Application Note for Laser Processing
Electrically focus tunable lens EL-10-42-OF
SCAPS Optotune-DSD driver board
Update: 19.03.2020

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Application note for laser processing using EL-10-42-OF tunable lens and SCAPS Optotune-DSD driver board

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1. Introduction

Nowadays, the common solution available on the market for controlling the z-coordinate in laser processing is using a mechanical translation. However, the major limitations of this approach are the slow speed and a small range in z-travel. 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 how to integrate the Optotune's EL-10-42-OF tunable lens, controlled with the Optotune-DSD controller board which is developed by SCAPS GmbH, into a laser processing system. We provide general guidelines for using the EL-10-42-OF lens in combination with the Optotune-DSD controller board for fast 3D laser processing applications. The EL-10-42-OF lens is light, compact and has a fast response time as well as a long lifetime. Therefore, it is an ideal candidate to overcome the downsides of a mechanical solution.

With a special but simple optics design, a 3D laser processing system using the EL-10-42-OF lens can achieve the same spot size across the whole scan volume. The EL-10-42-OF lens is designed for pulsed lasers at near-infrared wavelength between 950 nm and 1100 nm. This opens the possibility to integrate the EL-10-42-OF lens into various laser processing applications as illustrated below.
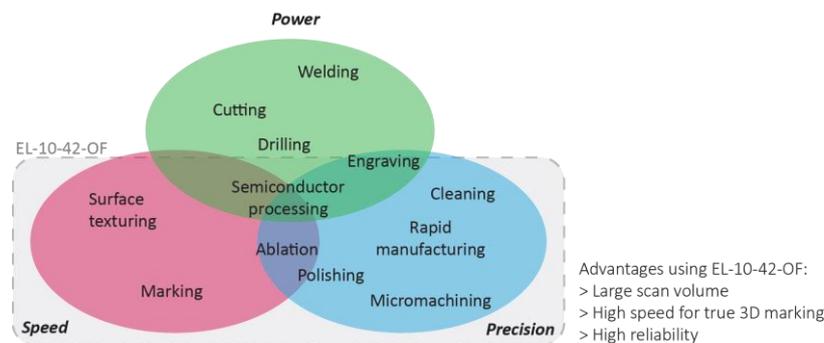
1.1. Overview of the necessary steps to integrate the EL-10-42-OF

To use the EL-10-42-OF lens in combination with the SCAPS Optotune-DSD driver for 3D laser processing, the following steps are required for the integration into a laser processing system:

1) Perform mechanical integration. For details, see Section 2.
2) Prepare the cable for the SCAPS Optotune-DSD board and the galvo scan head. For example, we use a Y-junction type cable by splitting the cable from the main controller card into two cables for which one is connected to the SCAPS Optotune-DSD driver board and the other one is connected to the galvo scan head. For more details, see SCAPS Optotune-DSD Manual page 8 & 13.
3) Prepare the power and the heater cables plugged into the SCAPS Optotune-DSD board. For details, see SCAPS Optotune-DSD Manual page 7 & 12.
4) Install the software and firmware for the SCAPS Optotune-DSD board. For details, see SCAPS Optotune-DSD Manual page 14.
5) Calibrate the lens using SCAPS Optotune-DSD software. For details, see SCAPS Optotune-DSD Manual page 16.
6) Create a correction grid file if necessary. Normally for a system without using an f-theta lens, the correction grid needs to be done once. For instructions using the tool provided by SCAPS, see Section 3 of this application note.
7) Perform the z-calibration of the laser processing system. In Section 3 and Appendix 1, you find detailed instructions for the z-calibration using SCAPS SAMLight software.
8) You are ready to go.

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2. System integration

2.1. Controlling EL-10-42-OF lens with Optotune-DSD driver board

Optotune-DSD is an FPGA-based digital driver board designed to control the EL-10-42-OF lenses. 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 a compact laser marker presented in Appendix 3 & 4 and schematically shown in the left panel of Figure 1.

The communication between the PC (the user) and the digital controller card is often established via a serial bus, e.g. USB. Within the extended XY2-100 protocol, the signal used to control the z axis is already available, in addition to the x- and y-axes that control the galvo mirrors. The digital signal output from the controller card for the z-axis can be directly sent to the Optotune-DSD board, as shown on the left panel of Figure 1 . The right panel of Figure 1 shows another possible integration, in case the customer is using the controller board from SCAPS. Then, the bi-directional XY-SCAPS communication protocol can be applied. Both situations allow for fast 3D laser processing. The processing speed without f-theta lens has been demonstrated to be 6 m/s on a 45° tilted object and 15 m/s on a 2D plane with working distances comparable with a setup using a 160mm f-theta lens and the EL-10-42-OF for the z-axis.

