

Application note for 3D laser processing
using STOT-EL-10-42-OF tunable lens
and
STOT-DSD controller board

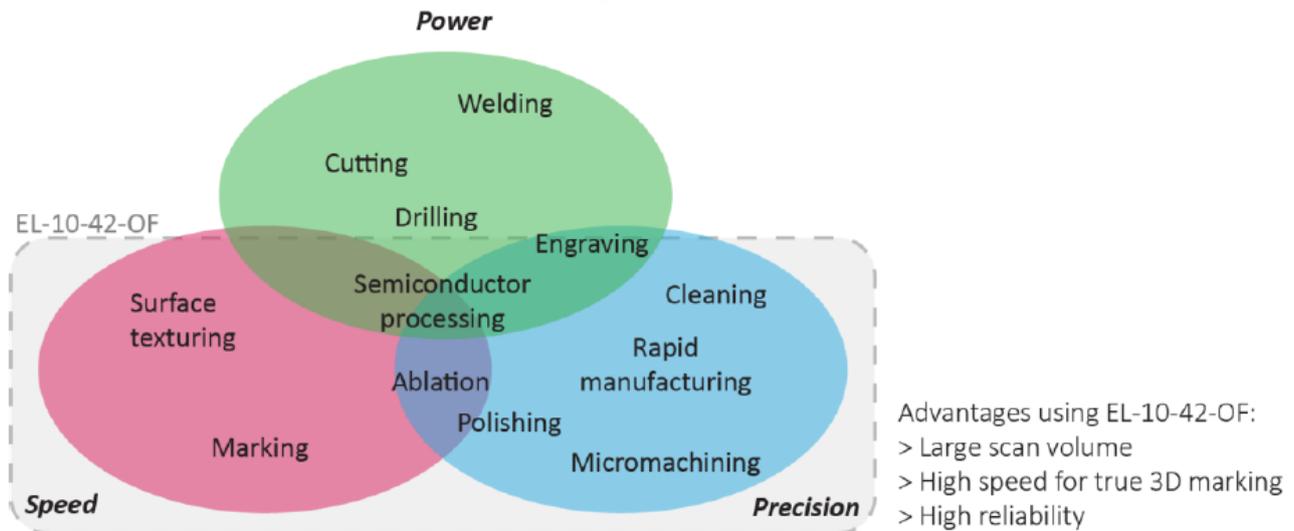


1. Introduction

Nowadays, the common solution available on the market for laser processing in 3 dimensions is using the mechanical translation. By moving vertically the marking plane or alternatively by translating a fixed lens with a motor, the z-coordinate can be tuned and controlled. However one major limitation of the former approach is the slow translation speed because it requires massive parts to be moved. The latter allows only a small range in z-travel of about 60 mm for a typical configuration involving an f-theta lens. Owing to the mechanical actuation, the speed by which the spot is shifted is limited. The delicate movable parts are limited in their lifetime, require lots of space to be integrated in an existing system and often need to be water cooled.

In this Application Note, we describe the integration of our electrically tunable lens STOT-EL-10-42-OF with STOT-DSD controller board. We will provide general guidelines of using a STOT-EL-10-42-OF lens in combination of STOT-DSD controller board for 3D laser marking and engraving applications (without an f-theta lens). STOT-EL-10-42-OF lens is light, compact and has fast response time (10-millisecond range) as well as long lifetime. Therefore it would be an ideal candidate to overcome many of the downsides of a mechanical solution while at the same time ensuring reduced costs and compact design.

The 3D laser marking system using STOT-EL-10-42-OF lens can also achieve small spot sizes or large scan volumes. Optical designs are on request. STOT-EL-10-42-OF is designed for pulsed lasers of near-infrared wavelength between 950 nm and 1100 nm. This opens the possibility to integrate the STOT-EL-10-42-OF into various laser processing applications.



2. Controlling EL-10-42-OF lens with STOT--DSD controller board

STOT-DSD is an FPGA-based digital controller board and is designed to control STOT-EL-10-42-OF lenses. The board is composed of two layers for which the top one is Digital Servo Interface (DSI-1-O16) and the bottom one is Digital Servo Controller (DSC-1). While the EL-10-42-OF lens shifts the laser spot in z- (vertical) direction, the galvo mirrors deflect the laser spot in the x-y- (horizontal) plane. This approach is implemented in the compact laser marker presented in section 4.2 and schematically shown on the left panel of Figure 1.

The communication between the PC (the user) and the XY2-100 digital controller card is often established via a serial bus, e.g. USB. Within the extended XY2-100 protocol, the z-axis used to control EL-10-42-OF lens is already available, in addition to the x- and y-axes that control the galvo mirrors. The controller card transmits the digital signal for the x- and y-axis to the scan head for controlling the galvo mirrors. The digital signal of the z-axis can be directly sent to STOT-DSD board. The right panel of Figure 1 shows another possible integration, in case the customer is using the controller card from SCAPS. Bi-directional XY-SCAPS communication protocol can be used. Both situations allow for fast 3D laser processing. The marking speed has been demonstrated to be 6 m/s on a 45° tilted object and 15 m/s on a 2D plane.

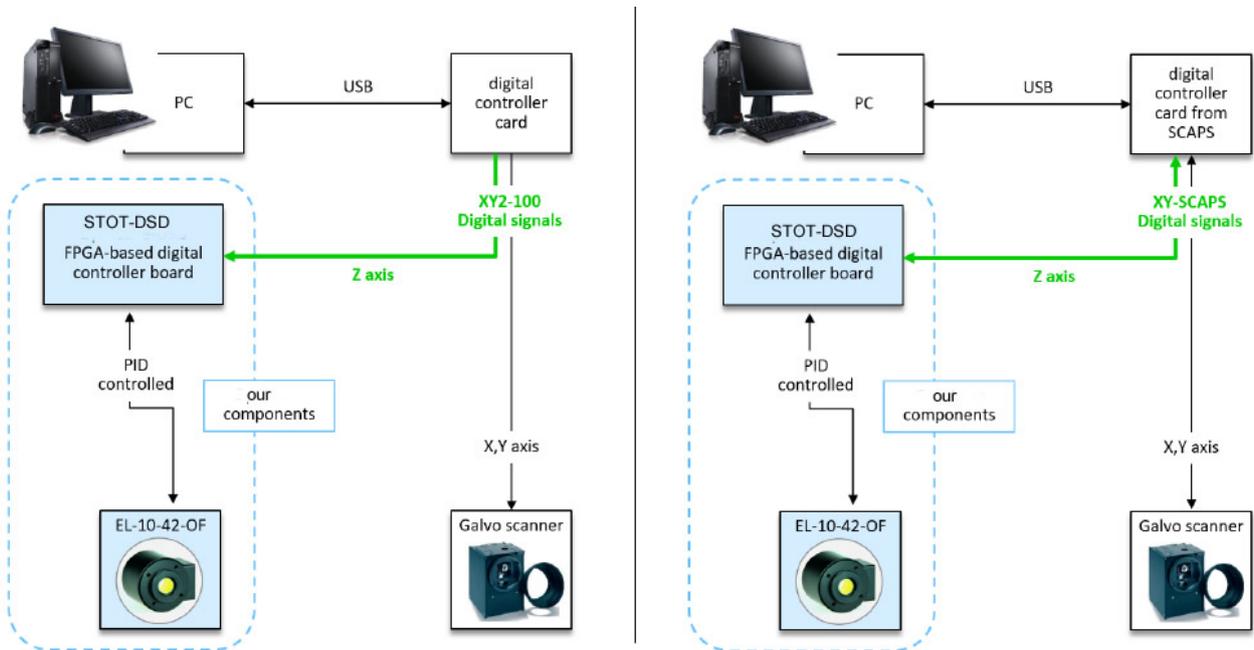


Figure 1: Integration of STOT-EL-10-42-OF lens within a digital protocol that provides x,y and z-signals. The output signal from the controller card for the z axis can be directly fed into the STOT-DSD board for the control of STOT-EL-10-42-OF lens.

