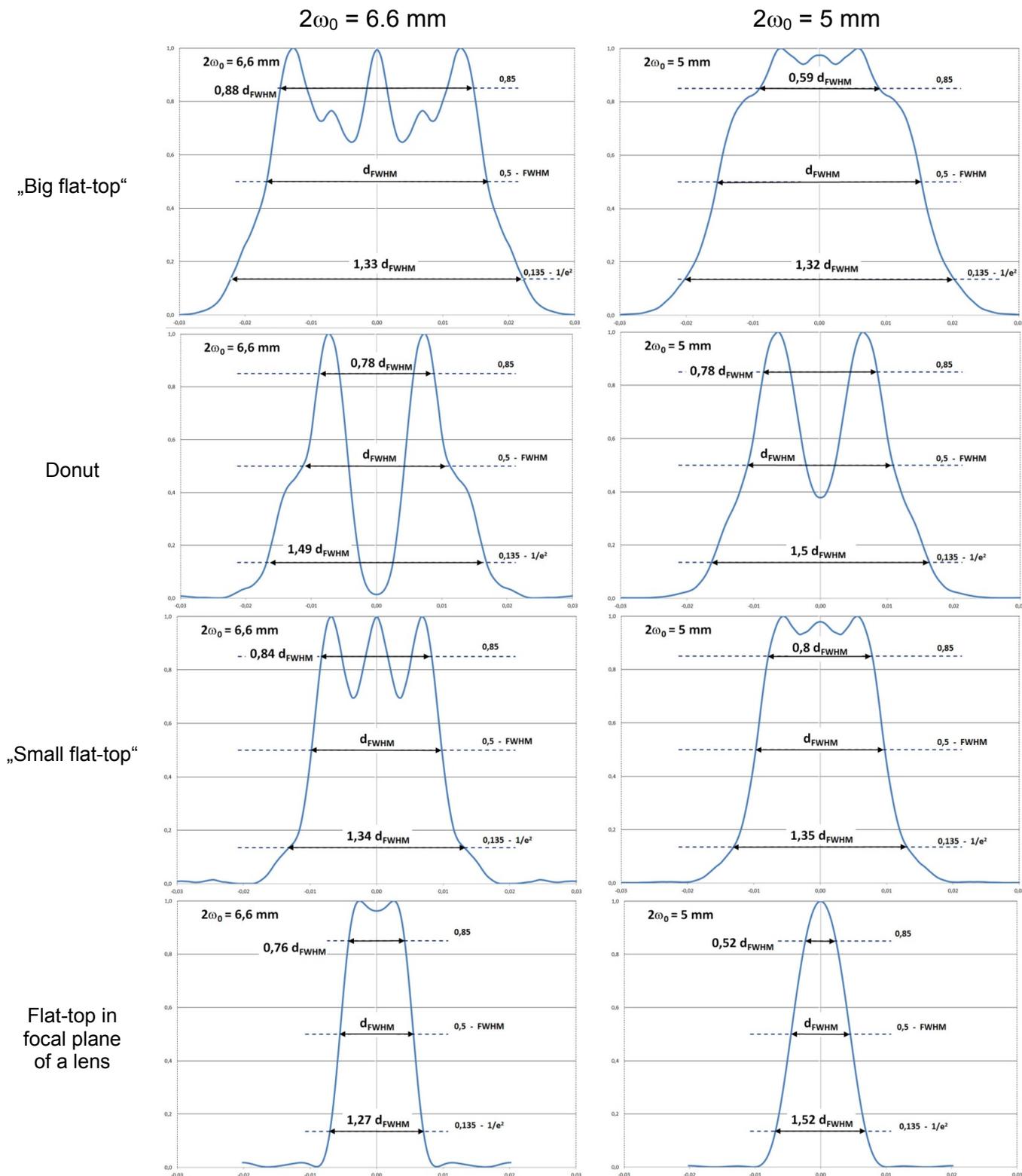


Figure 6 Principle of the *F- $\pi$ Shaper* operation and examples of beam profiles.

### 4.4 Theoretical spot profiles

Results of calculations using the optical design software for various input beam diameters in various working planes are presented in below table. Conditions:

- Focal- $\pi$ Shaper\_xxx\_Q-5;
- input beam size variable,  $2\omega_0 = 6.6 \text{ mm}$ ,  $5 \text{ mm}$  ( $1/e^2$ );
- $\lambda = 532 \text{ nm}$ ;
- Gaussian input beam of ,  $M^2 = 1$ ;
- Focusing by diffraction limited lens of 80mm focal length.



#### 4.5 Location of $F$ - $\pi$ Shaper in equipment

Typically the  $F$ - $\pi$ Shaper should be located after a beam expander, which is necessary to optimize the input beam diameter, but ahead of the diffraction limited focusing lens.

Output beam after the  $F$ - $\pi$ Shaper is of the same divergence like input beam, therefore there is no problem to apply galvo-mirror scanning head between the  $F$ - $\pi$ Shaper and the lens. Example of typical implementation of a laser system with  $F$ - $\pi$ Shaper is shown in below figure.

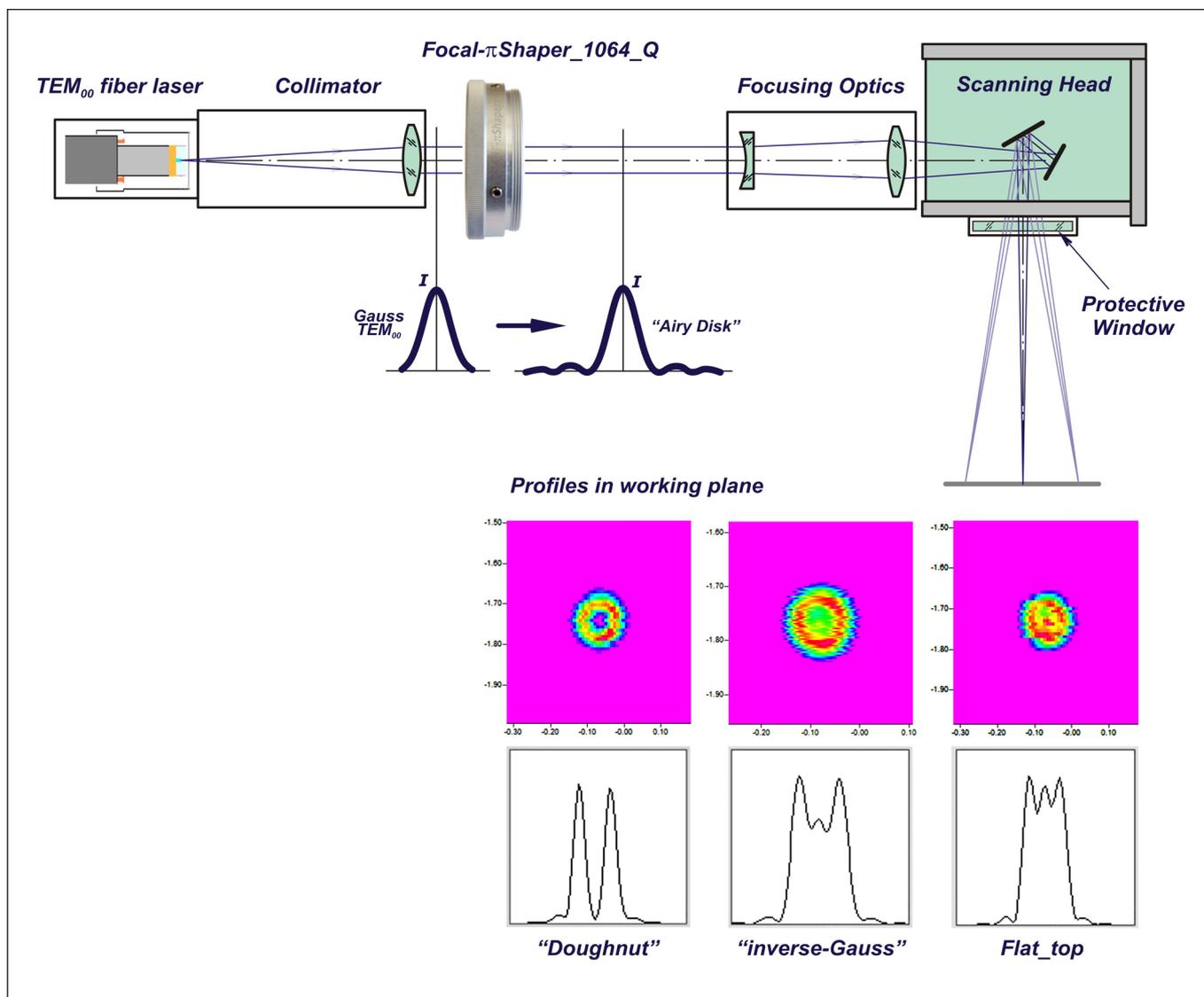


Fig. 7 Example of positioning the  $F$ - $\pi$ Shaper in laser equipment for Selective Laser Melting (SLM).

Since the output beam has low divergence it is possible to apply an additional beam expander after the  $F$ - $\pi$ Shaper but before the scanning head in order to get a smaller final spot.

#### 4.6 Mounting

The  $F$ - $\pi$ Shapers have mounting threads compatible with ones widely used in industry collimators Optoskand and similar ones:

- with CA 20 mm and mounting outer/inner threads M30x0.75,
- with CA 38 mm and mounting outer/inner threads M58x1.

The main idea was to realize the  $F$ - $\pi$ Shaper device to be mounted at the output of a customer collimator with providing the output mounting thread of the same nominal diameter /pitch - this eases the device integration in customer equipment and doesn't require any additional adaptors.

It is supposed the  $\pi$ Shapers to be mounted in an optical system by means of dedicated threads; other means of mounting should be discussed with a Supplier.

#### 4.7 Requirements to Focusing optics

Any types of focusing optics can be applied: F- $\Theta$  lenses, microobjective, telecentric, reflective, etc.

The only condition is the focusing lens has to be **diffraction limited** one, i.e. the wave aberration should be less than  $\lambda/4$  over whole working field, for whole clear aperture.

Since the **F- $\pi$ Shaper** optimizes conditions of interference in zone near the focal plane it is very important that a focusing lens installed after the **F- $\pi$ Shaper** to be a **diffraction limited lens** and don't introduce any aberrations disturbing the wave front.

To evaluate the quality of a lens it is recommended to carry out a simple experiment: to focus a TEM<sub>00</sub> laser beam with the lens **without any beam shaper**, and measure the spot size in waist of the focused beam with using a beam profiler or by performing the material processing on a thin layer material. The spot diameter has to be close to a theoretical value calculated using the formula

$$d = \frac{4 \cdot \lambda \cdot F_1}{\pi \cdot D} \cdot M^2$$

where **d** - spot diameter at  $1/e^2$  intensity,  $\mu\text{m}$ ;  $\lambda$  - wavelength,  $\mu\text{m}$ ; **D** -  $1/e^2$  beam diameter at a lens input, mm; **F** - focal length of a lens, mm; **M**<sup>2</sup> - beam parameter.

As a rule, the deviation of experimental value from theoretical one shouldn't exceed 15-25%.

**Note: If a final spot diameter is several times bigger than a theoretical value then realizing of a necessary beam shaping effect is questionable!**

To align the **F- $\pi$ Shaper**, as well as to get better understanding of its operation principle it is recommended to start to work with a lens of **1 meter** focal length, so the laser spot is of several hundreds of microns size, the depth of field is several tens of mm; evidently these conditions are very comfortable to use a camera-based beam profiler for measuring the irradiance distributions. This makes it possible to analyze the beam profile behaviour while the beam propagating in space through moving the beam profiler along the optical axis in zone close to focal plane of that 1 meter lens, see the Appendix 1 where "Recommended alignment procedure" for **F- $\pi$ Shaper** of one type is presented.

#### 4.8 Alignment

Proper operation of the **F- $\pi$ Shaper** presumes its alignment with respect to the input laser beam, particularly reaching symmetry of output profile being characterized by circular fringes around the central lobe, Fig.5.

The **Focal- $\pi$ Shaper\_XXX\_Q-XXX** devices require only X/Y lateral alignment and they are equipped with X/Y alignment screws, see Fig.2 and 3.

On the stage of alignment it is recommended to provide maximum input beam of  $1/e^2$  diameter, then beam shaping effect is most pronounced. On the late stage of the adjustment procedure the input beam diameter has to be tuned using an external zoom beam expander or other means, please, see the p.4.3 of the paper in Appendix 2.