Note: Optotune-DSD board is especially developed to control the EL-10-42-OF lens. In laser processing applications, pulsed and high-power laser beams are used, posing considerable challenges on the precision of the optical feedback (OF) control. Tiny amounts of stray light still introduce an offset on the OF, shifting the actual set value. Although the remaining shift is canceled electronically, for efficient OF control the laser repetition rates >= 20 kHz are recommended.
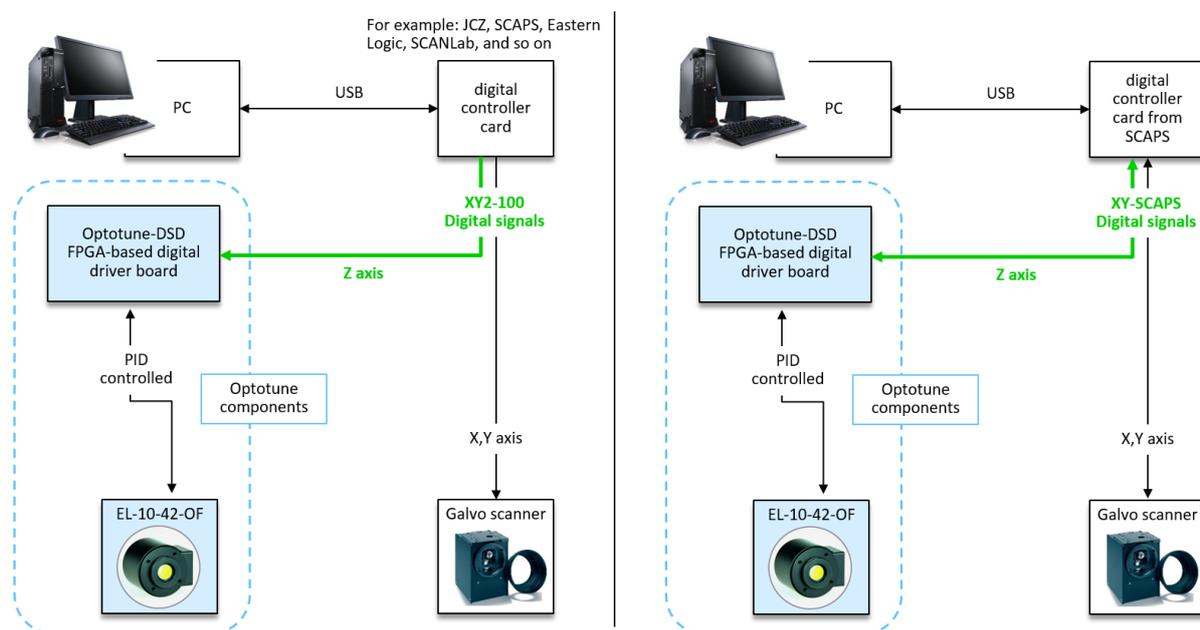

Figure 1: Integration of EL-10-42-OF lens within a digital protocol that provides x,y and z-signals. The output signal from the controller card for the z axis can be directly fed into the Optotune-DSD board for the control of EL-10-42-OF lens.

2.2. Integration with f-theta lens

In addition to the standard integration example shown in the previous section, we summarize various optical layouts in combination with the EL-10-42-OF lens depending on different applications. In Figure 2 the resulting z-tuning range in combination with different f-theta lenses is shown.

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The output laser beam has a diameter of about 6 mm. The EL-10-42-OF lens is placed on the beam path from the laser output to the galvo scanner. The beam is then reflected by the galvo mirrors that allow beam deflection along x- and y-direction on the target. The field size shown in the simulation results from the mirror deflection angle of +/- 10°. The z-position of the laser spot is controlled by tuning the focal length of EL-10-42-OF lens. For the f-theta lens with a longer focal length, the resulting z-tuning range as well as the scan field size increases. In each configuration, the focal length of the EL-10-42-OF is tuned over the maximal range (from -2 diopter to +2 diopter). Field flattening and final focusing onto the processing plane are done by the f-theta lens. This configuration is simple to implement since the EL-10-42-OF is integrated between the laser and the scan head without additional optics.