2.1. Calibration of the z-axis

STOT-DSD board controls the optical power of the lens and hence allows for shifting the laser spot in z-direction (see Figure 2). It is necessary to perform a calibration between the control voltage and the laser spot's physical z-position in millimeter due to a nonlinearity in the voltage applied versus optical power characteristics.

The detailed steps for the z-axis calibration with EL-10-42-OF lens in SAMLight are listed in Appendix. After calibration, the set signal directly represents the tuning range in z-direction between Z_{min} and Z_{max} , as shown on the right panel of Figure 2. The actual z-tuning range depends on the optical layout in which the STOT-EL-10-42-OF is integrated, see section 4.2. The calibration procedure has to be done once and can be integrated e.g. via a lookup table in the marking software. It is recommended to measure at least five calibration points. More points will increase the precision of the calibration.

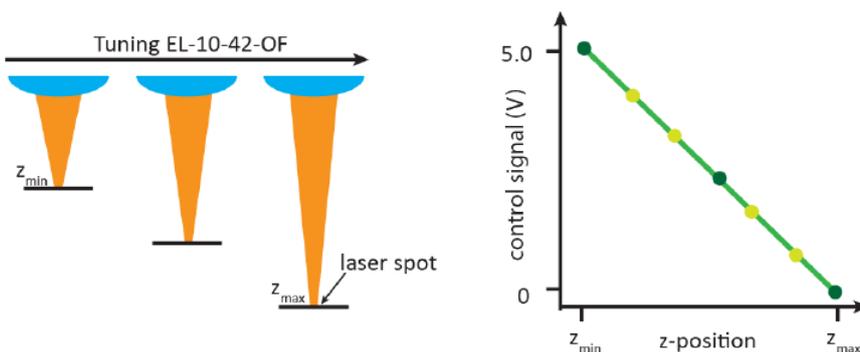


Figure 2: The left panel shows how the z-position of the laser spot is changed by tuning STOT-EL-10-42-OF. The right panel illustrates the calibration curve of control signal (0-5 V) versus the focal positions in z axis. The light green points represent further points required to increase the precision of the calibration.

3. Lens response time

Using the STOT-EL-E-OF-A electronics to control the STOT-EL-10-42-OF, we characterize 3 different situations (step, sinusoidal and triangular signal) that cover most of the "generic" trajectories required in 2.5D laser processing. The results reflect the combined effects of finite bandwidth of the control electronics (dominating part) and the physical limit of the lens itself.

3.1. Step response

Using STOT-DSD board to control the STOT-EL-10-42-OF, we characterize the lens response by ramping the applied voltage up and down and record the optical feedback signal.

The lens response is measured in order to evaluate the lens settling time and quantify the speed of focus change. Through this measurement we can determine how accurate the lens position can be achieved and also the tuning can be examined. The applied voltage at the input of STOT--DSD board is ramped up and down with adjustable speed. In Figure 4 the cyan curve is the input signal applying 20% and 80% jump length respectively with a ramp speed of 7000 bit/ms (this high speed is only for test purposes). The optical feedback signal of the lens is represented by the black data. One can see that during the ramp, the lens is in a controllable way following the red curve which is modeled based on the control algorithm. In both rising and falling edges, it takes about 8 ms for the 80% jump length and 4.5 ms for the 20% jump length to reach the set value. The data are acquired with the DSD software that SCAPS provides.

In a more detailed analysis we investigate the scaling of the response time for different jump lengths using the same ramp speed. The results are depicted in Figure 4 showing that the lens response time decreases with smaller jump lengths. Compared to the results measured using an STOT-EL-E-OF-A analog controller board, the response time is about a factor of 1.5 faster.

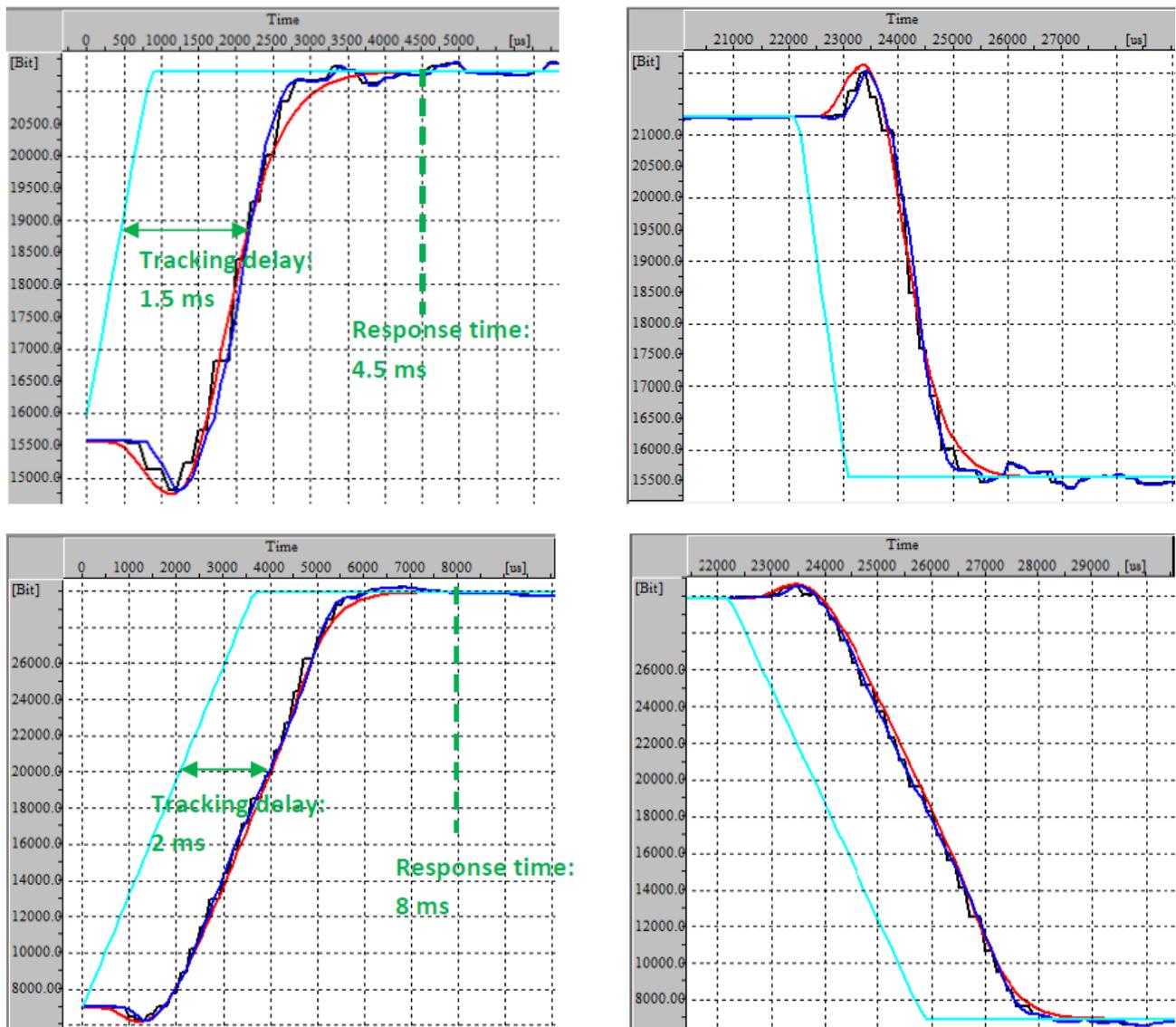


Figure 3: The response of STOT-EL-10-42 lens controlled with STOT-DSD board for different jump lengths (20% for top two plots and 80% for bottom two plots). The optical feedback signal is shown in

blue. The cyan data shows the applied voltage at the input of STOT-DSD control board. Both falling and rising edge show a very similar response time.