The recommended alignment procedure is presented in Appendix 1 on example of analogous **Focal- $\pi$ Shaper\_9** beam shaper.

**Note: By of working with beam shapers it is strongly recommended to apply beam profilers! Alignment procedure can be done with using camera-based beam profilers.**

**Note: To analyze the final spots of several tens of microns, it is recommended to use beam profiling instruments dedicated for focused laser beams, like Focus Monitor.**

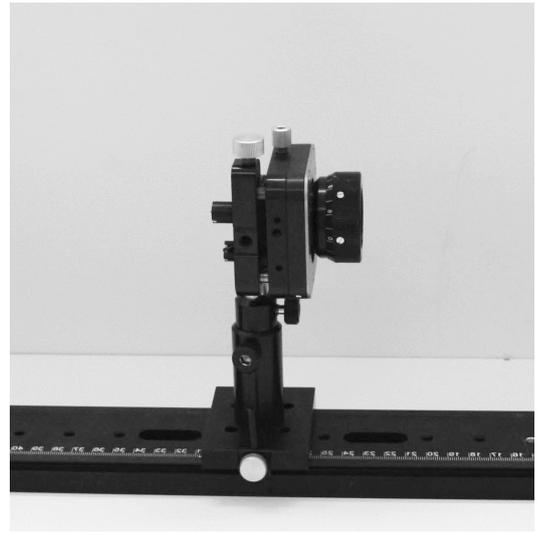


### $\pi$ Shaper Mount

This is a 5- or 4-axis Mount providing alignment in 2 lateral shift X/Y and 2 tilts around X/Y.

This device is usually recommended to be applied while delivery of  $\pi$ Shaper or Focal- $\pi$ Shaper.

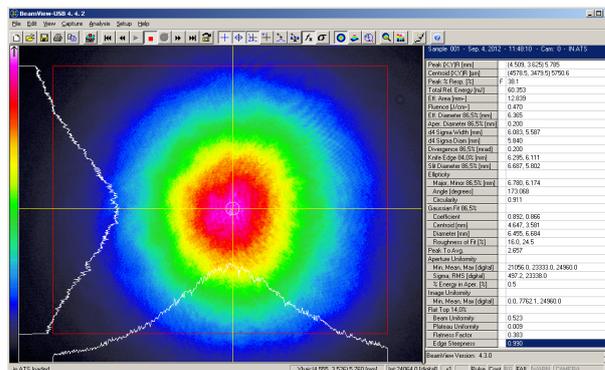
It is possible also to use other opto-mechanical devices providing similar functionality of alignment.



## 2. Alignment procedure for the Aligner

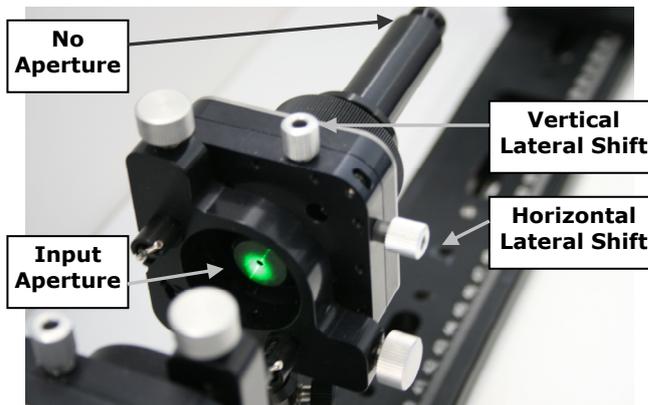
**Action:**

- to install the Laser and the Beam Expander,
- to install the camera-based beam profiler,
- to put the crosshair of beam profiler in center of the laser spot, this will ease further procedure.



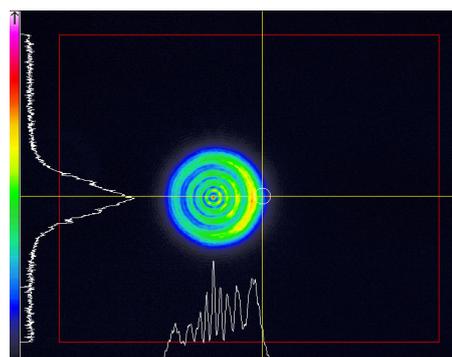
**Action:** to install the Aligner in the  $\pi$ Shaper Mount :

- entrance aperture of 2 mm diameter,
- **NO** aperture at the exit.



| Apertures, mm |     |
|---------------|-----|
| In            | Out |
| 2             | -   |

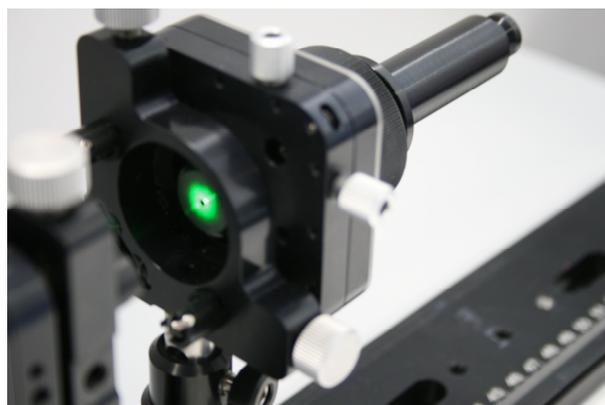
**Comment:**  
The Aligner is misaligned in horizontal direction



**Action:** to do lateral shifting in horizontal direction with checking the spot with camera to provide symmetric diffraction pattern being centred with the crosshair.

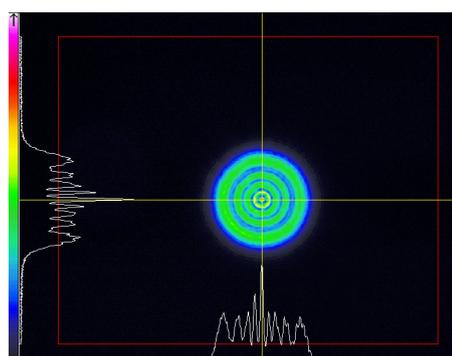
**Important:** Use lateral shifts (X/Y) only when ONLY entrance aperture is installed!

The knobs of lateral shifts are marked in above photo; the resulting spot is shown in right photo and next screenshot.

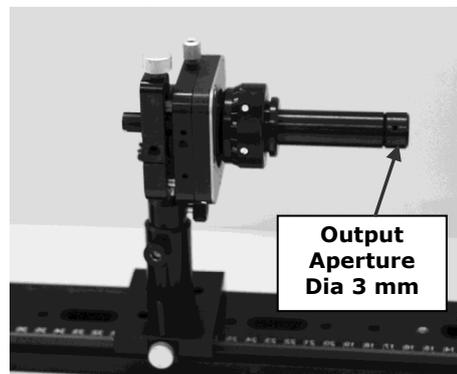


| Apertures, mm |     |
|---------------|-----|
| In            | Out |
| 2             | -   |

**Comments:**  
The entrance aperture of the Aligner is aligned in vertical and horizontal directions. Diffraction pattern is symmetric. The center of rings coincides with the crosshair.

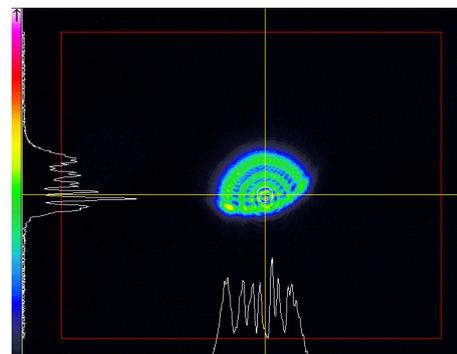


**Action:** to install the Output Aperture of 3 mm diameter.



| Apertures, mm |     |
|---------------|-----|
| In            | Out |
| 2             | 3   |

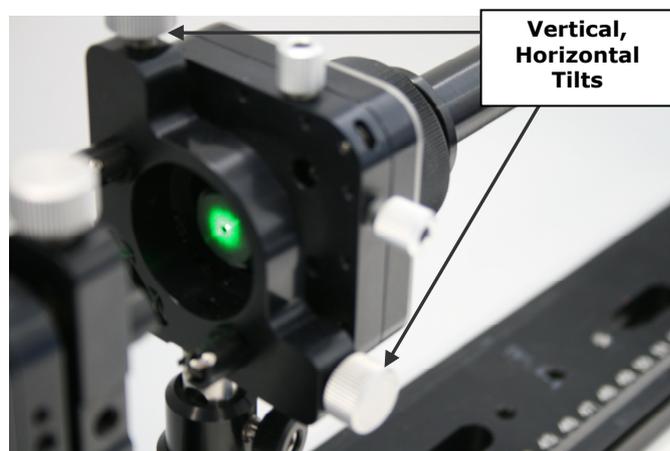
**Comment:**  
There exists angular misalignment in vertical direction



**Action:** to do tilt in vertical direction with checking the spot with camera to provide symmetric diffraction pattern being centred with the crosshair.

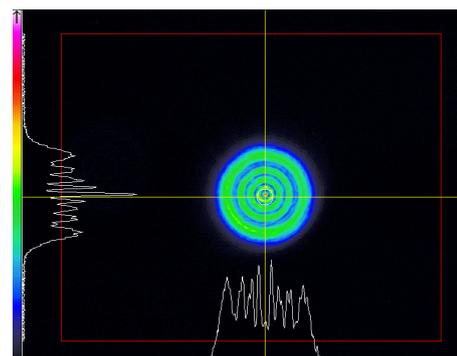
**Important:** Use primarily the tilts around X/Y, lateral shifts to be used AFTER tilts to correct the alignment.

The knobs of tilts around X/Y are marked in the right photo.

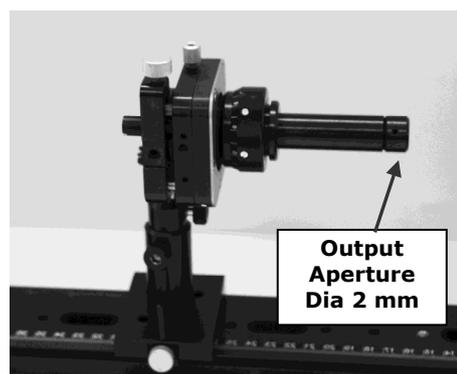


| Apertures, mm |     |
|---------------|-----|
| In            | Out |
| 2             | 3   |

**Comments:**  
Full beam after input 2mm aperture passes through the output 3 mm aperture.  
Diffraction pattern is symmetric.  
The center of rings coincides with the crosshair.

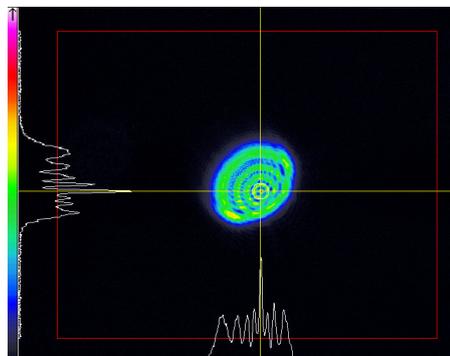


**Action:** to install the Output Aperture of 2 mm diameter.



| Apertures, mm |     |
|---------------|-----|
| In            | Out |
| 2             | 2   |

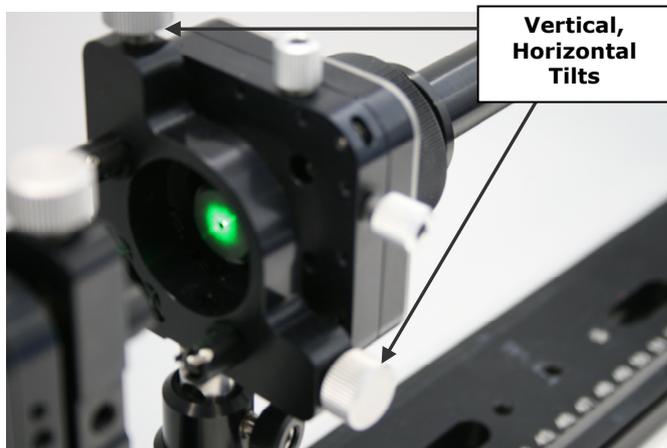
**Comment:**  
There exists angular misalignment in horizontal and vertical directions.



**Action:** to do tilt in horizontal and vertical directions with checking the spot with camera to provide symmetric diffraction pattern being centred with the crosshair.