Note: There are remaining field distortions due to imperfections of the f-theta optics. Those effects are slightly enhanced when operating the f-theta lens with the EL-10-42-OF because of the introduced convergence or divergence of the input beam that enters the f-theta lens. For best processing quality, this has to be taken into account on the software side by e.g. introducing a correction grid.
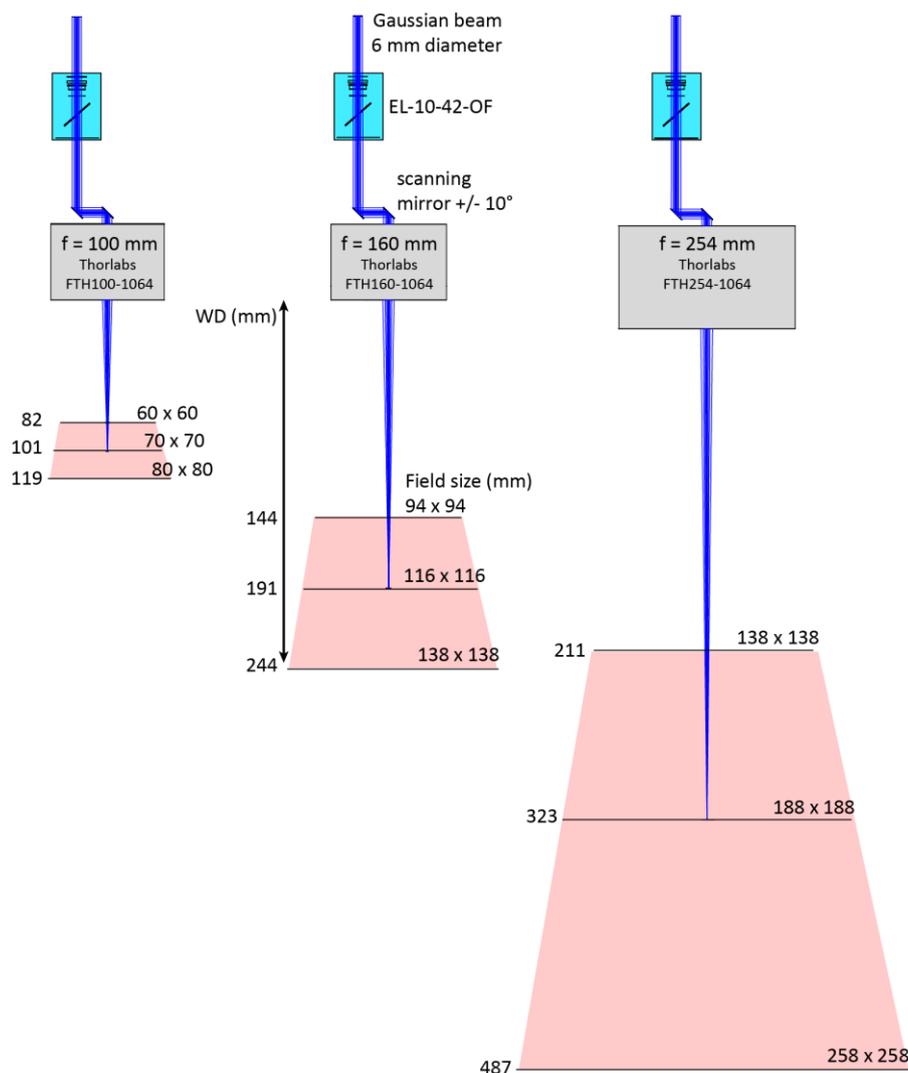

Figure 2: Laser scanning system with the EL-10-42-OF, galvo scanning mirror and different f-theta lenses f = 100, 160 and 254 mm. The corresponding z-scanning range and change of working distance (WD) is indicated by the black arrow. The red color indicates the scan volume for the different situations.

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2.3. Integration without an f-theta lens

Without an f-theta lens, both field flattening and tuning in z-direction is accomplished by the EL-10-42-OF lens. 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 and minimum to no change in spot size throughout the whole scan volume. However, in the absence of the f-theta lens, additional optics are required between the laser and the scan head for the laser beam focusing. Depending on the position and focal length of these lenses, different working distance ranges and scan field sized can be achieved. Contact us for support with your desired configuration

Optotune designed a 3D module with mounting for multiple fixed lenses in addition to the EL-10-42-OF. Standard 1-inch spherical fixed focus lenses can be used. The 3D module is placed between the laser and the scan head as illustrated in Figure 5. Depending on the fixed focus lenses used, different configurations can be achieved as illustrated in Figure 6. The 3D module as shown in Figure 3 can be purchased from Optotune. Alternatively, the STEP file is available for your own manufacturing.

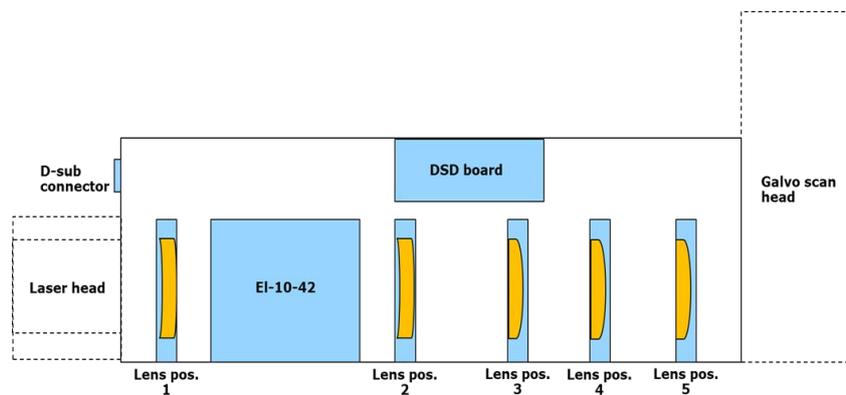*Figure 3: Rendering of Optotune's 3D module design*