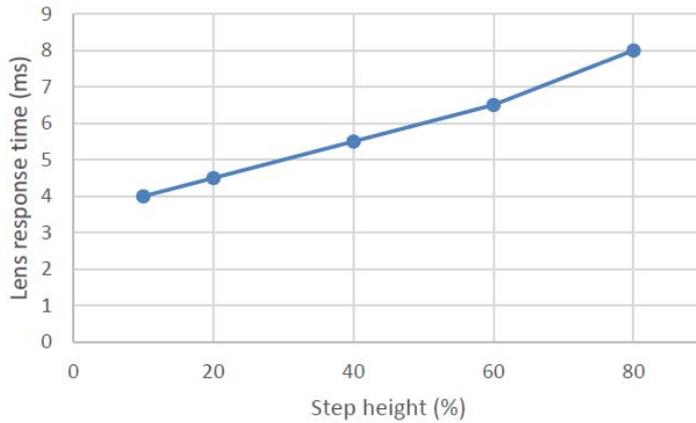


Figure 4: Summary of the response time versus different step heights.

4. Optical layout and configuration: without an f-theta lens

Without an f-theta lens, both field flattening and tuning in z-direction is accomplished by the tunable lens. For this full 3D processing approach, field flattening is crucial in order to avoid defocusing of the laser spot. The left panel of Figure 5 illustrates this effect: the focus of the laser is maintained only on the gray, spherical surface while the actual processing plane is flat. The spot is defocused which leads to blurred edges of the marked structure and eventually to no marking. By using STOT-EL-10-42-OF lens, this undesirable effect is avoided and refocusing of the spot is accomplished, as illustrated on the right panel of Figure 5.



Figure 5: The left panel shows the defocused laser spot on the marking plane. By tuning the EL-10-42-OF the laser spot remains focused on the marking plane, see right panel.

The major advantage of a system without an f-theta lens is the enlarged size of the scan field together with an increased z-range. In order to maximize the resolution in z-direction the optical leverage of the STOT-EL-10-42-OF with fixed-focus optics should be adjusted such that the focal tuning range matches with the required tuning range in z-direction. The approach without an f-theta lens is attractive not only considering the reduced costs but also increasing the horizontal scan field as well as the z-range.

4.1. Constant spot size over z-tuning range

Generally, when tuning STOT-EL-10-42-OF lens to shift the laser spot along z-direction, the numerical aperture NA of the whole optical system changes. As a consequence, the diffraction limited spot size also changes since $\times \sim f/D \sim NA^{-1}$.

However the combination of several fix focus lenses with the STOT-EL-10-42-OF provides enough degrees of freedom to realize an optimized configuration that maintains the spot size versus tuning. This is illustrated in Figure 6, where the STOT-EL-10-42-OF is combined with a beam expander (L1, L2) and a final focusing lens (L3).

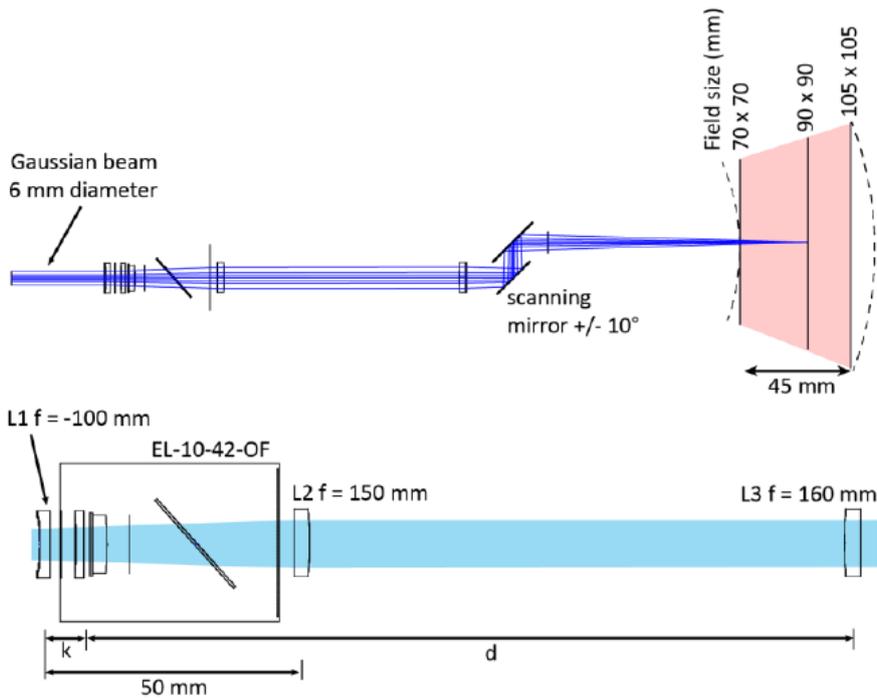


Figure 6: Exemplary optical design where the spot size remains constant over the full tuning range. The lower image is a detailed view of the optical system shown above.

When choosing the right distance d between the STOT-EL-10-42-OF and L3, the NA and hence the spot size remains constant independent of the tuning state of the STOT-EL-10-42-OF. This holds in general for different k , beam expansion factors (mag) and focal length of L3. The scaling of these parameters is:

1. Changing k : affects the resulting z-tuning range only to second order.
2. Changing mag: results in different z-tuning ranges.
3. Longer focal length of L3: increases the working distance and tuning range.

With the given parameters in the specific example of Figure 6 we set $k = 8$ mm and find an optimal d of 143 mm. This leads to a Gaussian $1/e^2$ beam diameter of 36mm over the full z-range. Note that the usable z-range is slightly smaller (45 mm) due to the required field flattening indicated by the curved, dashed lines.

4.2. Integration example of a 3D laser marking system

We implemented the configuration without an f-theta lens in the demonstration setup. When removing the f-theta lens, other focusing optics has to be implemented instead, which can be realized with standard 1 inch optics. The available empty space between the laser output and galvo head is enough to fit all lenses inside. A top view of the involved optics is shown in Figure 7. Also note the white Teflon washer between the STOT-EL-10-42-OF and the holder plate for thermal isolation.