**Important:** Use primarily the tilts around X/Y, lateral shifts to be used AFTER tilts to correct the alignment.

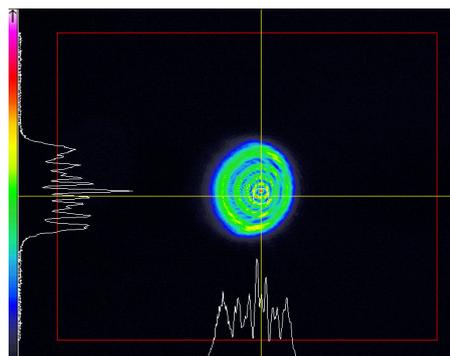
The knobs of tilts around X/Y are marked in the right photo.



| Apertures, mm |     |
|---------------|-----|
| In            | Out |
| 2             | 2   |

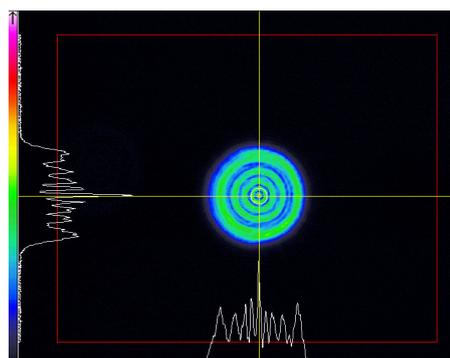
**Comments:**  
Angular misalignment is almost eliminated in vertical direction but still strong in horizontal direction.

**Action:** to do tilt in horizontal direction with checking the spot with camera to provide symmetric diffraction pattern being centred with the crosshair.

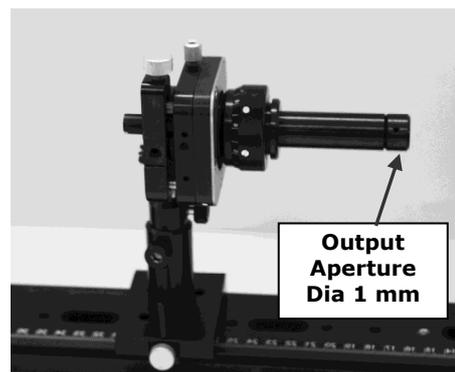


| Apertures, mm |     |
|---------------|-----|
| In            | Out |
| 2             | 2   |

**Comments:**  
The beam after input 2mm aperture passes through the output 2 mm aperture.  
Diffraction pattern is symmetric.  
The center of rings coincides with the crosshair.



**Action:** to install the Output Aperture of 1 mm diameter.

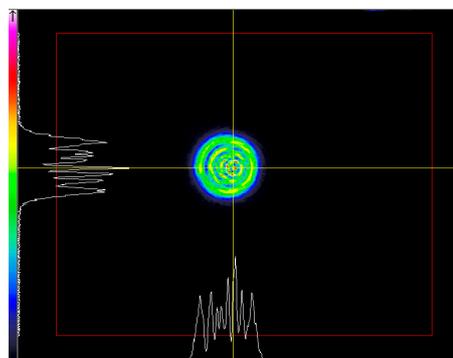


| Apertures, mm |     |
|---------------|-----|
| In            | Out |
| 2             | 1   |

**Comment:**

There exists angular misalignment in horizontal direction.

**Action:** to do tilt in horizontal direction with checking the spot with camera to provide symmetric diffraction pattern being centred with the crosshair.



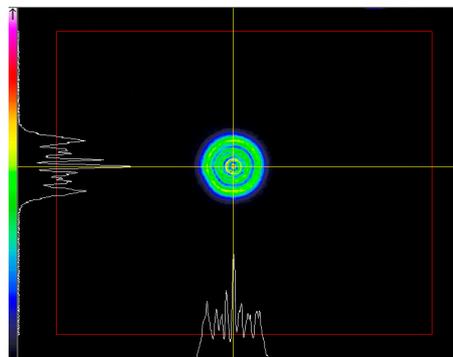
| Apertures, mm |     |
|---------------|-----|
| In            | Out |
| 2             | 1   |

**Comments:**

The Aligner is aligned.

Diffraction pattern is symmetric.

The center of rings coincides with the crosshair.



### 3. Alignment procedure for the Focal- $\pi$ Shaper

Aligning of the Aligner means the Mount is close to the optimum position and the Focal- $\pi$ Shaper can be installed. Because of production tolerances there might be necessary to tune the position of the Focal- $\pi$ Shaper.

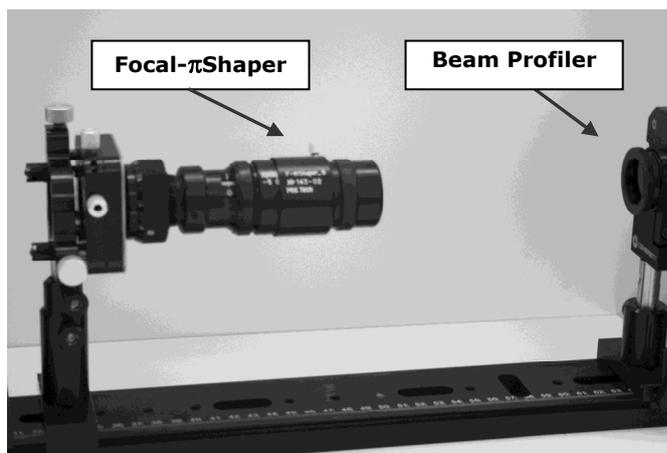
**Action:** to install the Focal- $\pi$ Shaper and camera-based beam profiler.

Typical view of beam profile pattern is shown in next figure.

**Important:**

The output intensity profile *SHOULDN'T BE* Flattop!  
It should have central laser spot and several rings, so similar to Airy disk distribution.

When proper alignment the centre of those rings to be in coincidence with the peak of central laser spot.



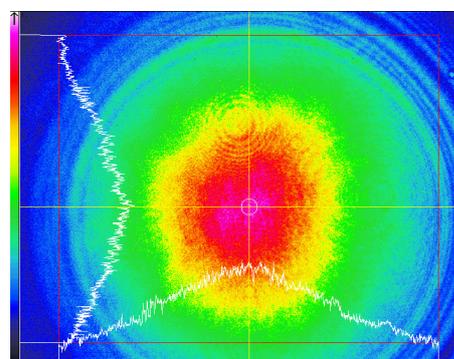
**Comments:**

- there exists certain misalignment in vertical and horizontal directions – the rings should be “raised” and shifted left.

**Action:** to do *lateral shifting* in vertical and horizontal directions with checking the spot with camera to provide symmetric diffraction pattern being centred with the crosshair.

**Important:** Use lateral shifts (X/Y) only!

It is recommended also to locate the beam profiler at longer distance.



**Important:** When small input beam size the rings can be not good seen, then it is recommended either to enlarge temporarily the input beam size for alignment purposes, or another way – scanning full range of lateral shifts on Mount in both directions to make the rings visible.

The right figure shows typical view of beam profile after F- $\pi$ Shaper at 0.9 m distance.

**Comments:**

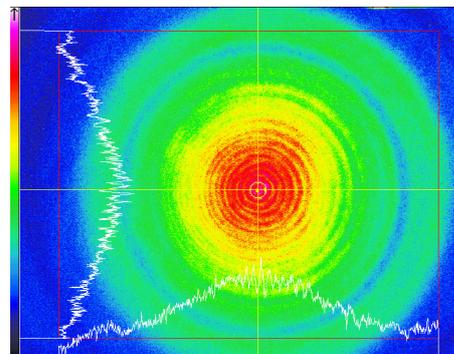
- the image demonstrates good symmetry.

Next step is analyzing the pattern near the focal plane of a lens.

For alignment purpose it is convenient to apply 1 meter lens:

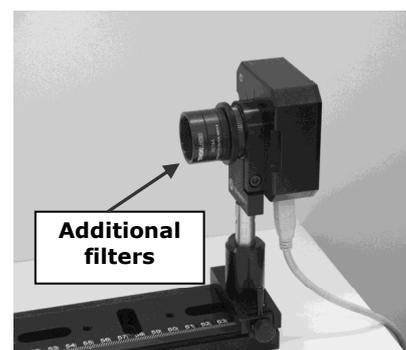
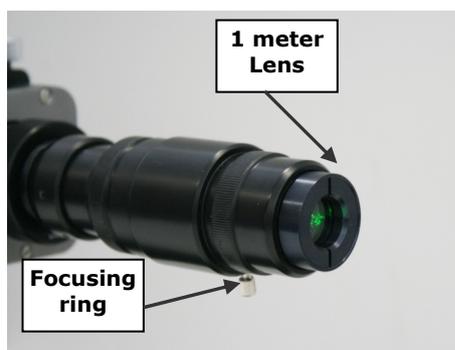
- negligible aberrations,
- relatively large spots, several hundreds of microns, that can be caught by the popular camera based beam profilers.

By finishing the alignment that 1 meter lens should be replaced by a working focusing lens.



**Actions:**

- to install the 1 meter lens at the Focal- $\pi$ Shaper exit,
- to install additional neutral filters on the beam profiler, typically +2D, to prevent damaging of camera due to increased irradiance,
- to put the beam profiler after the F- $\pi$ Shaper at distance approx. 1 meter,



- by rotating the focusing ring (see on right) to find the position of the beam waist, this will be a starting point for further adjustments,
- by rotating the focusing ring to shift the waist far from 1 meter lens, in order to analyze the profiles BEFORE the waist,
- to reach the profile looking as a donut, see the next picture.

**Important:** To move the waist far from the lens it is necessary to rotate focusing ring in direction of negative values on the scale engraved on the F- $\pi$ Shaper case,  
*The rule: Negative values correspond to negative optical power, hence to shifting the profiles FROM the lens.*

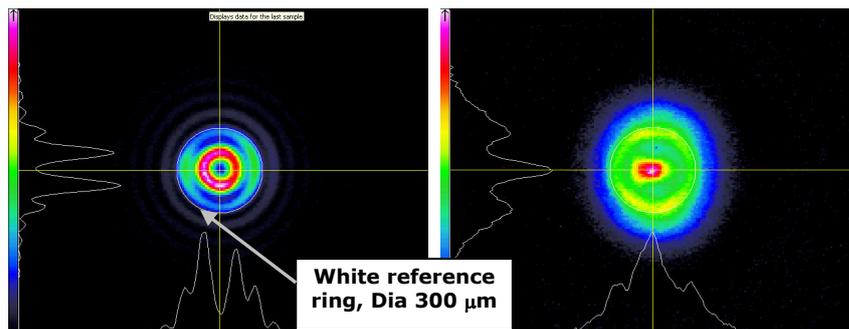
The right figure shows examples of profile.  
 Spot diameter is about 300  $\mu\text{m}$ .

**Comments:**

- there exists certain misalignment in horizontal direction.

**Action:**

- to do tilt in vertical direction with checking the spot with camera to provide symmetric diffraction pattern.



**Important:** It is convenient to use a reference ring like white ring of 300  $\mu\text{m}$  diameter on the above and below pictures.

**Important:** Use primarily the tilts around X/Y, lateral shifts to be used AFTER tilts to correct the alignment.

**Important:** As a rule by aligning it is necessary to “move” the spot in direction of maximum intensity, in case of above pictures – to the left.

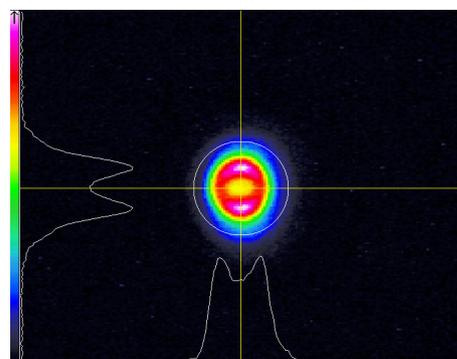
The right figure shows typical view of beam profile for the aligned F- $\pi$ Shaper.

**Comments:**

- the image demonstrates good symmetry,
- the profile in vertical direction has deeper intensity in the centre due to ellipticity of initial laser beam.

To reach the flattop intensity it is necessary to adjust input beam diameter.

The optimum beam diameter depends on a profile of initial TEM<sub>00</sub> laser beam, typically for the Focal- $\pi$ Shaper 9 the optimum  $1/e^2$  diameter to be 4-4.5 mm.