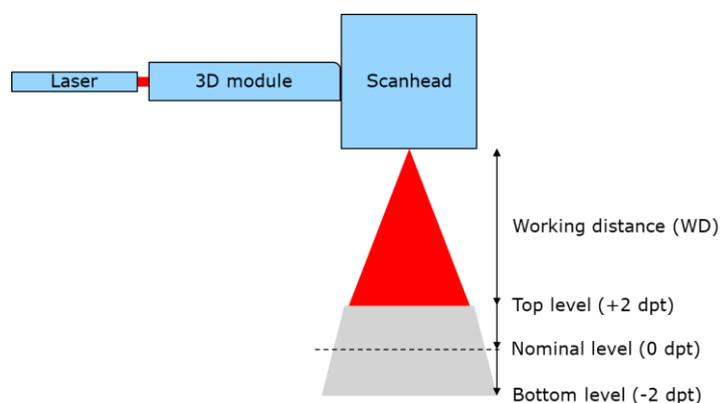*Figure 4:Schematics of Optotune's 3D module with the 5 fixed lens positions*

Figure 5:Integration of the 3D module in a 3D laser processing setup

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Constant spot size

3D module configuration				System specification				
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)
5	175			Top	40 x 40	55	43	43
		10		Nominal	80 x 80	102	43	43
				Bottom	130 x 130	165	43	43

Similar field size and working distance like with 160mm f-theta (with 1.5X beam expander)

3D module configuration				System specification				
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)
2	-100			Top	95 x 95	120	45	46
3	150	14		Nominal	135 x 135	170	46	47
5	250			Bottom	190 x 190	240	47	48

Similar field size and working distance like with 160mm f-theta (with 1.66X beam expander)

3D module configuration				System specification				
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)
2	-75			Top	100 x 100	130	40	41
3	125	14		Nominal	135 x 135	170	40.5	41.5
5	250			Bottom	180 x 180	225	41	42

Similar field size and working distance like with 254mm f-theta (with 1.5X beam expander)

3D module configuration				System specification				
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)
2	-100			Top	150 x 150	190	60	61
3	150	14		Nominal	220 x 220	280	65	66
5	350			Bottom	360 x 360	450	75	76

Similar field size and working distance like with 254mm f-theta (with 1.66X beam expander)

3D module configuration				System specification				
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)
2	-75			Top	160 x 160	205	55	56
3	125	14		Nominal	220 x 220	280	60	61
5	350			Bottom	330 x 330	410	64	65

Large field sizes

3D module configuration				System specification				
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)
1	-100			Top	460 x 460	550	76	79
4	250	25		Nominal	680 x 680	820	92	95
5	1000			Bottom	950 x 950	1155	117	119

Figure 6: Fixed lens setups and corresponding optical performance achieved with Optotune's 3D module

160mm F-Theta lens

3D module configuration				System specification				
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)
				Top	94x94	144	26	32
		10		Nominal	116x116	191	26	27
				Bottom	138x138	244	26	58

Figure 7: Optical performance of a typical 2D laser processing setup with a 160mm f-theta lens

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# 3. System calibration

3.1. Lens calibration

After the EL-10-42-OF lens has been installed in a laser processing machine, it has to be calibrated for its dynamic behavior in the installed orientation. This can be performed either within SCAPS SAMLight software if the SCAPS USC-3 controller card is used, or with a stand-alone lens calibration software from SCAPS for all other controller cards. The lens is compatible with any controller card that can output X-Y-Z axis through the XY2-100 interface. For details how to perform the lens calibration, please see SCAPS Optotune-DSD Manual page 16.
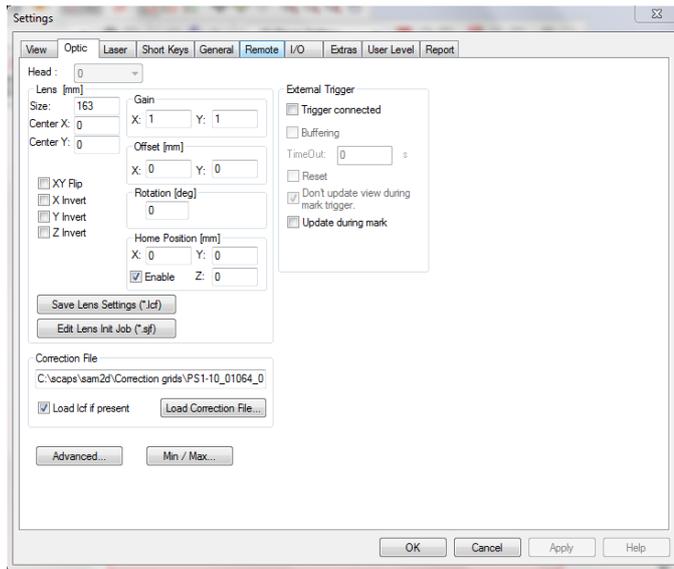
3.2. Correction grid