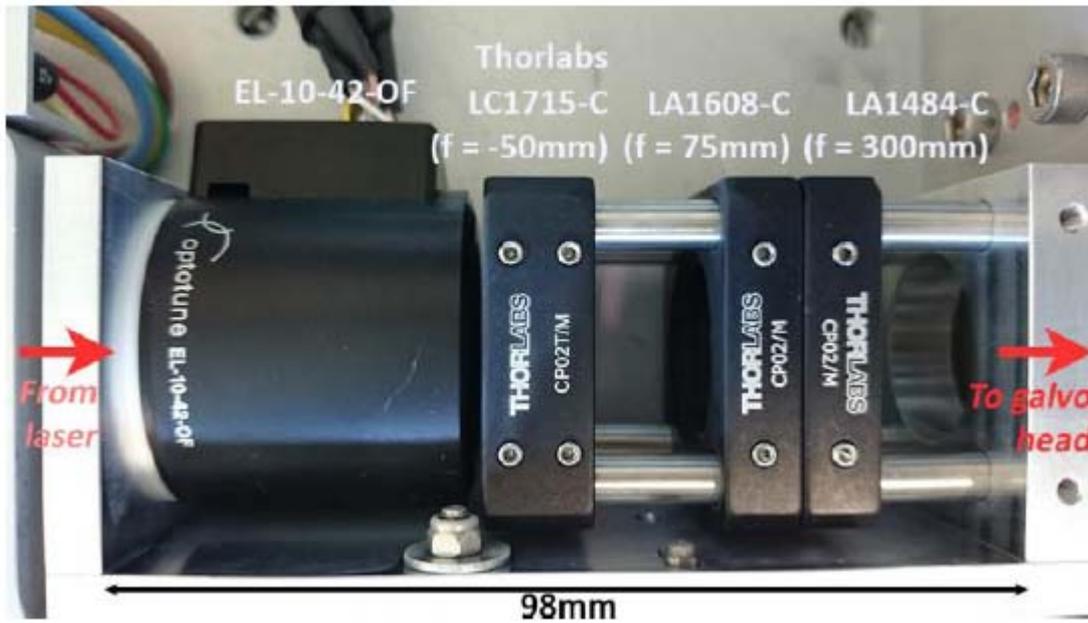


Figure 7: Image of the optical setup for an f-theta free marking system, placed between the laser output and the scanning head.

The corresponding optical layout is illustrated in Figure 8, based on the following idea: the STOT-EL-10-42-OF as the first lens tunes the beam divergence from a divergent to a converging beam (within a tuning range of $-2...+2$ dpt). The next lens with $f = -50\text{mm}$ diverges the beam in order to achieve an increased beam diameter of about a factor 2. The $f = 75\text{mm}$ lens collimates the beam which is then focused by the $f = 300\text{mm}$ lens onto the working plane. The beam expansion is necessary in order to achieve spot sizes and marking quality comparable to those of the f-theta system ($f = 160\text{mm}$). In other words: when keeping the ratio f/D constant, which is precisely the numerical aperture NA, the spot size is maintained.

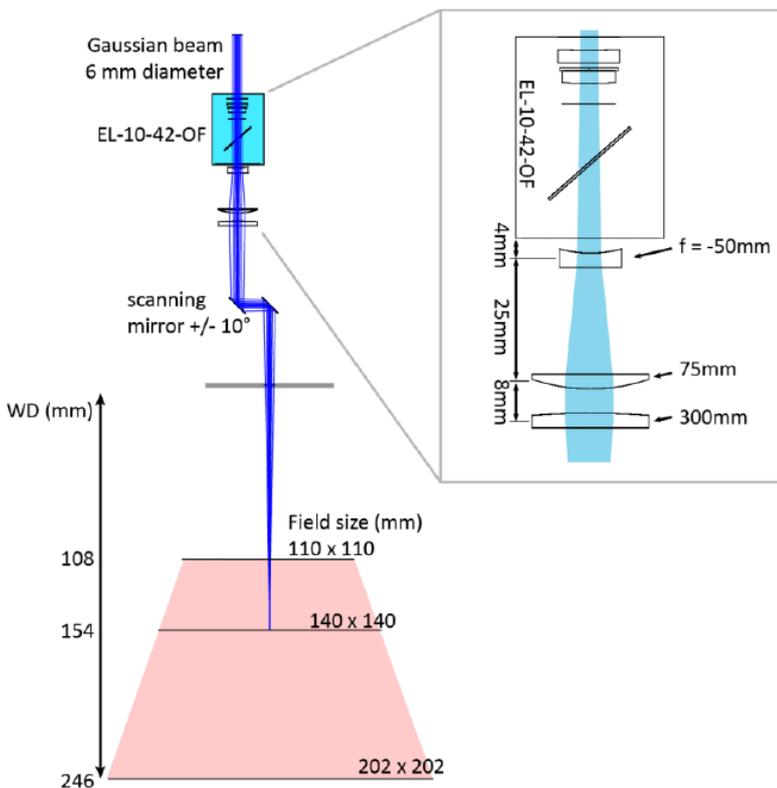


Figure 8: Optical layout of an f-theta free marking system. The schematic on the right shows the involved optical elements. As a first element, the STOT-EL-10-42-OF tunes the beam divergence. The $f = -50$ mm lens diverges the beam further to achieve a beam expansion of about a factor 2. The $f = 75$ mm lens collimates the beam, which gets focused by the $f = 300$ mm lens onto the working plane.

4.3. Marking results

A typical result that is achieved with the presented system is shown in Figure 9. The ruler on the right hand side is horizontally oriented, illustrating the field flattening capabilities. The left side shows a ruler marked at an inclination of 45°, representing an extreme case where full 3D marking is required. The maximum field size at the highest z-position is 110 x 110 mm. The maximal marking speed is up to 15 m/s on a 2D plane. For marking on a 45° tilted surface, the speed of 6 m/s has been achieved.