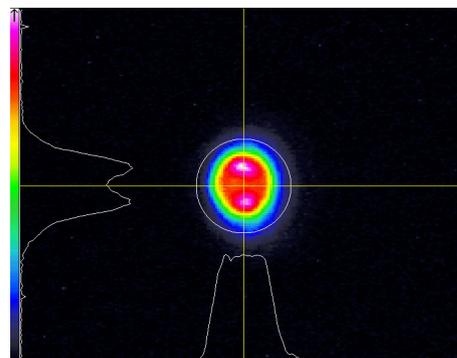
**Action:**

- to tune the input beam diameter by external zoom beam expander .

Example of resulting spot is shown in right figure.

**Comments:**

- the profile is flattop in horizontal direction,
- the image demonstrates good symmetry,
- the profile in vertical direction has deeper intensity in the centre due to ellipticity of initial laser beam.



**Important:** It is recommended to use a zoom beam expander ahead of the Focal- $\pi$ Shaper in order to simplify the final procedure of adjusting the input beam diameter.

**Important:** The fine tuning of beam size internally can be done by rotating the magnification ring of the Focal- $\pi$ Shaper;  
 it is necessary to keep in mind that the range of size variation is limited by +/-15% only and by rotating the magnification ring there happens shift of the waist of resulting beam and it is necessary to compensate that shift by rotating the focusing ring.

After finishing the alignment of the Focal- $\pi$ Shaper with respect to the laser it is necessary to remove the 1 meter lens and use a working focusing lens.

**Important:** The sequence of profiles created by focusing of a beam after the Focal- $\pi$ Shaper will be repeated with the working lens as well, but the spot *size* will be changed *proportionally* to change focal length, while *distances along the optical axis* are changed in *square proportion*.

## APPENDIX 2

## BEAM SHAPING OF FOCUSED BEAMS FOR MICROPROCESSING APPLICATIONS

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Alexander Laskin<sup>1</sup>, Hansung Bae<sup>2</sup>, Vadim Laskin<sup>1</sup>, Aleksei Ostrun<sup>3</sup><sup>1</sup> AdIOptica Optical Systems GmbH, Rudower Chaussee 29, 12489 Berlin, Germany<sup>2</sup> ShinHoTek, #602 Uni-Tech Vil 1141-2, Baekseok 1-dong, Goyang-si, 410-837 Korea<sup>3</sup> St. Petersburg National Research University of Information Technologies, Mechanics and Optics, Kronverkskiy pr, 49, 197101, St.Petersburg, Russia**1. Abstract**

Beam shaping of focused laser beams to control intensity distribution in a laser spot is important optical task in various micromachining applications like scribing, PCB drilling and others. Developing of workable optical solutions is based on diffraction theory, and one of important for practice conclusions is that flat-top intensity profile in focal plane of a focusing lens is created when the input beam has Airy-disk intensity distribution. To meet requirements of modern microprocessing machinery the beam shaping optics should be capable to operate with CW and ultra-short pulse lasers, popular F- $\Theta$  lenses and microscope objectives, galvo scanners, 3D scanning systems. All these requirements were taken into account and fulfilled while developing refractive field mapping beam shapers Focal- $\pi$ Shaper, realizing optical approach to optimize conditions of interference near the focal plane and providing variety of profiles: flat-top, donut, inverse-Gauss. Other important features are: extended depth of field similar to Rayleigh length of comparable TEM<sub>00</sub> beam, easy integration in industrial equipment, simple adjustment procedure and switching from one profile to another. Flexibility of refractive design allows implementing not only telescopic but also collimating beam shapers compatible with TEM<sub>00</sub> fiber lasers. There will be considered design basics of refractive beam shapers, examples of implementations, results of profile measurements and material processing.

**2. Introduction**

The beam shaping optics becomes more and more popular in various laser applications; at the same time many technical solutions used in industrial laser machinery are based on applying scanning

optics

as

versatile tools of material structuring, image recording, drilling, etc. Usually the optical systems with scanning mirror optics presume working with collimated laser beams entering the 2- and 3-axis galvo mirror scanners, and the focusing is provided by various F-theta lenses. It is well-known that focusing of a laser beam allows creating very small spots required in microprocessing applications; therefore transformation of intensity profiles of focused beams has great importance. As a solution it is suggested to apply refractive field mapping beam shapers, which principle of intensity profile transformation is based on careful manipulation of wave front of a beam with conserving the beam consistency. This approach allows creating a beam, which intensity distribution and phase front are prepared to be transformed to flat-top, inverse-Gauss or donut spots when focused by a diffraction limited lens. Since modern microprocessing applications presume applying of scanning optics we will consider beam shaper designs optimized to be applied just with scanners.

**3. Intensity Profile Transformation by Focusing: Theoretical considerations**

Focusing of laser radiation by a lens provides concentration of laser energy in a small, typically several microns or tens of microns, laser spots. To provide such small spots, comparable with wavelengths, the focusing lenses should have diffraction limited image quality over entire working field, i.e. the residual wave aberration should be less than quarter of wavelength [4].

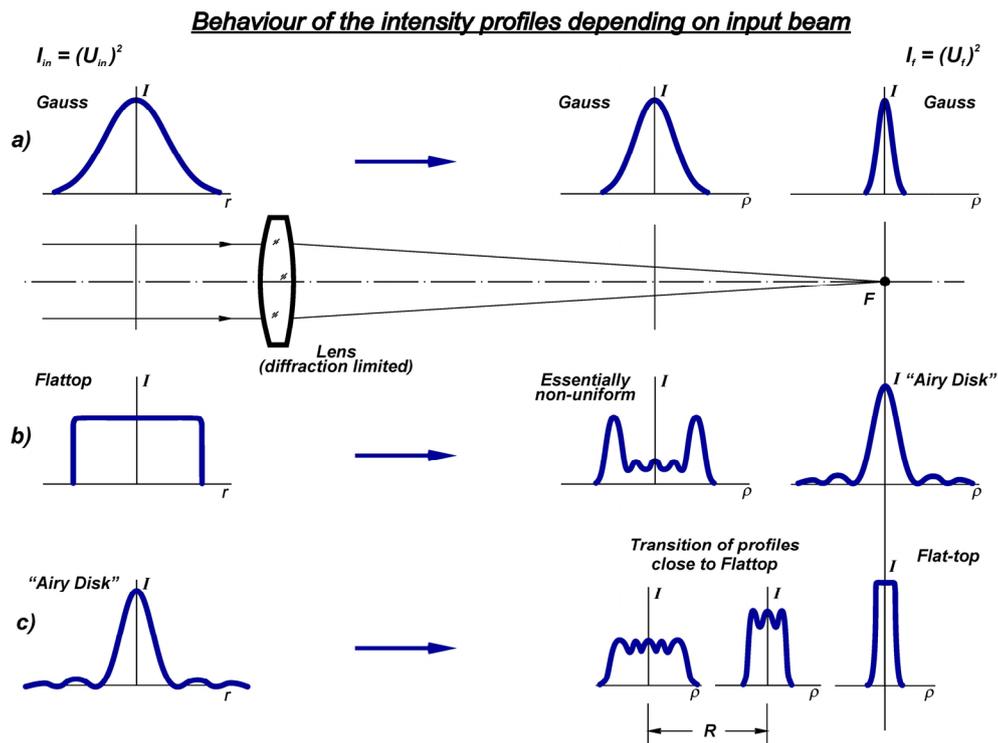


Fig. 1 Focusing of various laser beams by a lens.

Behaviour of laser beam profile in zone of focal plane of a focusing lens is an important issue to be considered for practice. This analysis can be done on the base of diffraction theory, which description can be found in books [1-4], here we emphasize on some important for further consideration features.

The Huygens-Fresnel Principle is the corner stone of the diffraction theory. According to that principle each point of a wave front can be considered as a center of a secondary spherical wavelet and by the light propagating in space the distribution of light in a particular plane or a surface can be defined as result of interference of those secondary wavelets. The rigorous mathematical theory for considering the diffraction effects was built by Kirchhoff, Helmholtz, Maxwell and other scientists in 19<sup>th</sup> century, for example, usually considerations concerning particular optical effects start from so called Fresnel-Kirchhoff diffraction formula [2]. Since the integral equations of mathematical description are quite complicated and impractical for engineering purposes there are used various simplifications like Fresnel approximation or Fraunhofer approximation [2,3].

A well-known and widely used conclusion from the diffraction theory is that the light field amplitude distribution in the special case of a focal plane of a lens is proportional to Fourier-image of input field amplitude distribution; examples of this transformation are shown in Fig. 1 and will be considered later. Summarizing analytical considerations concerning the Fourier transform by an optical system of circular symmetry one can express, in polar coordinates, the field amplitude distribution  $U_f$  in the lens focal plane by equation

$$U_f(\rho) = B \int_0^\infty U_{in}(r) J_0(2\pi\rho r) r dr \quad (1)$$

where  $U_{in}$  is field amplitude at the lens input,  $\rho$  is polar radius in the lens focal plane,  $r$  is polar radius at the lens input,  $J_0$  is the Bessel function of the first kind, zero order,  $B$  is a constant. This expression is accordingly referred to as the Fourier-Bessel transform, or alternatively as the Hankel transform of zero order.

In most of laser technologies the result of influence of the laser radiation on material is evaluated with using intensity distribution of a beam. Therefore,

for practical usage it is necessary to express the intensity distribution  $I_f$  in the focal plane of a lens through the function of field amplitude, for this purpose the well-known relationship [2] can be used

$$I_f(\rho) = [U_f(\rho)]^2 \quad (2)$$

Just the intensity distribution  $I_f$  is shown in Fig. 1 where examples of beam profile transformation are depicted.

The case of a beam focusing by a lens has great importance in considering the optical effects in various laser technologies since this is a mostly used way to create laser spots of a necessary size on a workpiece. Usually, analyzing the beam intensity profile in the focal plane of a lens is quite enough; especially when propagation TEM<sub>00</sub> laser beams is investigated. However, when an optical system contains beam shapers and intensity distribution transformation while the light propagating becomes more complicated it is necessary to consider intensity profile behavior in other zones of optical system as well, for example very important is the zone surrounding the focus of a lens.

Since the Fourier-transform is just a special case of intensity distribution description being valid for focal plane of a lens only, a complete detailed analysis of the beam profile behavior in zone of the lens focus requires applying of general mathematical descriptions of diffraction theory, for example the already mentioned Fresnel-Kirchhoff diffraction formula. Usually that interference analysis requires quite intensive mathematical computations, using special software for optical calculations. Let us omit the cumbersome mathematical computations and present here results of calculations for the cases most interesting for the practice of laser technologies:

- focusing of a TEM<sub>00</sub> (Gaussian) laser beam,
- focusing of a flat-top beam,
- creating a flat-top spot in zone of lens focus.

The results of analysis of intensity profile transformation for these cases are presented in Fig. 1 in form of graphs.

According to the Huygens-Fresnel principle the intensity distribution in a plane of analysis is an interference pattern created by interference of

secondary wavelets. Evidently, while the beam propagating in space the conditions for interference get changes and, hence, that pattern varies in different planes of analysis. In other words, *in each plane after the lens the intensity profile differs from one of a neighbor plane, and features of this profile variation depends on the initial beam profile at the entrance of the lens.*

The example a) in Fig. 1 corresponds to TEM<sub>00</sub> or Gaussian beam being most popular in laser technics, the initial intensity distribution is described in polar coordinates by equation

$$I_{in}(r) = I_{in0} e^{-2r^2/\omega_0^2} \quad (3)$$

where  $I_{in}$  is intensity at the lens input,  $\omega$  is a waist radius of the Gaussian beam,  $I_{in0}$  is a constant.

Focusing of such a beam with a diffraction limited lens leads to creating near focal plane a spot with, again, Gaussian intensity distribution and diameter  $d$  defined by the equation

$$d = 2\omega'_0 = \frac{2\lambda f}{\pi\omega_0} M^2 \quad (4)$$

where  $\lambda$  is a wavelength,  $\omega_0$  is waist radius of focused beam,  $f$  is the lens focal length,  $M^2$  is laser beam quality factor.

Essential feature of focusing the Gaussian beam is that its intensity profile stays just Gaussian over all distance of the beam propagation, only size is varying! Result of interference for an intermediate plane (between lens and focal plane) is again the Gaussian intensity profile; this is a well-known feature widely used in laser technics,

But this brilliant feature is valid for Gaussian beams only! In case of any other profile the intensity distribution behavior differs.

This is very good seen in diagrams of the example b), Fig. 1 corresponding to the flat-top initial beam. It is a well-known conclusion of diffraction theory, described in all literature sources by considering photo or astronomic optics, that in the focal plane the intensity  $I_f$  is described by the function called as Airy Disk

$$I_f(\rho) = I_{f0} \left[ \frac{J_1(2\pi\rho)}{2\pi\rho} \right]^2 \quad (5)$$

where  $J_1$  is the Bessel function of the first kind, first order,  $I_{f0}$  is a constant.