In order to correct the nonlinearity induced by the galvo mirrors in a laser processing 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 a tool from the control software vendors. For a system without using an f-theta lens, the correction is different depending on different optical layouts, resulting in 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 Optotune tunable lens in the laser processing system.
2. Construct the look-up table for the Z axis.
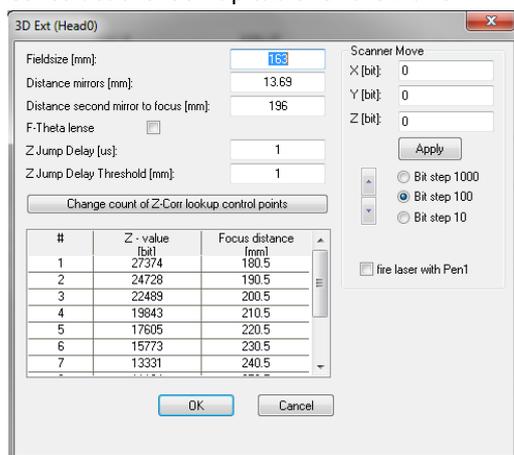
3. Make sure the target is at the position where the Z level is zero.
4. Go to SAMLight -> Settings -> System -> Optic
   a. Apply a correction file. This can either be the neutral correction file (default one in SAMLight) or any existing correction file (*.ucf) which need to be improved. Make sure NOT 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.

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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.
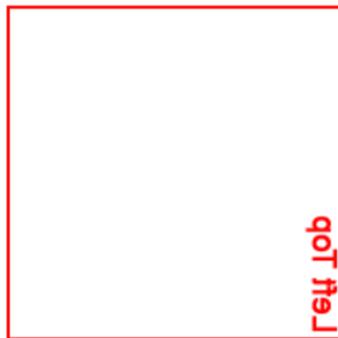

Axes: normal, X: normal, Y: normal   Axes: normal, X: inverted, Y: normal

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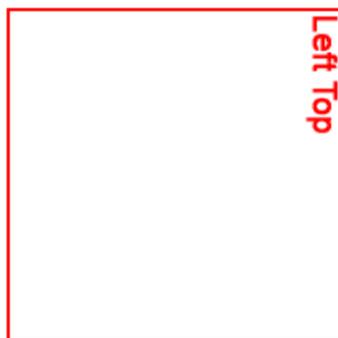

Axes: normal, X: normal, Y: inverted

Axes: normal, X: inverted, Y: inverted

Axes: flipped, X: normal, Y: normal


Axes: flipped, X: inverted, Y: normal


Axes: flipped, X: normal, Y: inverted

Axes: flipped, X: inverted, Y: inverted

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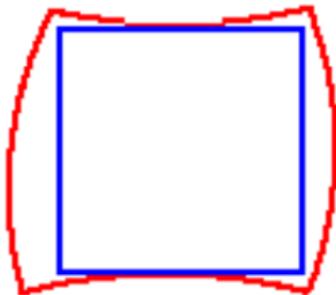
7. Set the field size to the side length of the insquare. (SAMLight -> Settings -> System -> Optic -> Lens Size).

8. Create a new job file with 11x11 (=121) centered points covering the whole field in SAMLight.
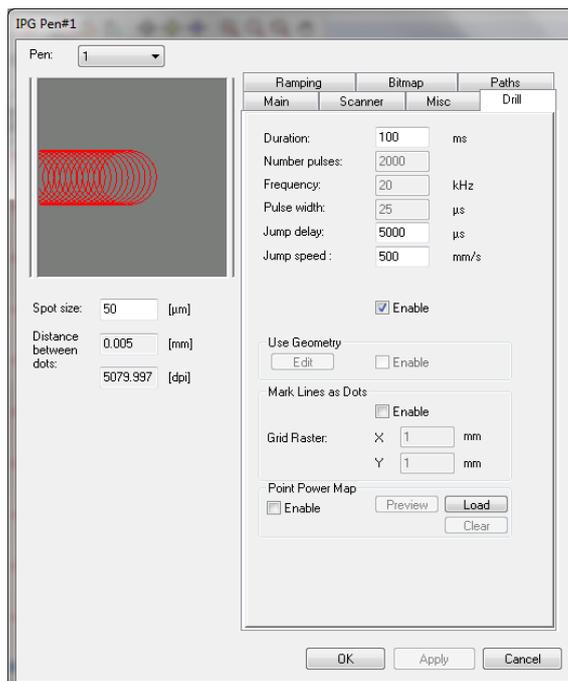
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a. The way to create the points is the following: Create a "Point" entity and position this point to the left bottom of the field. This means, set the X and Y coordinate to -Field size/2.
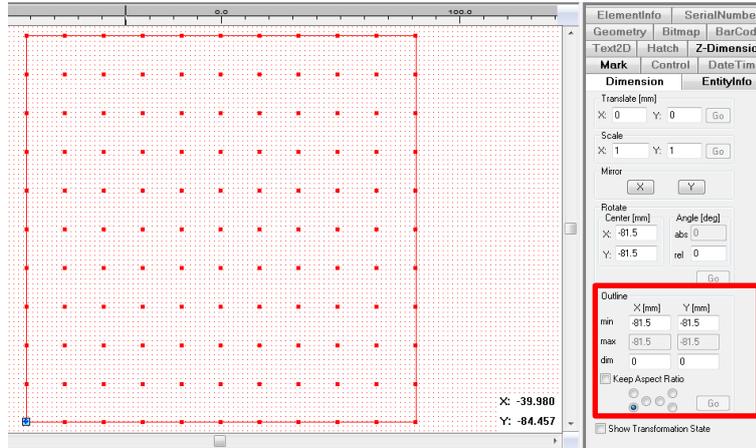
b. To generate the rest of the points, create 11x11 (=121) array copies of this point and set the increment to Field size/10. (EntityInfo Property Page)
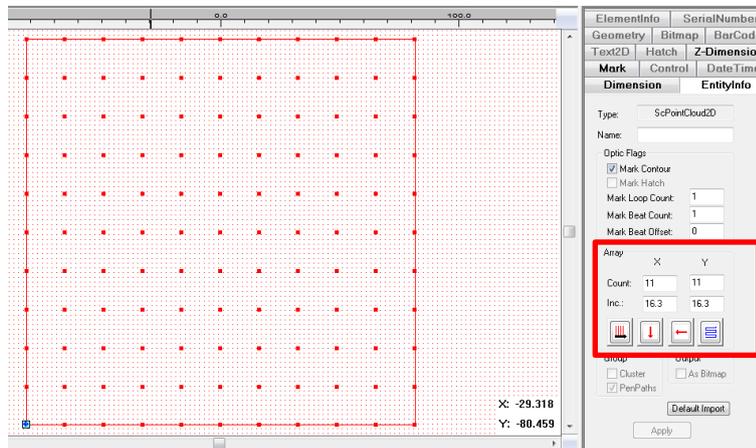
9. Mark these points with drill mode. Set the drill jump delay to a reasonably high value to ensure the scanner is in the desired position before each mark.