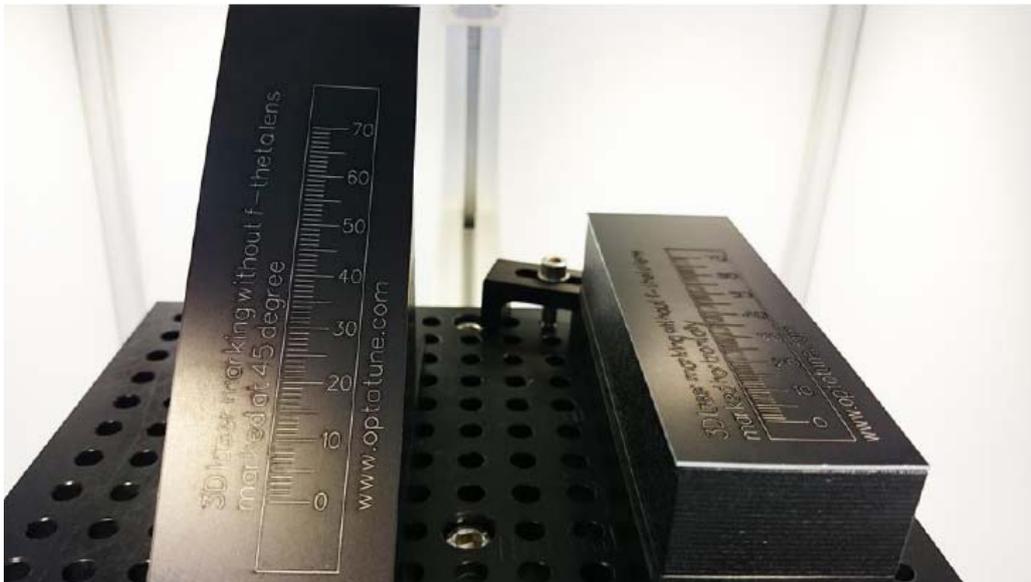


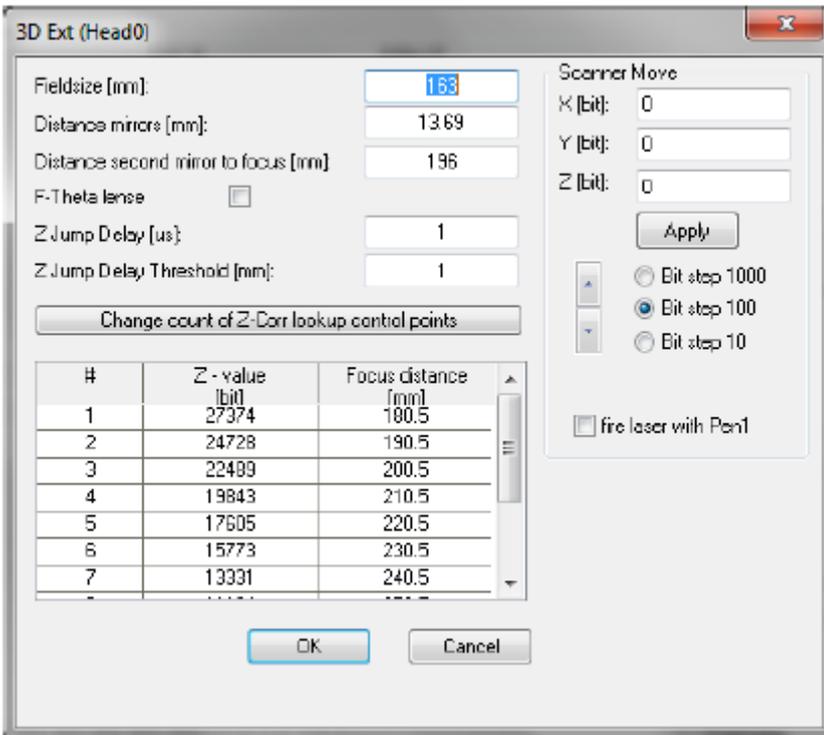
Figure 9: Real example of the 3D marking capabilities. On the right, a horizontal ruler is marked to illustrate the field flattening capabilities. The left shows a ruler marked on a 45° tilted surface.

4.4. Correction grid

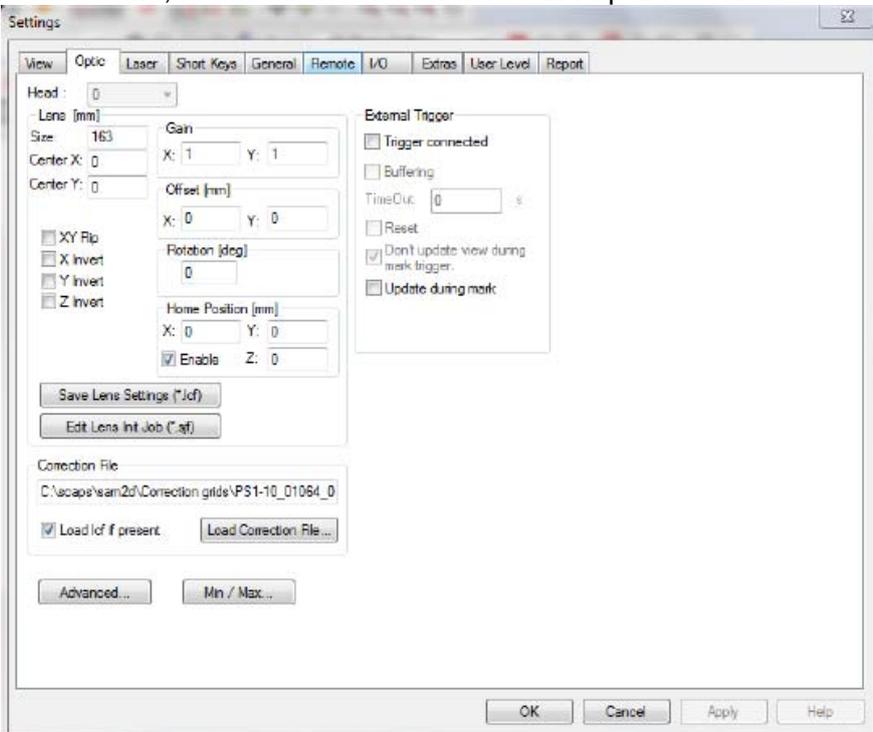
In order to correct the nonlinearity induced by the galvo mirrors in a laser marking system, a correction file loaded in the control software is required. Normally the correction file is provided by the scan head supplier and can be modified by the tool from the control software vendors. For the 3D laser processing, the correction is different depending on different optical layouts used in the marking system which have different nonlinear behavior.

We describe step by step how to modify a correction file from the existing one. The example illustrated here uses the calibration point method using `sc_corr_table` tool from SCAPS in combination with SAMLight. Note: parts of the texts below are copied directly from SCAPS `sc_corr_table` Manuel.

1. Place and mount the tunable lens in the laser marking system.
2. Construct the look-up table for the Z axis.

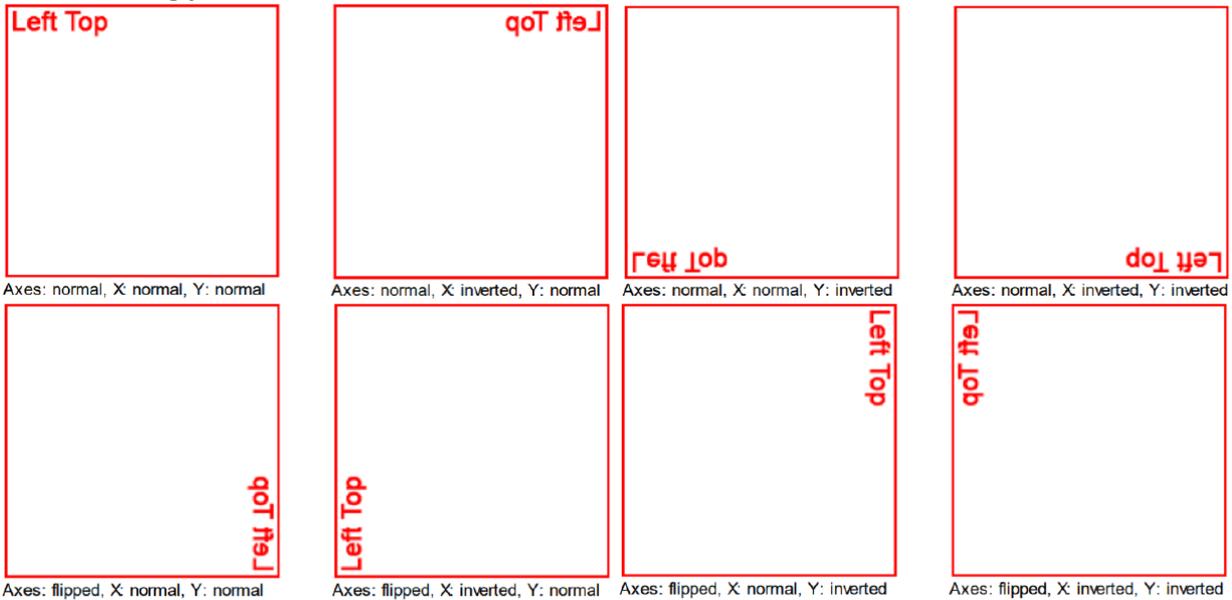


3. Make sure the target is at the position where the Z level is zero.
4. Go to SAMLIGHT -> Settings -> System -> Optic
 - a. Apply a correction file. This can either be the neutral correction file (default one in SAMLIGHT) or any existing correction file (*.ucf) which need to be improved. Make sure NOT to check the box Load lcf if present.
 - b. Set X gain and Y gain to 1 and offsets and rotation to 0.
 - c. Set field size (Lens Size) to 100 mm and set Center X and Center Y to 0. Note: the following figure is the example from our marking system with a field size of 163 mm.
 - d. Make sure, all checkboxes for inversion and flip are inactive.



5. Load the job \jobfiles\100mm_Square.sjf and mark it.
 - a. Check whether the orientation of "Left Top" is correct in the marking result.
 - b. If yes, go to Step 6.
 - c. If not, change the current state of Axes, X axis and Y axis to get the proper orientation of the coordinate system. Close SAMLIGHT and open \tools\sc_corr_table. Import the currently applied

correction file (*.ucf). Go to Correction -> Orientation of coordinate system and set Axes, X axis and Y axis accordingly.