In the space between the lens and its focal plane the interference pattern gets strong variation both in size and in intensity distribution. One can see an essentially non-uniform profile corresponding to intermediate plane of analysis; it differs both from Airy Disk and flattop functions and is, evidently, useless for practical applications.

As we see the focusing of a flattop beam never leads to creating a spot with uniform intensity, neither in focal plane nor in intermediate planes:

*If an application needs a laser spot of uniform intensity (flat-top or top-hat) there is no sense to focus a flat-top beam!*

This doesn't mean, however, that a flat-top collimated beam cannot be used to create a small laser spot of uniform intensity. When an imaging approach (not focusing!) is applied, it is possible to create flat-top spots of several tens of  $\mu\text{m}$  size using imaging optical systems combined from scanning optics and additional collimating system. This technique is out of scope of this paper, some details and examples of imaging in scanning optics are considered in [6,7].

The beam focusing layout c) in Fig. 1 corresponds to very important for practice case of creating a small laser spot with uniform intensity profile just in the lens focal plane. Realizing this approach requires solving of the inverse problem – which intensity distribution should be at the entrance of a lens in order to get a flat-top spot in focal plane? This problem was, for example, discussed in paper [5]. Mathematical computations based on the inverse Fourier-transform technique give a solution that the input beam to have the intensity distribution described just by Airy Disk function, analogous to formula (5) with input beam radius  $r$  instead of  $\rho$ . Thus, *to generate a flat-top laser spot in the focal plane of a lens the input beam should have essentially non-uniform intensity distribution described by Airy disk function.*

Further analysis shows that the interference pattern in the space between the lens and its focal

plane isn't constant; it gets variation both in size and in intensity distribution and flat-top and close to flat-top profiles are created not only in the focal plane but in some regions in space between the lens and its focal plane. Thus, the flattop profile in focal plane is just a special case of the continuous variation of intensity distribution and, as will be shown later the optimum, from the point of view of practice, working planes are shifted from the focal plane towards the lens. Creating of the beam with Airy Disk intensity distribution is the function of the field mapping beam shaper *Focal- $\pi$ Shaper* that operate as telescopic optical systems and can be easily integrated in optical layouts with scanning optics.

#### 4. Beam Shaping of focused beams

We discuss in this chapter refractive field mapping beam shaping optics intended to realize the above considered optical approach of creating flat-top spot in focal plane: basic design, features of using the beam shapers and some practical advices.

##### 4.1 Optical design of Focusing Beam Shaper

The refractive field mapping beam shapers like *Focal- $\pi$ Shaper* provide at the output a beam which intensity distribution is described by Airy Disk function that is an optimum one to create in focal plane of a focusing lens spot with flat-top, inverse-Gauss or donut profiles. Basic idea of the beam shaper operation is shown in Fig. 2.



Fig. 2 Principle of the *Focal- $\pi$ Shaper* operation.

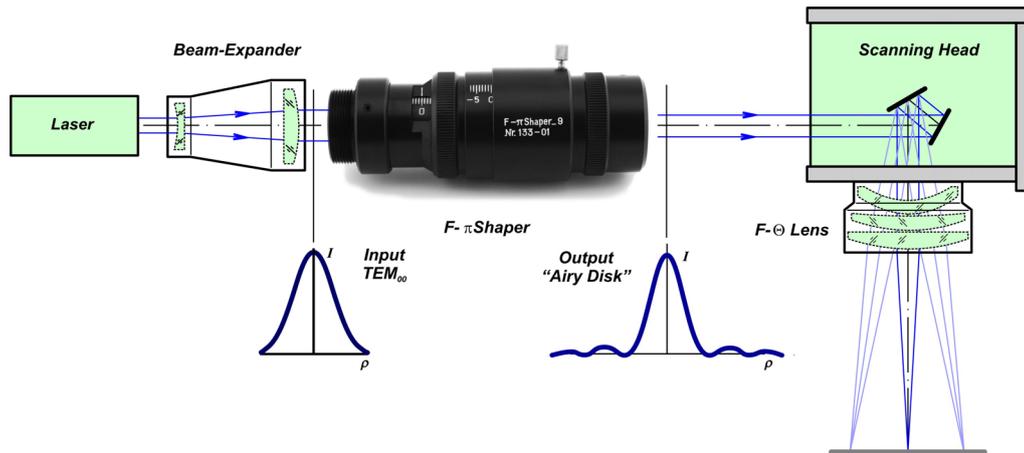


Fig. 3 Optical system with *Focal- $\pi$ Shaper* and scanning optics.

Most important features and basic principles of the *Focal- $\pi$ Shaper* are:

- telescopic refractive optical systems transforming the Gaussian to Airy Disk intensity distribution;
- flat-top, donut, inverse-Gauss and other profiles can be generated by the same device;
- operation with input  $TEM_{00}$  beams;
- operation in a certain spectral band;
- optical design without internal focusing;
- movable optical components are intended to optimize the final spot profile and to bring the plane of optimum profile in the working plane;
- compact design;
- easy integration to an optical setup and adaptation to a laser source;
- operation with any diffraction limited focusing lens;
- wide range of distances between the *Focal- $\pi$ Shaper* and the lens.

Example of optical layout of focusing the laser beam with using the *Focal- $\pi$ Shaper* and scanning optics is presented in Fig. 3.

Since the *Focal- $\pi$ Shaper* operates as a telescope with magnification about  $1^x$  it can be easily integrated in existing equipment.

The beam in space between the *Focal- $\pi$ Shaper* and scanning head is collimated. On the other hand due to careful handling with wave front in the beam shaper the output profile is stable over long distance. Therefore the distance between the *Focal- $\pi$ Shaper* and the focusing lens isn't critical; it can be chosen once but should be invariable during the system operation.

Varying the beam size at the *Focal- $\pi$ Shaper* entrance leads to variation of resulting intensity profile of the final spot, therefore, varying the beam size ahead of the *Focal- $\pi$ Shaper* is a good mean to provide flat-top, donut and inverse-Gauss profiles. Choosing the plane of optimum profile and bringing it to the working plane of existing equipment is realized by internal focusing of the *Focal- $\pi$ Shaper*. Thus, the beam shaper the system can be quickly adjusted.

#### 4.2 Beam profile behaviour

As above discussed the behavior of intensity distribution of a light beam is described by diffraction theory and in a common case the intensity is variable while a beam propagation in space: both beam size and its intensity profile are variable. A special case is just  $TEM_{00}$  beam, which Gaussian profile stays stable and only size is variable.

Since the output beam from the *Focal- $\pi$ Shaper* has not Gaussian but Airy disk distribution its behaviour has to be analysed using the Kirchhoff integral [2,3]. We present in this paragraph comparison of results of theoretical and experimental researches of intensity profile transformation near the focal plane of a lens. The Fraunhofer approximation of the Fresnel-Kirchhoff diffraction formula was used for theoretical calculations; experimental measurements of intensity distributions were made using a camera-based beam profiler.

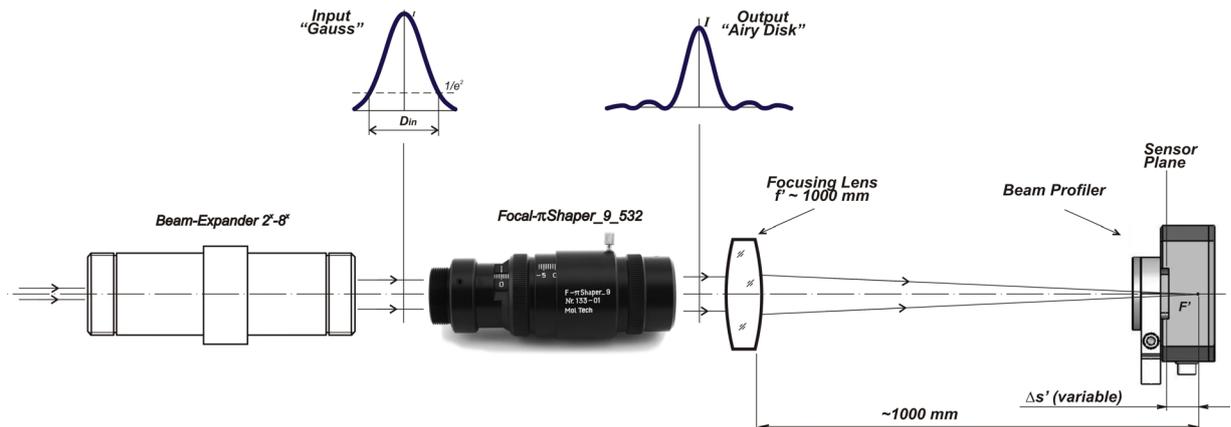


Fig. 4 Experimental optical layout to measure intensity profiles near the lens focal plane.

The experimental setup is presented in Fig. 4: the  $TEM_{00}$  laser beam of  $\lambda = 532\text{ nm}$  is expanded up to  $1/e^2$  diameter  $D_{in}$  at the *Focal- $\pi$ Shaper* entrance. Output beam with Airy disk intensity distribution is then focused by a lens of 1000 mm focal length,