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To avoid temperature drifts, test processing 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 ($X_{i, Measured}$ and $Y_{i, Measured}$) 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:

$X_{1, SAMLight}$; $Y_{1, SAMLight}$; $X_{1, Measured}$; $Y_{1, Measured}$

$X_{2, SAMLight}$; $Y_{2, SAMLight}$; $X_{2, Measured}$; $Y_{2, Measured}$

$X_{3, SAMLight}$; $Y_{3, SAMLight}$; $X_{3, Measured}$; $Y_{3, Measured}$

$X_{4, SAMLight}$; $Y_{4, SAMLight}$; $X_{4, Measured}$; $Y_{4, Measured}$

...

$X_{121, SAMLight}$; $Y_{121, SAMLight}$; $X_{121, Measured}$; $Y_{121, Measured}$

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 processing systems without using an f-theta lens.

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3.3. Z-calibration

Optotune-DSD board controls the optical power of the lens and hence allows for shifting the laser spot in z-direction (see Figure 8). It is necessary to perform a calibration between the control signal 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 1.

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 8. The actual z-tuning range depends on the optical layout in which the EL-10-42-OF lens is integrated. The calibration procedure has to be done once and typically the data can be stored in a lookup table in the laser processing software. It is recommended to measure at least ten calibration points. More points will increase the precision of the control.
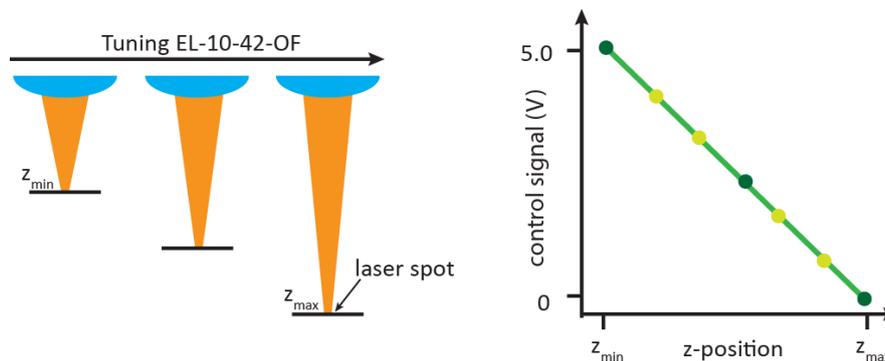

Figure 8: The left panel shows how the z-position of the laser spot is changed by tuning EL-10-42-OF. The right panel illustrates the calibration curve of control signal versus the focal positions in z axis. The light green points represent further points required to increase the precision of the calibration.

## 4. Further information & support

Our application engineers are happy to help you with the integration of our products in your design. Don't hesitate to contact us at sales@optotune.com or to call us at +41 58 856 3000.