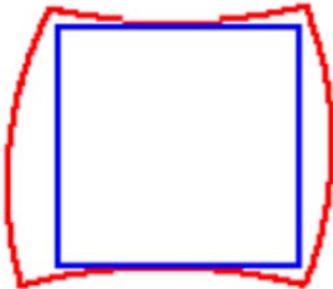


d. File -> Export and overwrite the existing correction file.

e. Close sc_corr_table and Open SAMLIGHT again

f. Mark 100mm_Square.sjf job again and check if the orientation is correct now. Note: Do not use the checkboxes XY Flip, X Invert and Y Invert in SAMLIGHT. Repeat Steps c., d. and e. until the orientation in the SAMLIGHT is the same as the reality.

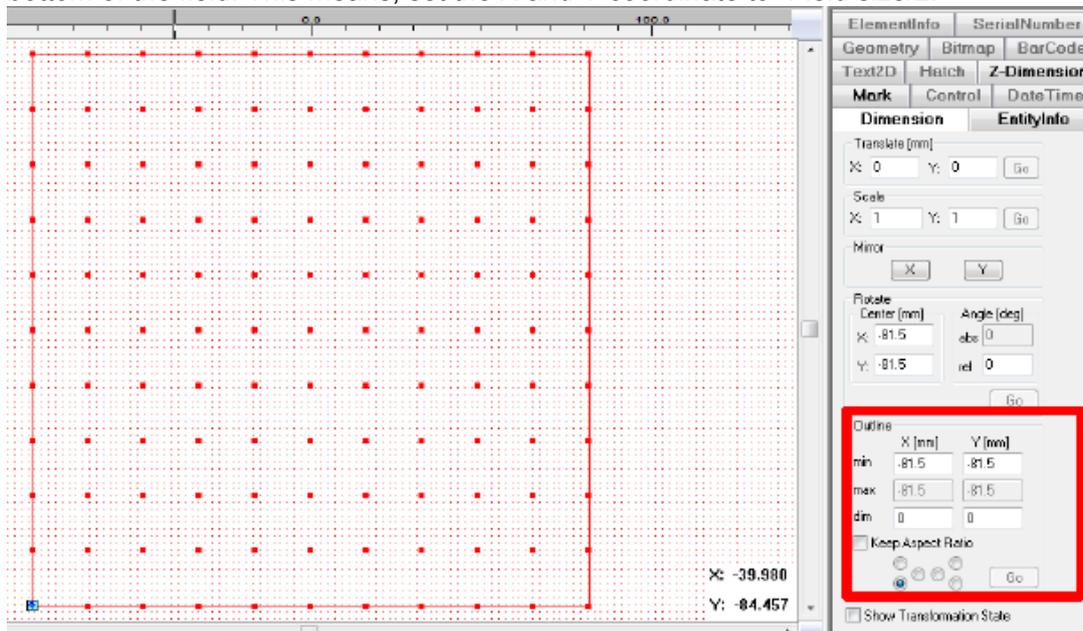
6. Find the biggest square which fits totally into the distorted square.



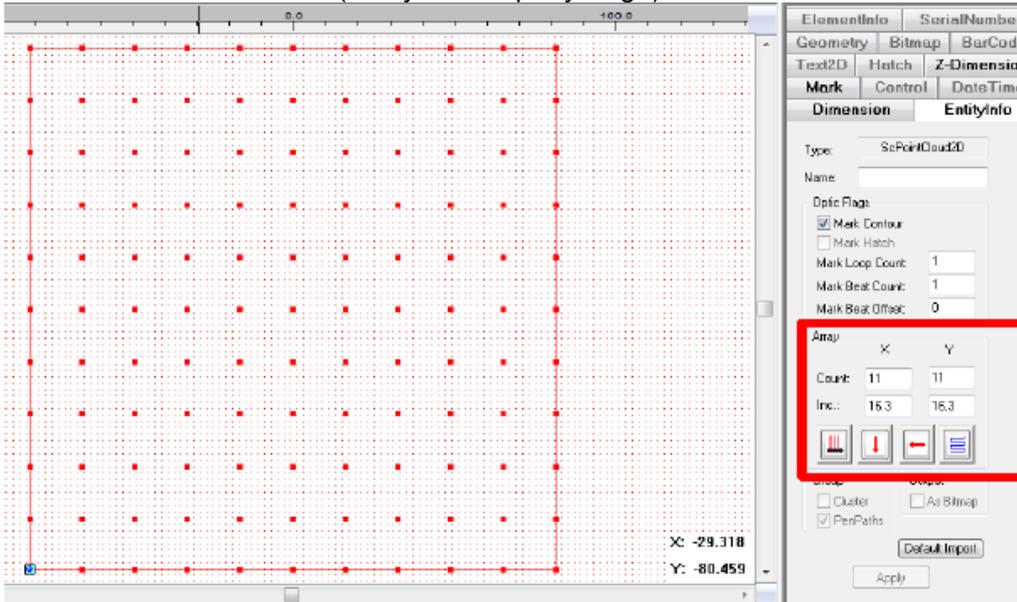
7. Set the field size to the side length of the insquare. (SAMLIGHT -> Settings -> System -> Optic -> Lens Size).

8. Create a new job file with 11x11 (=121) centered points covering the whole field in SAMLIGHT.

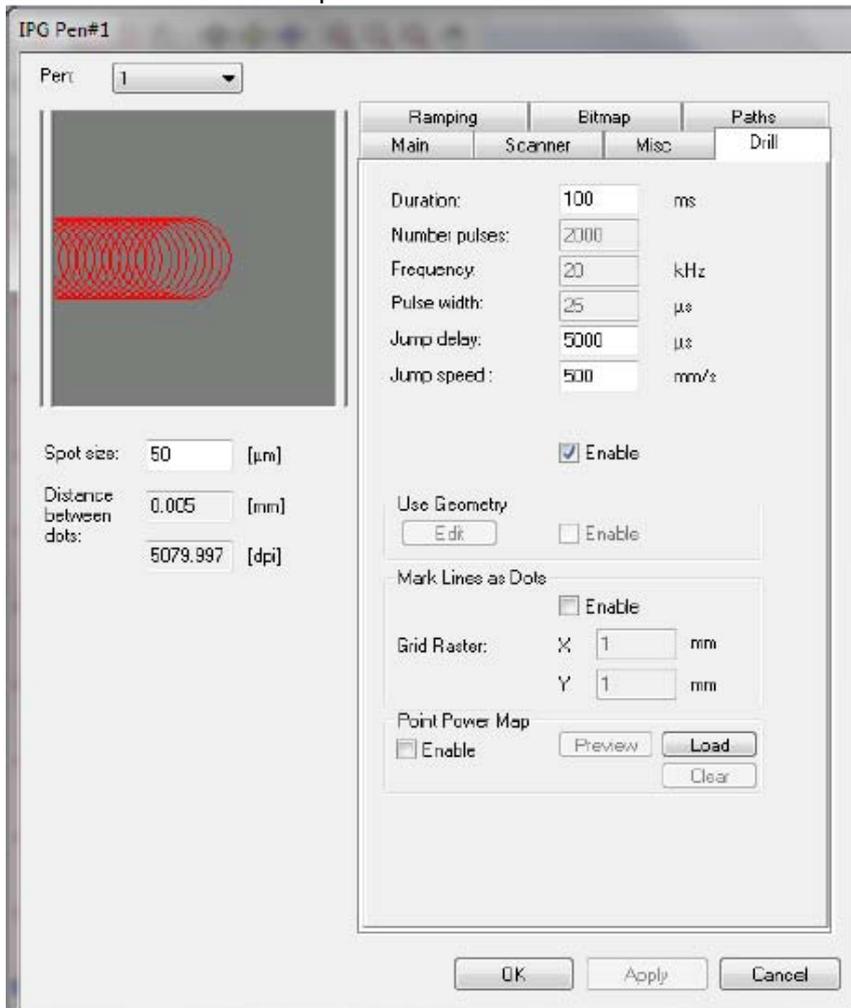
a. The way to create the points is the following: Create a "Point" entity and position this point to the left bottom of the field. This means, set the X and Y coordinate to -Field size/2.



b. To generate the rest of the points, create 11x11 (=121) array copies of this point and set the increment to Field size/10. (EntityInfo Property Page)



9. Mark these points with drill mode. Set the drill jump delay to a reasonably high value to ensure the scanner is in the desired position before each mark.