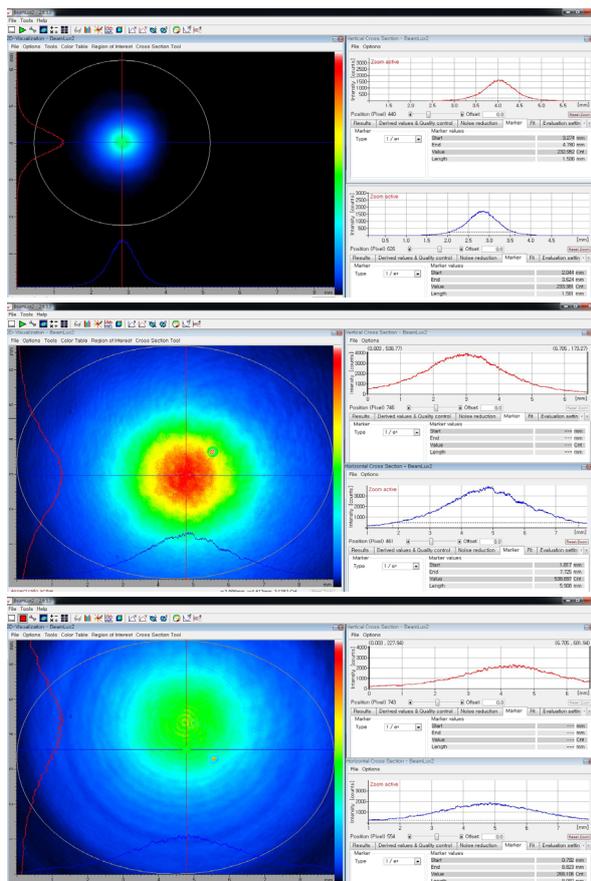


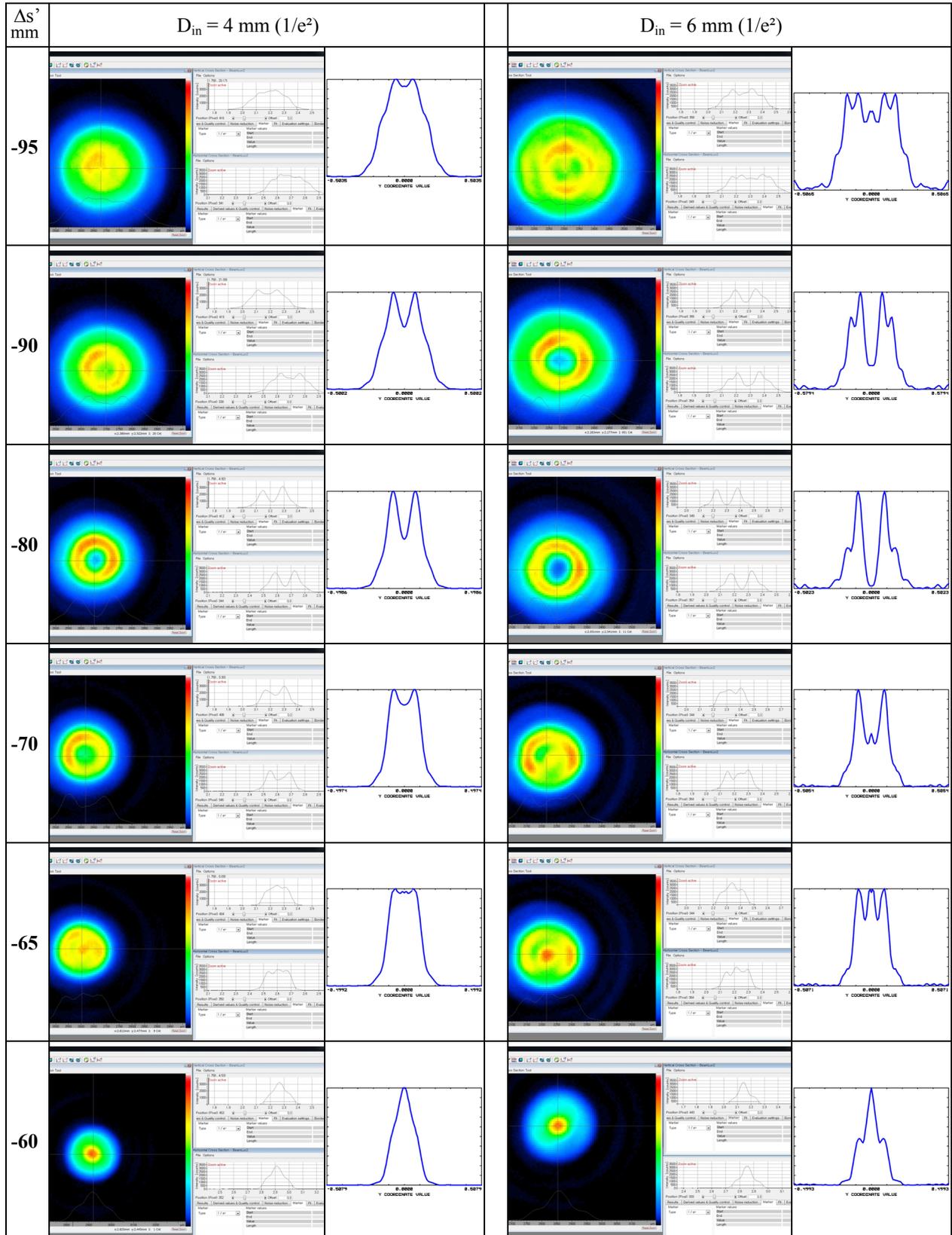
Fig. 5 Measured intensity profiles: top –laser output, middle and bottom – correspondingly *Focal- $\pi$ Shaper* input and output.

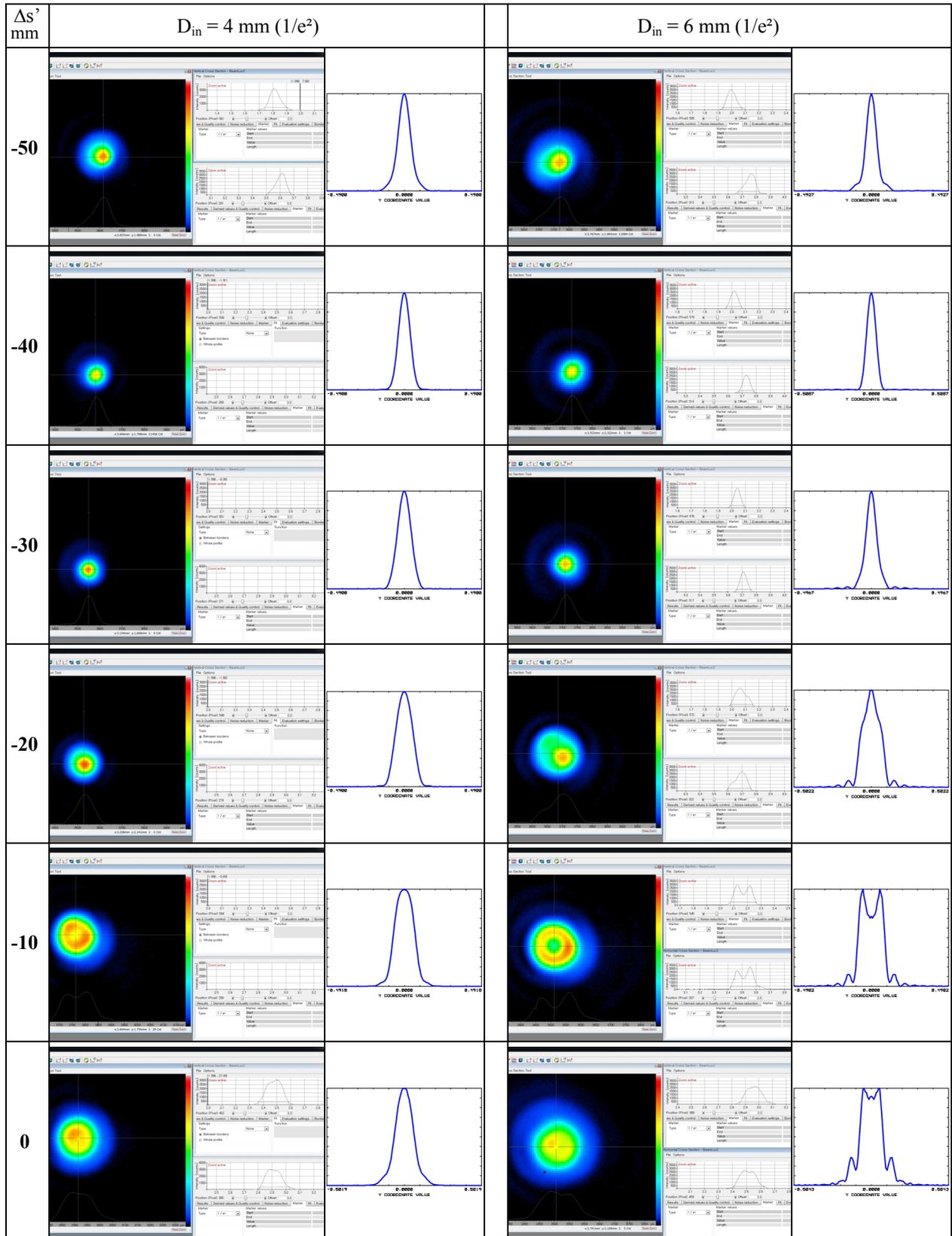
so the resulting laser spots have size of several hundreds  $\mu\text{m}$  and can be caught by a camera-based beam profiler. Typical view of measured intensity distributions are shown in Fig. 5: top - Gaussian beam from the laser, middle - expanded beam at the *Focal- $\pi$ Shaper* input, bottom – beam shaper output with a characteristic ring around the central spot – this is typical pattern just for the Airy disk beams.

The measurements of intensity distributions are conducted for input beams with  $1/e^2$  diameter  $D_{in} = 4$  and 6 mm, the experimental distributions are combined with theoretical calculated normalized profiles and presented in Table 1 for shifts  $\Delta s'$  from focal plane. These data allow making some important conclusions about the intensity distribution behavior near the lens focus.

Comparing to an ordinary Gaussian laser beam, which size changes by focusing but intensity distribution stays unchanged and is described by the Gaussian function, the Airy beam is characterized by variation of both size and profile. According to the Huygens-Fresnel principle the intensity distribution in a certain plane is result of a beam interference: in case of Gaussian beam the result is just the Gaussian beam (the Gaussian function is the eigen function of diffraction integral), but in case of a beam after the beam shaper one can observe a sequence of interferometric patterns, and one of them is just a spot with uniform intensity is created in the lens focal plane.

Table 1 Comparison of experimental and normalized theoretical intensity distributions





One should note here that correct analysis approach presumes considering of generalized light beams and characteristics of optical systems. There are some features that are very important for further considerations:

- focus is a characterizer of a lens, one can say that the focus “belongs” to the lens, not to the beam,
- waist of Gaussian beam characterize the Gaussian beam itself (i.e. “belongs” to the beam) and the waist of a focused beam is usually close the lens focus; it is considered in practice that the beam waist coincides with the lens focal plane – this approximation is valid for lasers with short wavelengths, typically less than 2  $\mu\text{m}$ , but should be always checked when longer wavelengths, for example, for CO<sub>2</sub> lasers,
- location of the waist of a general beam has to be defined through analysis of beam profile along the optical axis; for example, as will be shown further, the waist of a focused Airy beam is shifted to the focusing lens.

The data of the Table 1 show good correspondence between theoretical and experimental data, let’s consider some characteristic features of beam profile behavior.

According to the *Focal- $\pi$ Shaper* design the input beam to be Gaussian with 6 mm  $1/e^2$  diameter, therefore we consider first the data of right columns of the Table 1. The profile in the lens focal plane, corresponding to position  $\Delta s' = 0$ , is close to flat-top. Since the beam shaper provides approximation of Airy beam the theoretical resulting profile has some deviation from a perfect flat-top in form of side-lobes, while the experimental data with real laser demonstrate a flat-top spot without side-lobes but with some smoothness of spot edges, the central part of spot has uniform intensity.

When shifting the observation plane (moving the camera beam profiler) closer to the lens, the spot size is getting smaller and the intensity distribution is transformed to Gaussian-like function. In particular example the spot in position  $\Delta s' = -40$  has minimum diameter and presents the waist of the focused beam. By further shifting of the camera one can see homogenized profiles in positions  $\Delta s' = -65$  and  $\Delta s' = -95$ , as well as with inverse-

Gauss and donut profiles in intermediate positions  $\Delta s' = -70$  and  $\Delta s' = -80$ . This profiles sequence “Gaussian-like - homogenized – donut – homogenized” repeats when further moving to the lens, however the spot size is growing as well, and those big spots are rarely interesting in practice and aren’t considered here. Similarly we don’t consider profiles behind the lens focus since that part of focused beam is divergent, the profiles aren’t stable and energy is spreading rapidly.

Evidently, the intensity distribution in zone of a lens focus experiences strong transformation due to essential variation of the beam phase front – the beam changes from convergent to divergent, and the front curvature is extremely high in focal plane [3]. As result the profile created in the focal plane is not stable, it is rather an interesting mathematical solution, but most often it is difficult to use that spot because of short depth of field. As will be shown later the profile in a lens focal plane becomes even more unstable in case of astigmatic laser beams that is typical for solid-state lasers. Therefore, it is usually recommended in practice to operate with spots in planes shifted to the lens where profile transformation is smoother and there exist not only homogenized profiles but also donut and inverse-Gauss that are very important in applications like welding, selective laser melting where uniform temperature profile on a workpiece is optimum.

In order to formulate practical recommendations to work with focused Airy beams we suggest to consider Fig. 6 with schematic presentation of intensity distribution transformation in two cases of beam  $1/e^2$  diameter at the *Focal- $\pi$ Shaper* entrance: 6 mm and 4 mm.

Summarizing the beam profile behavior on example of 6 mm input beam when moving the observation plane to the lens one can state:

- the spot in focal plane is flat-top,
- the beam waist with Gaussian-like profile is locating at distance  $R$ ,
- further shift at distance  $R/2$  gives a spot with homogenized intensity - “small flat-top”, this spot is most interesting in practice,
- in more  $R/2$  distance the donut spot is created,
- one more  $R/2$  shift gives another spot with homogenized intensity - “big flat-top”.

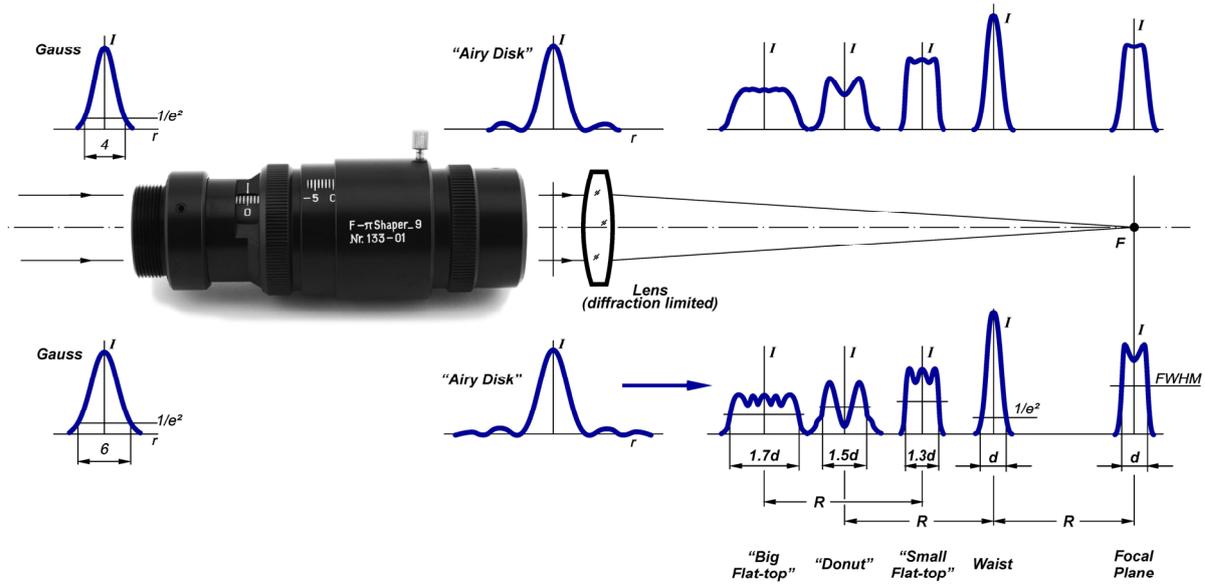


Fig. 6 To analysis of profiles by focusing the beam after *Focal-πShaper*.