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Appendix 1: How to perform z-calibration with EL-10-42-OF in SAMLight

The following procedure describes one possible way to calibrate the z-position of the processing laser spot against the control signal. The method has been successfully tested in a standard laser marking system described in Appendix 3 & 4. The laser processing software SAMLight (SCAPS) allows for easy integration of the z-calibration via a look-up table. The coordinate system is defined as:
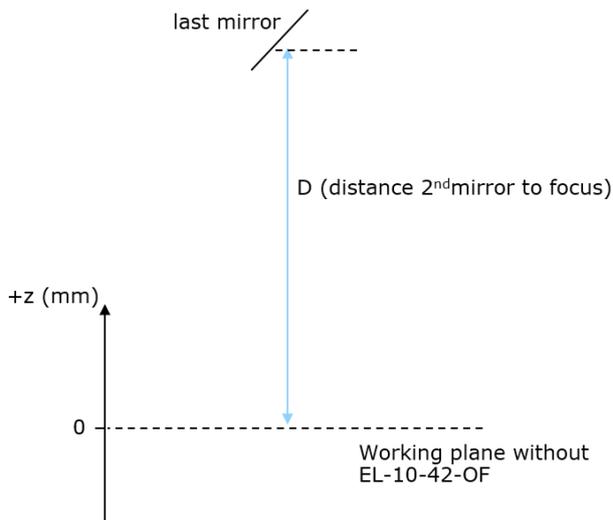
1. It is assumed that the distance D from second mirror to the working plane is already known (in the exemplary system, D = 250 mm). Before integrating the EL-10-42-OF lens, this has to be measured precisely, e.g. with the help of a mechanical z-stage.
2. As a first step, a temporary z-correction look-up table has to be created. The measurements done with this table will allow for deducing the final z-correction table.
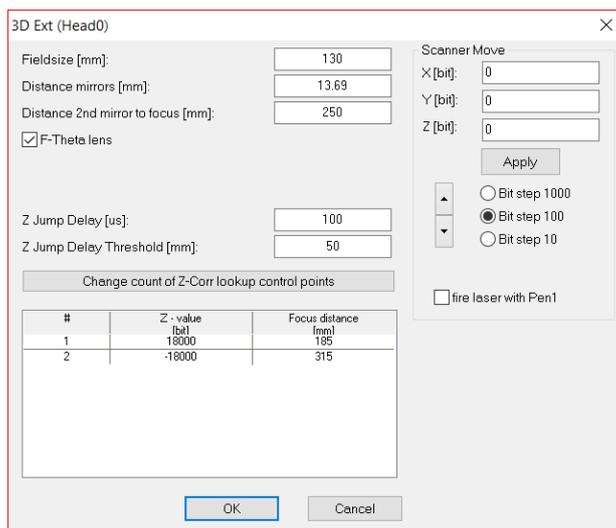
The table is defined only by the two DAC end points DAC_1 = -18000 and DAC_2 = 18000, which correspond to -1.8 dpt and +1.8 dpt respectively. This is the maximum allowed range of the lens control. The corresponding distances (mm) are calculated approximately as seen in the following table:

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DAC$_1$	-18000	D + (x,y-working area / 2) = D$_1$
DAC$_2$	+18000	D - (x,y-working area / 2) = D$_2$

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

Distance 2nd mirror to focus [mm]: 250
☑ F-Theta lens

4. Load the pre-defined job file "'Calibrate_Optic3D_Circle_-120_to_120.sjf'" in SAMLight.
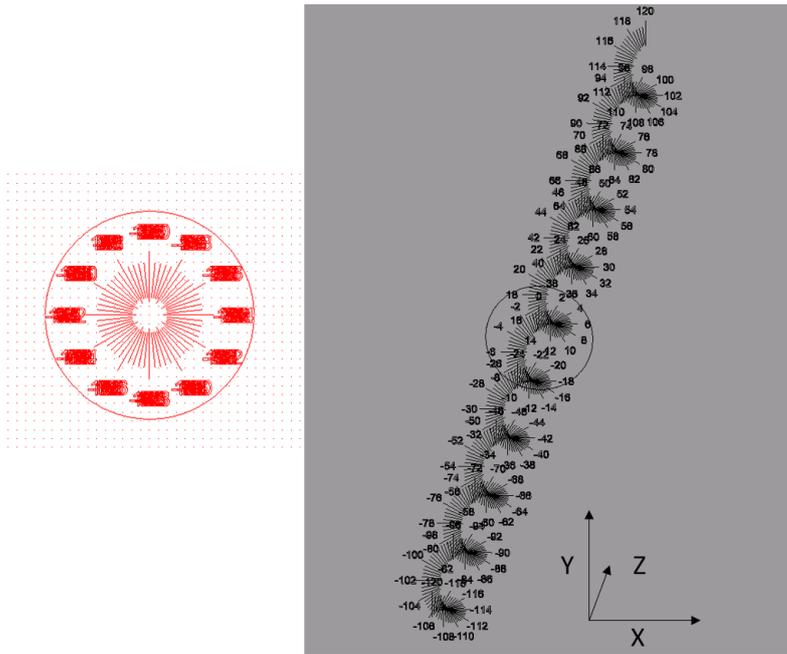
This job file serves as a vertical "ruler". It consists of lines ranging from -120…+120 mm in z-direction. The lines have 0.2 mm spacing in z. If your x,y-working area is smaller than this range, you have to delete a few lines in the job file such that the z-range < x,y-working area. Otherwise the error message "Galvo out of range" will appear when clicking "start mark".