To avoid temperature drifts, the test marking should be done with the scanner already at working temperature.

10. Create an ASCII text file, name it "sc_calib_points.txt" and save it in the folder \system.

11. Measure the coordinates (Xi, Measured and Yi, Measured) of all these marked points. The unit is in mm. Fill the SAMLight coordinates (the setting in SAMLight) and the measured reality coordinates into the "sc_calib_points.txt" using the following form:

X1, SAMLight; Y1, SAMLight; X1, Measured; Y1, Measured
X2, SAMLight; Y2, SAMLight; X2, Measured; Y2, Measured
X3, SAMLight; Y3, SAMLight; X3, Measured; Y3, Measured
X4, SAMLight; Y4, SAMLight; X4, Measured; Y4, Measured
...

X121, SAMLight; Y121, SAMLight; X121, Measured; Y121, Measured

12. Close SAMLight (save your job) and start \tools\sc_corr_table.

13. Use Correction -> Show calibration points to display the measured data. For improvement of the fit result, the function Delete worst point can be used.

14. Go to Correction -> Correct UCF by calibration points and choose the desired fit order in the drop down menu of 2D Fit-> Fit Order (Default mode: 3_Advanced).

15. After clicking "OK", two correction files are displayed. At the same time, both the original and the newly created correction files are saved in \Correction grids folder with different names.

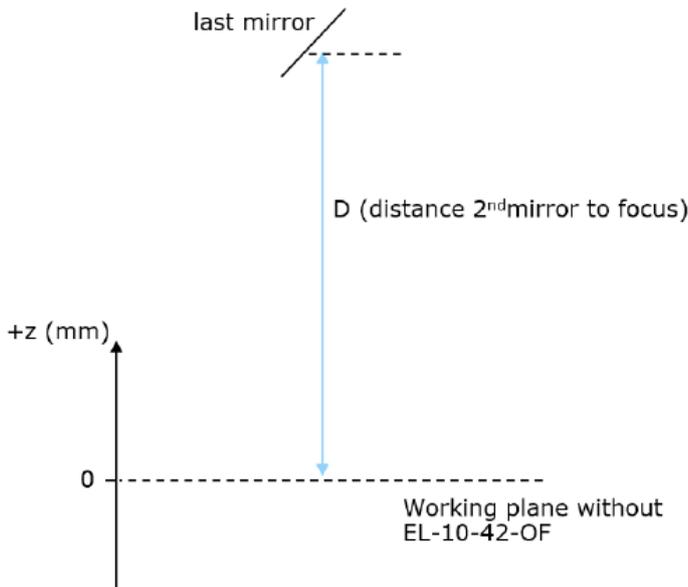
16. Apply the new *.ucf file to the settings. (SAMLight -> Settings -> System -> Optic)

17. Mark 100mm_Square.sjf job again and check if the new correction file is good enough or not.

There are many different methods to calibrate the nonlinearity and generate the correction files. The customer should contact the scan head manufacturer or the control software vendor for detailed information particularly for the 3D laser marking systems without using an f-theta lens.

Appendix: How to perform z-calibration with STOT-EL-10-42-OF in SAMLight

The following procedure describes one possible way to calibrate the z-position of the marking laser spot against the control voltage. The method has been successfully tested in a standard marking system described in this application note. The obtained precision is 500 μm . For higher precision, a beam profile measurement is recommended. The marking software SAMLight (SCAPS) allows for easy integration of the z-calibration via a look-up table. The coordinate system is defined as:



1. It is assumed that the distance D from second mirror to the working plane is already known (in the exemplary system, $D = 292.42 \text{ mm}$). Before integrating the STOT-EL-10-42-OF, this has to be measured precisely, e.g. with the help of a mechanical z-stage.
2. As a first step, a temporary z-correction look-up table has to be created. The measurements done with this table will allow for deducing the final z-correction table.

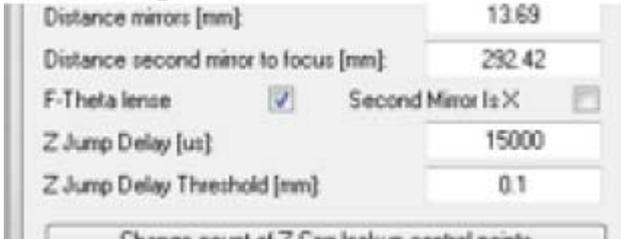
3D Ext

Fieldsize [mm]:	117		XYZ-Move									
Distance mirrors [mm]:	13.69		X [bit]: 0									
Distance second mirror to focus [mm]:	292.42		Y [bit]: 0									
F-Theta lense <input checked="" type="checkbox"/>	Second Mirror Is X <input type="checkbox"/>		Z [bit]: 0									
Z Jump Delay [us]:	15000		Apply									
Z Jump Delay Threshold [mm]:	0.1		<input type="radio"/> High <input checked="" type="radio"/> Normal <input type="radio"/> Fine									
Change count of Z-Corr lookup control points												
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th>#</th> <th>Z-value [bit]</th> <th>Focus distance [mm]</th> </tr> </thead> <tbody> <tr> <td style="text-align: center;">1</td> <td style="text-align: center;">32767</td> <td style="text-align: center;">233.92</td> </tr> <tr> <td style="text-align: center;">2</td> <td style="text-align: center;">0</td> <td style="text-align: center;">350.92</td> </tr> </tbody> </table>				#	Z-value [bit]	Focus distance [mm]	1	32767	233.92	2	0	350.92
#	Z-value [bit]	Focus distance [mm]										
1	32767	233.92										
2	0	350.92										
<input type="checkbox"/> fire laser with Pen1												
OK		Cancel										

The table is defined only by the two DAC end points DAC1 = 32767 and DAC2 = 0, which correspond to 0 and 5V respectively. This is the maximum allowed range of the lens' control voltage. The corresponding distances (mm) are calculated as seen in the table below:

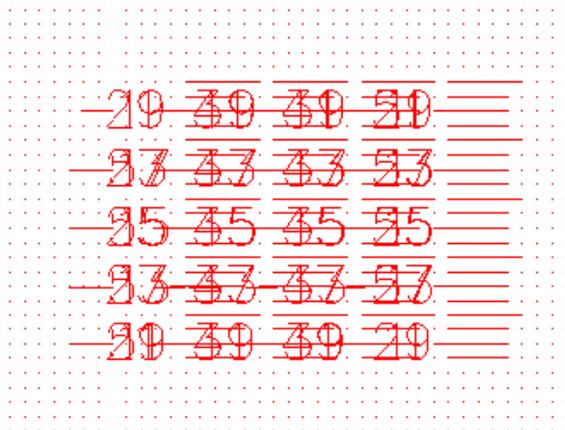
DAC ₁	32767	$D - (x,y\text{-working area} / 2) = D_1$
DAC ₂	0	$D + (x,y\text{-working area} / 2) = D_2$