That characteristic distance  $R$  is determined by properties of laser radiation propagation, it can be expressed through Rayleigh length  $z_R$  of a reference laser beam with the same wavelength  $\lambda$  and the same divergence  $2\Theta$  using well-known formulas [3]

$$R = 2z_R = \frac{2\pi\omega_0^2}{\lambda M^2} = \frac{8\lambda M^2}{\pi(2\Theta)^2} = \frac{8\lambda f^2 M^2}{\pi D^2} \quad (6)$$

where  $M^2$  is parameter of laser beam quality,  $f$  is focal length of focusing lens,  $D$  is  $1/e^2$  diameter of the laser beam at the focusing lens and  $\omega_0'$  is waist radius of a focused Gaussian beam that is defined as

$$\omega_0' = \frac{\lambda M^2}{\pi\Theta} = \frac{2\lambda f M^2}{\pi D} \quad (7)$$

The diameter  $D$  is 6 mm in the considered example where the *Focal-πShaper* presents a telescope with approximately  $1^\times$  magnification.

The spot sizes in different positions of focused beam is shown in Fig. 6:

- the FWHM flat-top spot diameter  $d$  in the lens focal plane is equal to  $2\omega_0'$ , i.e. is the same like  $1/e^2$  diameter of the waist of the reference beam,
- $1/e^2$  waist diameter is the same like in case of focused Gaussian beam, i.e. equal to  $d$ ,
- the FWHM diameter of the „small flat-top“ is 1.3 times bigger than one in focal plane,
- the FWHM diameter of the „big flat-top“ is  $1.7d$ ,

- the FWHM diameter of the donut spot equals  $1.5d$ .

The profiles in zone of lens focus being created with 6 mm diameter input beam are acceptable in many applications, however in the interesting in practice working planes of the “small flat-top” and “big flat-top” are characterized by strong modulation of intensity. Smoother intensity distributions are achieved when input beam size is reduced; corresponding data for  $D = 4$  mm are presented in left columns of the Table 1 and in top of Fig. 6:

- intensity modulation is suppressed in “small flat-top” and “big flat-top” spots,
- intensity minimum in center of donut spot is raised,
- spot sizes and their positions are practically the same like in case of 6 mm input beam,
- edges of the spot in focal plane are smoother.

Evidently, the reduced input beam size demonstrates better performance in area of “small flat-top” to “big flat-top” spots, and provides predictable results of material processing. Indeed, in practice choosing of optimum input beam diameter depends on intensity distribution of a real laser beam that deviates from a perfect Gaussian profile. In case of the *Focal-πShaper\_9* the optimum input beam  $1/e^2$  diameters lie typically in range 4 – 5 mm.

#### 4.3 Laser Beam Expansion by an Auxiliary Lens

As shown in previous paragraph variation of input beam size leads to variation of resulting profile – this is a known feature of field mapping beam shapers like *Focal- $\pi$ Shaper* [1]. And providing an optimum beam diameter is important while building optical systems of research setups or equipment.

A widely used approach to changing the laser beam size is applying of a beam expander. There are many commercially available models, including fixed and zoom beam expanders, motorized versions. To regret the strong competition among the beam expander manufacturers forces to reduce production costs that is achieved often through simplifying the optical design. For example, the optical systems are properly corrected to operate with axial beam only; therefore there might appear strong aberrations like coma while a beam expander tilt or internal misalignment of optical components. This isn't so "painful" when working with Gaussian beams, because due to the nature of laser radiation the energy is concentrated in a beam centre, so a Gaussian laser beam "forgives" imperfections of optical systems applied. But in case of beam shaping and careful handling with beam wavefront it is necessary to avoid any sources of wave aberrations.

Example of beam expansion of a laser beam using a commercial beam expander is presented in Fig. 7. There is evident distortion of profile in output beam that will influence on resulting intensity

distribution by beam shaping of focused beam. Therefore, when

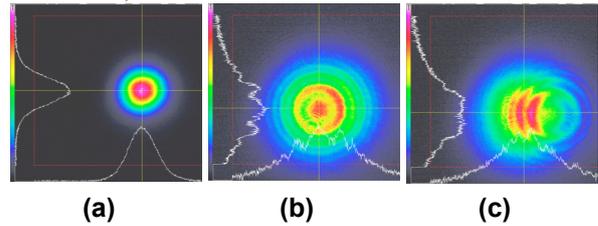


Fig. 7 Profiles by expansion of  $TEM_{00}$  laser beam using a beam expander: (a) input beam, (b) output of *centered* and (c) *slightly tilted* expander.

possible it is recommended to skip using a beam expander ahead of a beam shaper.

Very often by building an optical system of industrial equipment or a research setup it is possible to provide certain space between a laser and a beam shaper. This space can be used to correct the beam size by providing corresponding beam divergence: partially due to natural divergence of laser beam, partially by applying an auxiliary lens at the laser output. This approach is illustrated by layouts in Fig. 8.

Suppose a beam at a laser output has diameter  $D$  and divergence  $2\Theta$ ; we consider here values at  $1/e^2$  intensity and  $D$  relates not to waist but to beam size at laser exit. The required beam diameter for a beam shaper is  $D'$ , and the distance between the laser and the beam shaper is  $L$ . Due to the natural divergence the beam has diameter  $D'$  at the beam shaper entrance, so the auxiliary Lens has to introduce certain additional divergence in order to provide the divergence angle  $2\Theta'$ . One should note, the beam shaper has to be capable to compensate this resulting

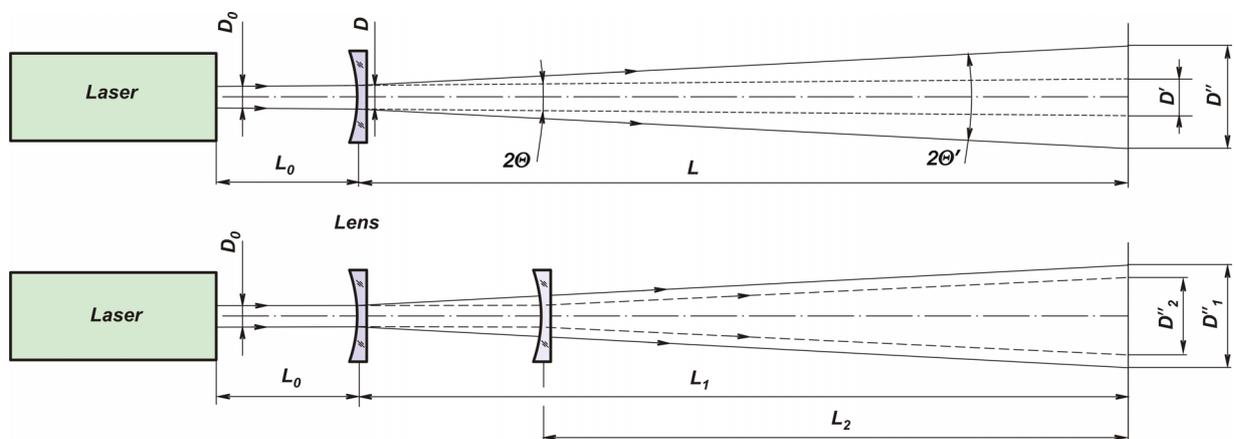


Fig. 8 Layouts to correct beam size using an auxiliary lens.

total input divergence angle  $2\Theta'$ , then the maximum allowed angle  $2\Theta'$  is defined by the beam shaper specifications, in *Focal- $\pi$ Shaper* it is  $\pm 5$  mrad, under some conditions  $\pm 10$  mrad.

From the geometry of rays shown in Fig. 8, we can write

$$2\Theta' = \frac{D'' - D}{L} \quad (8)$$

$$f' = \frac{DL}{D + 2\Theta L - D''} \quad (9)$$

where  $f'$  is focal length of the auxiliary lens.

The Eq. (8) allows evaluating required full divergence angle and check whether this correction approach is realizable with a particular beam shaper. The Eq. (9) is used to calculate the Lens focal length.

Let's consider examples:

- 1) Laser output:  $D = 1$  mm and  $2\Theta = 3$  mrad (waist  $2\omega = 0.5$  mm inside laser,  $M^2 = 1.1$ ); available length  $L = 1000$  mm; required  $D'' = 5$  mm (for *Focal- $\pi$ Shaper 9*); then  $2\Theta' = 4$  mrad – acceptable by the beam shaper,  $f' = -1000$  mm.
- 2) Laser output:  $D = 8$  mm and  $2\Theta = 0.2$  mrad; length  $L = 600$  mm; required  $D'' = 5$  mm; then  $2\Theta' = 5$  mrad – acceptable by the beam shaper,  $f' = 1538$  mm.

In both examples the auxiliary lens to be of low optical power and, hence, doesn't require precise alignment when installed in optical system. In majority of practical cases it is possible to use off-the-shelf lenses.

Moving the auxiliary lens makes it possible to tune the beam size at the beam shaper entrance; this is illustrated by layout in bottom of Fig. 8. From the geometry the resulting beam diameter  $\Delta D''$  can be defined by expression

$$\Delta D'' = D_1'' - D_2'' = (L_1 - L_2) \frac{2\Theta L_2 - D_1}{f'} \quad (10)$$

Thus, when certain air gap after a laser is available the optimum input beam diameter for a beam shaper can be adjusted using a single off-the-shelf lens.

#### 4.4 Alignment

As optical devices designed to work with axial beams the refractive field mapping beam shapers operate in relatively narrow angular field, therefore one has to take care for their proper alignment with respect to a laser and other components of an optical system. Due to optical design implementation the *Focal- $\pi$ Shapers* aren't sensitive to misalignments - typical tolerances are characterized by lateral translation error 0.1 mm and tilt of 5 arcmin with respect to laser beam. Evidently, these tolerances aren't tough and can be provided using ordinary 4-axis mounts. To quicken the alignment procedure it is usually recommended to apply alignment tools like ones described in [8].

Pointing laser beam instability should be analyzed while the beam shaper alignment. It is common to perform adjustments at low power operation mode of the laser to provide safe work conditions and prevent damaging of tools like beam profilers, filters, etc.; then the laser is switched in full power mode for a process. Due to features of laser design there might be deviation of a beam while switching between the low and full power operation modes that would inevitably lead to essential lateral shift of the beam at a beam shaper entrance. This effect becomes more pronounced in case of long air gap between laser and beam shaper, and is very critical for solid-state lasers. Example of this lateral shift is illustrated in Fig. 9: when switching laser power from 0.5 W (left) to 10 W (right) while distance from laser to the *Focal- $\pi$ Shaper* is 3.5 meter there appears a lateral shift of about 1 mm (!) - this is essential misalignment that results strong distortion of final spot profile.

To avoid this misalignment it is recommended to perform adjustments in full power mode and use beam profilers with dedicated attenuators.

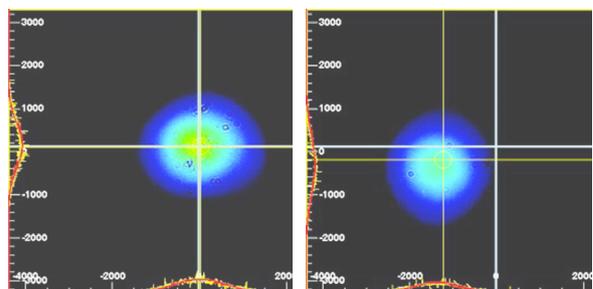


Fig. 9 Pointing error of solid-state laser: *left* – low power, *right* – full power operation modes.