3. When using an f-theta lens, the corresponding check box in SAMLight has to be enabled.

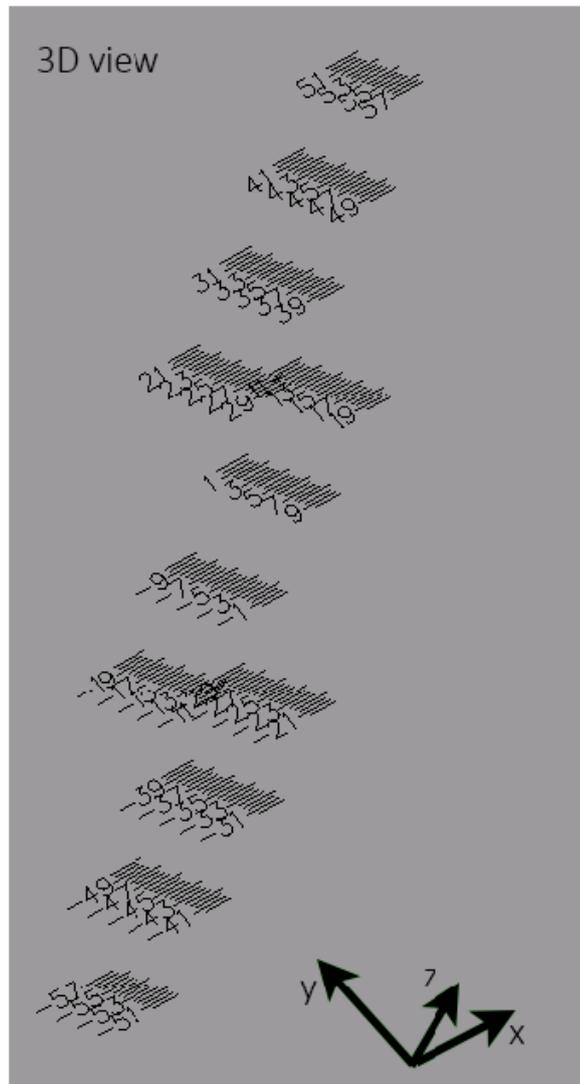


4. Load the pre-defined marking job file "Find_DAC_Values.sjf" in SAMLight.

Top view



3D view



This job file serves as a vertical "ruler". It consists of lines ranging from -57...+57 mm in z-direction. The lines have 0.5 mm spacing. If your x,y-working area is smaller than this range, you have to delete a few lines in the job file such that the z-range < x,y-working area. Otherwise the error message "Galvo out of range" will appear when clicking "start mark".

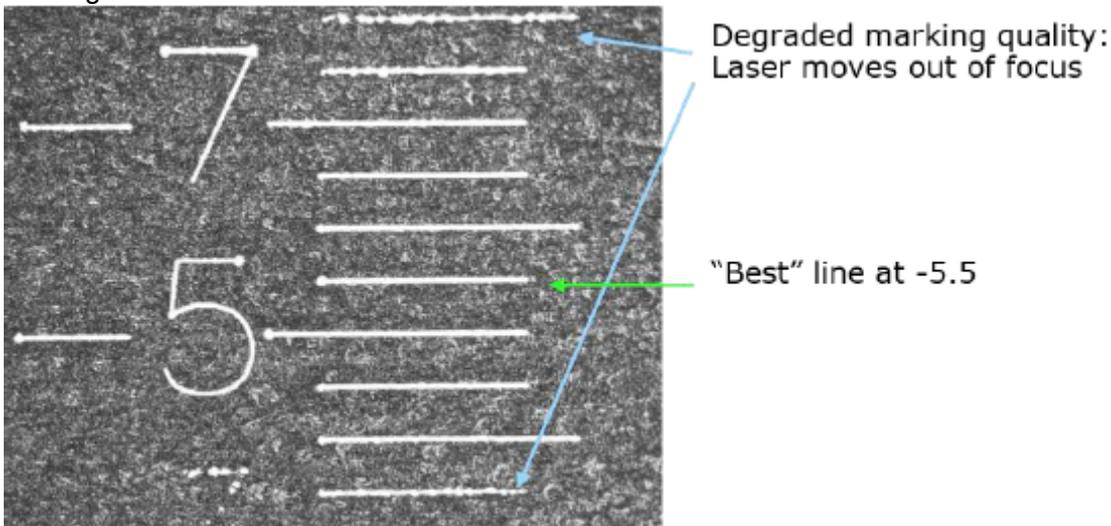
5. Next, define the number of z-values of the final z-correction table in a separate spread sheet. The points have to be within the maximum physical z-tuning range (e.g. -45...+45 mm). For example:

z-value (mm)
-38.7
-17.5
0
29.8
42.6

6. Position a marking sample (e.g. anodized aluminum plate) at the first point of the final z-correction table (e.g. 39.82 mm in this example). According to the definition of the coordinate system, a negative z-value (mm) means below the zero plane and a positive value above the zero plane. This is consistent with the definition of the coordinate system in SAMLIGHT. Start marking the job file.

7. Change the z-position of the marking sample to the next point of the final z-correction table and mark the job file again. Repeat this procedure for all z-values.

8. Extract the marked z-position values F_z from the marking sample. To do so it is helpful to analyze the samples under a standard microscope (e.g. 8x magnification). This increases the precision when locating the "best" line that was in focus.



9. After this analysis, your z-correction table might look like shown below. At z-value = 0 mm, the marked value on the sample is not necessarily zero due to a possible offset. The calibration will take this offset automatically into account.

z-value (mm)	F_z (marked value on sample)
-38.7	-34
-17.5	-17.5
0	-1
29.8	34
42.6	48.5

10. Next, calculate the distances $D_z = D - F_z$ with $D = 292.42$ mm in this example. As a next step, in order to establish the linear relation between the DAC values and the values D_z we have to calculate

$$DAC_z = a \cdot D_z + b$$

with the coefficients (from step 2.)

$$a = \frac{DAC_2 - DAC_1}{D_2 - D_1}, \quad b = \frac{D_2 \cdot DAC_1 - D_1 \cdot DAC_2}{D_2 - D_1}$$

Now, the table looks like below

z-value (mm)	F_z (marked value on sample)	D_z	DAC_z
-38.7	-34	326.42	6861
-17.5	-17.5	309.92	11482
0	-1	293.42	16103
29.8	34	258.42	25906
42.6	48.5	243.92	29966

11. As a final step, one has to calculate D – (z-value). D is the distance from 2nd mirror to working area. The final look-up table implemented in SAMLight, highlighted in red, looks like:

z-value (mm)	F_z (marked value on sample)	D_z	DAC_z	z-value absolute (mm)
-38.7	-34	326.42	6861	331.12
-17.5	-17.5	309.92	11482	309.92
0	-1	293.42	16103	292.42
29.8	34	258.42	25906	262.62
42.6	48.5	243.92	29966	249.82

The two red columns are used in SAMLight as the final z-calibration look-up table. Note that in SAMLight, the “Focus distance (mm)” has to be entered in ascending order:

Z-value (bit)	Focus distance (mm)
29966	249.82
25906	262.62
16103	292.42
11482	309.92
6861	331.12

12. Optional: one can perform a verification measurement. If the calibration is correct, one obtains the same values when repeating steps 5 to 8. The exemplary measurement shown below confirms this relation. The deviations are small and within the precision of the method described in step 8.