#### 4.5 Influence of astigmatism of input beam

Astigmatism is a physical effect when a focused beam has two separate focuses for two orthogonally related sections, usually meridional and sagittal ones [3,4]. A laser beam can become astigmatic because of laser design itself, variation of operation parameters (current on pumping laser diodes, repetition rate, pulse duration, etc.) as well as due to astigmatism induced by components of optical system (mirrors, lenses). Astigmatism is an inherent property of radiation of some types of solid state lasers; it is usually suppressed in modern lasers for determined parameters of operation through optimisation of their design, but appears when parameters deviation from those optimum values. Fiber laser and fiber-coupled lasers demonstrate usually weak astigmatism.

Most often astigmatic beams have elliptic shape; it is also possible when a wide collimated beam of several millimetres or centimetres diameter is round but is inherently astigmatic. A simple and effective way to visualize and evaluate astigmatism is the beam focusing and analysis of intensity profiles around the beam waist. Example of profiles before, after and in waist of focused slightly astigmatic Gaussian laser beam is presented in Fig.10:

- the spots before and after the waist are elliptic,
- their long axis are turned at  $90^\circ$  - this is typical behaviour of astigmatic light beams,
- the spot in waist is round.

When working with an ordinary Gaussian beam the influence of astigmatism on a process is not strong, since the spot in the waist is round and certain increasing of its diameter doesn't bring essential change in result of processing. But in case of beam shaping of focused beam astigmatism leads to characteristic change of resulting profile – the circular symmetry of intensity distribution is lost and section profiles have different view. Example of flat-top spot in the lens focal plane is shown in

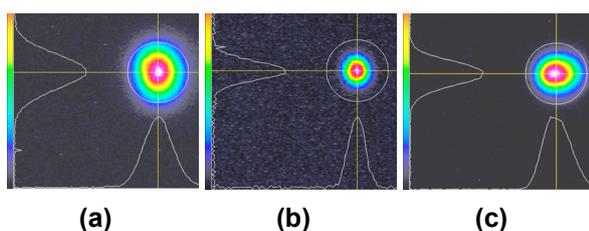


Fig. 10 Profiles by focusing of astigmatic laser beam: (a) before waist, (b) in waist and (c) behind waist.

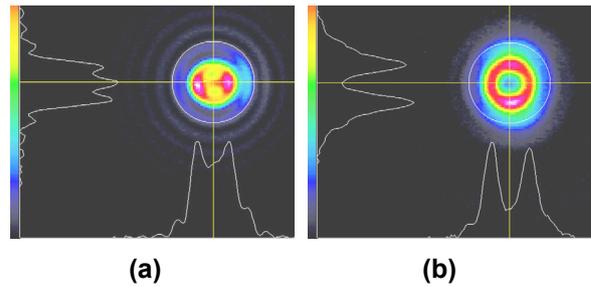


Fig. 11 Profiles of focused astigmatic beam: (a) – flat-top in focal plane, (b) – donut shape.

Fig. 11 (a); in many applications it is possible to work with such a spot and get acceptable processing results, but the unsymmetrical intensity profile has to be taken into account.

Interesting fact is that even in case of astigmatic laser beam the donut spot demonstrates regular round shape, Fig. 11 (b). This feature can be used to simplify the alignment procedure – when a beam shaper is aligned using 4-axis mount it is recommended to put a beam profiler just in the plane of donut spot and use round shape of profile as a criterion of proper alignment.

Astigmatism can be also introduced by components of optical path: lenses, beam expanders, mirrors. Therefore, it is always advisable to simplify the optical system, for example to avoid using of beam expanders as discussed in previous paragraphs.

#### 4.6 Notes to work with F- $\Theta$ lenses

The considered beam shapers for focused beams are intended to be used with any diffraction limited lens, which wave aberration doesn't exceed  $\lambda/4$  value over whole working field. Majority of commercially available widely used in industrial application F- $\Theta$  lenses fulfil this condition, there are however some features relating to their optical design.

F- $\Theta$  lenses present multi-lens optical systems providing flat working field – the lens focal plane. Therefore the focal length of an F- $\Theta$  lens isn't constant over whole working field, it depends on the field angle. In popular lenses this focal length difference from the field centre to periphery reaches 10-15%; this variation can be detected by analysing effective spot sizes even with ordinary TEM<sub>00</sub> beam.

As shown in previous paragraphs the intensity distribution of focused Airy beam near the lens focus depends on the lens focal length and distance from the focal plane. Therefore there exists certain

variation of spot sizes and profiles for spots in centre and periphery of working field. Usually this effect isn't strong but has to be taken into account while evaluation of results of processing.

Telecentric F- $\Theta$  lenses have less variation of focal length, and its influence is practically negligible.

## 5. Experimental Results of Microprocessing

Even edges and reduced heat affected zone (HAZ) are common aims in various micromachining applications. Beam shaping and providing flat-top or other intensity profiles of the laser spot (donut, inverse-Gauss) is one of key techniques of improving those applications, and using the *Focal- $\pi$ Shaper* brings flexibility in realization of these techniques. We present in this chapter some results of material processing.

### 5.1 Scribing on glass

The optical layout presented in Fig. 3 was used to improve laser scribing of glass using TEM<sub>00</sub> ultrashort pulse laser to create trenches of 6-7 microns width. Comparison of results of scribing with a pure TEM<sub>00</sub> laser beam and with *Focal- $\pi$ Shaper 9\_1064* installed ahead of the scanning head is presented in Fig. 12.

The difference in quality of scribing is evident: irregular trench edge and wide HAZ in case of TEM<sub>00</sub> beam, and even trench edges, steep walls and practically absent HAZ when *Focal- $\pi$ Shaper* is used.

Evidently, with using the *Focal- $\pi$ Shaper* it is possible to enhance the quality and reliability of scribing process.

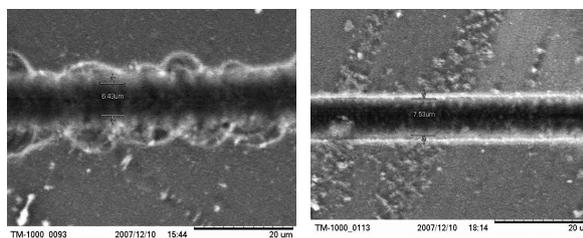


Fig. 12 Scribing by TEM<sub>00</sub> femtosecond Laser: *left* - TEM<sub>00</sub> laser beam, *right* - after the *F- $\pi$ Shaper* (Courtesy of Altechna)

### 5.2 Scribing of thin-film material

Laser scribing of thin layers is widely used in photovoltaics technologies, patterning in display

production and many others. Example of realization of this technique to ablate 210 nm thin film of photovoltaics material is demonstrated in Fig. 13, where

- top screenshot presents initial profile of UV laser ( $\lambda=343$  nm, pulse duration 500 fs),
- the central screenshot shows profile of flat-top spot near focal plane of F- $\Theta$  lens,
- view of the resulting trench of 40  $\mu\text{m}$  width (100 $\times$  microscopy) is shown in bottom left picture, and
- profile measurements for the resulting trench are presented in bottom right pictures.

The initial laser beam is astigmatic, therefore the resulting flat-top spot, Fig. 13, centre, has difference of intensity distribution in vertical and horizontal directions. Nevertheless, it is possible to reach high quality trench of 40  $\mu\text{m}$  width with steep edges and not damaged beneath layer.

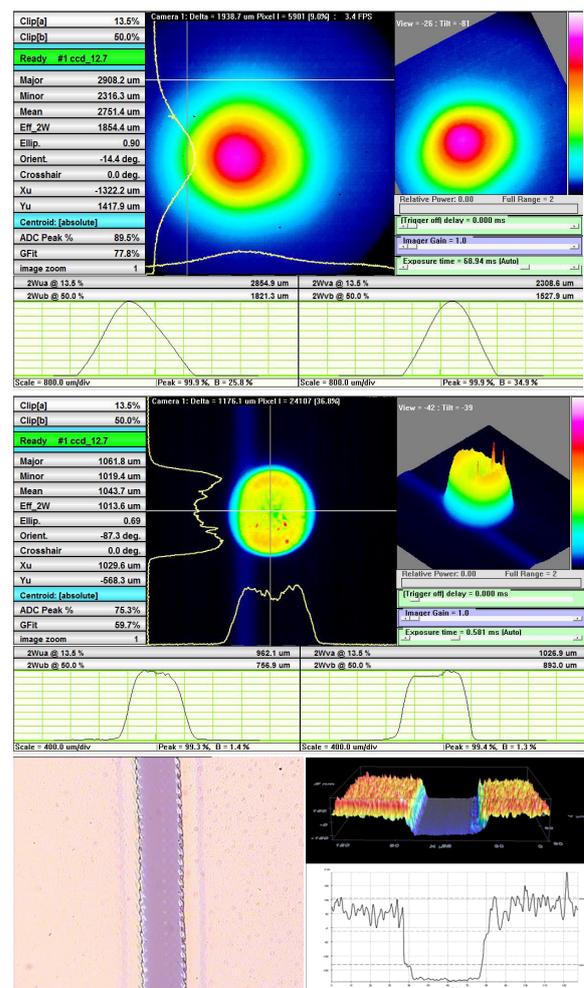


Fig. 13 Scribing by TEM<sub>00</sub> UV fs laser: *top* – input beam, *middle* – flat-top focused spot, *bottom left* – trench view, *right* – confocal microscopy analysis. (Courtesy of ALPhANOV)

### 5.3 Ablation of Silicon

Processing of silicon is important in microelectronics, Fig. 14 presents measured profiles and results of ablation in earlier discussed three characteristic spots: “small flat-top”, donut, “big flat-top”. The profile of initial TEM<sub>00</sub> laser with  $\lambda = 1030$  nm and pulse duration 8 ps is shown in Fig. 14 (a), it has some imperfections (diffraction fringes) due to beam clipping in previous optical system, nevertheless the resulting intensity distributions in working planes near the lens focus are close to theoretical ones, and the ablation process demonstrates holes with predictable sizes and depths as well as with even edges and steep walls.

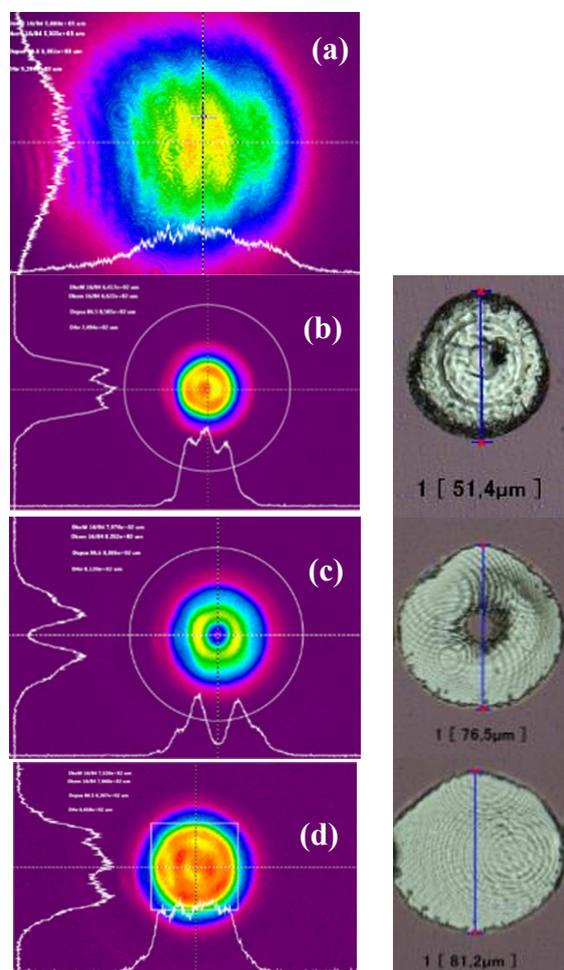


Fig. 14 Silicon ablation using picosecond laser: (a) initial laser profile, (b) “small flat-top”, (c) donut, (d) “big flat-top” spots and corresponding ablation results on right.

(Courtesy of Ernst-Abbe-Fachhochschule Jena )

### 6. Conclusions

Refractive beam shapers of field mapping type transforming a Gaussian beam to a beam with Airy disk intensity distribution provide assured beam shaping of focused laser beams and creating spots with flat-top, inverse-Gauss and donut profiles. The data presented demonstrate good correspondence of theoretical and experimental data. The considered examples of this type of beam shaping in micromachining techniques confirm its applicability in scientific and industrial applications.

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