5. Next, define the following table in a spread sheet. The points have to be within the maximum physical z-tuning range. For example:

Target height [mm]	Scanner height [mm]	Focus dist [mm]
-50.00	50.00	300.00
-40.00	40.00	290.00
-30.00	30.00	280.00
-20.00	20.00	270.00
-10.00	10.00	260.00
0.00	0.00	250.00
10.00	-10.00	240.00
20.00	-20.00	230.00
30.00	-30.00	220.00
40.00	-40.00	210.00
50.00	-50.00	200.00

6. Position a sample at one point in the table (e.g. 0 mm in this example). Start the job file.
7. Change the z-position of the sample to the next point in the table and mark the job file again. Repeat this procedure for all z-values.

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8. Extract the marked z-position values F_z from the 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.

Best marked focus at -0.6 mm
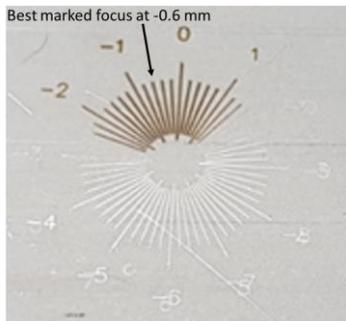
9. After this analysis, your z-correction table might look like shown below. At z-value = 0 mm, the marked value on the sample is not necessarily zero due to a possible offset. The calibration will take this offset automatically into account.

-30.00	30.00	280.00		-40.00
-20.00	20.00	270.00		-28.00
-10.00	10.00	260.00		-16.00
0.00	0.00	250.00		-2.00
10.00	-10.00	240.00		12.00
20.00	-20.00	230.00		24.00
30.00	-30.00	220.00		36.00
40.00	-40.00	210.00		48.00

10. Next, calculate the distances $D_z = D - F_z$ with D = 250 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
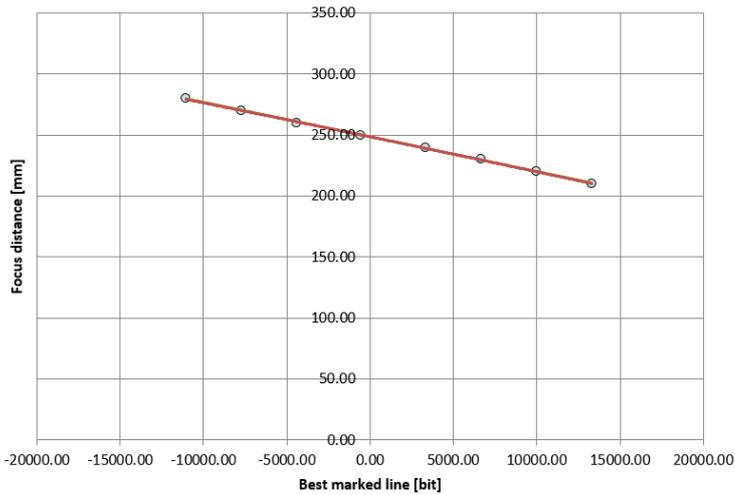
$$DAC_z = a \cdot D_z + b$$

with the coefficients (from step 2.)

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

The calculation of those values has been implemented in the EXCEL sheet. The table looks like below

Marking result from temporary lookup table				
Target height [mm]	Scanner height [mm]	Focus dist [mm]	Best marked line	Best line [bit]
-50.00	50.00	300.00		#N/A
-40.00	40.00	290.00		#N/A
-30.00	30.00	280.00	-40.00	-11076.92
-20.00	20.00	270.00	-28.00	-7753.85
-10.00	10.00	260.00	-16.00	-4430.77
0.00	0.00	250.00	-2.00	-553.85
10.00	-10.00	240.00	12.00	3323.08
20.00	-20.00	230.00	24.00	6646.15
30.00	-30.00	220.00	36.00	9969.23
40.00	-40.00	210.00	48.00	13292.31
50.00	-50.00	200.00		#N/A

11. As a final step, one has to create the final look-up table. Here we fit "Best line [bit]" with "Focus dist [mm]" with a second-order polynomial in order to cope with any nonlinearity in the optical system.

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Next substitute the given bit values into fitted equation in order to obtain an array of Focus dist [mm] as follows:

Calibrated quadratic lookup table	
Z value [bit]	Focus dist. [mm]
18000	196.47
13500	209.74
9000	222.85
4500	235.80
0	248.59
-4500	261.22
-9000	273.69
-13500	286.00
-18000	298.15

This two 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.

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 deviations are small and within the precision of the method described in step 8.

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Appendix 2: Lens response time

Using the Optotune-DSD board to control the EL-10-42-OF lens, 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 controlled as well as the tuning can be examined. The applied voltage at the input of Optotune-DSD board is ramped up and down with adjustable speed. In Figure 9 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 10 showing that the lens response time decreases with smaller jump lengths. Compared to the results measured using an EL-E-OF-A analog driver board, the response time is about a factor of 1.5 faster.

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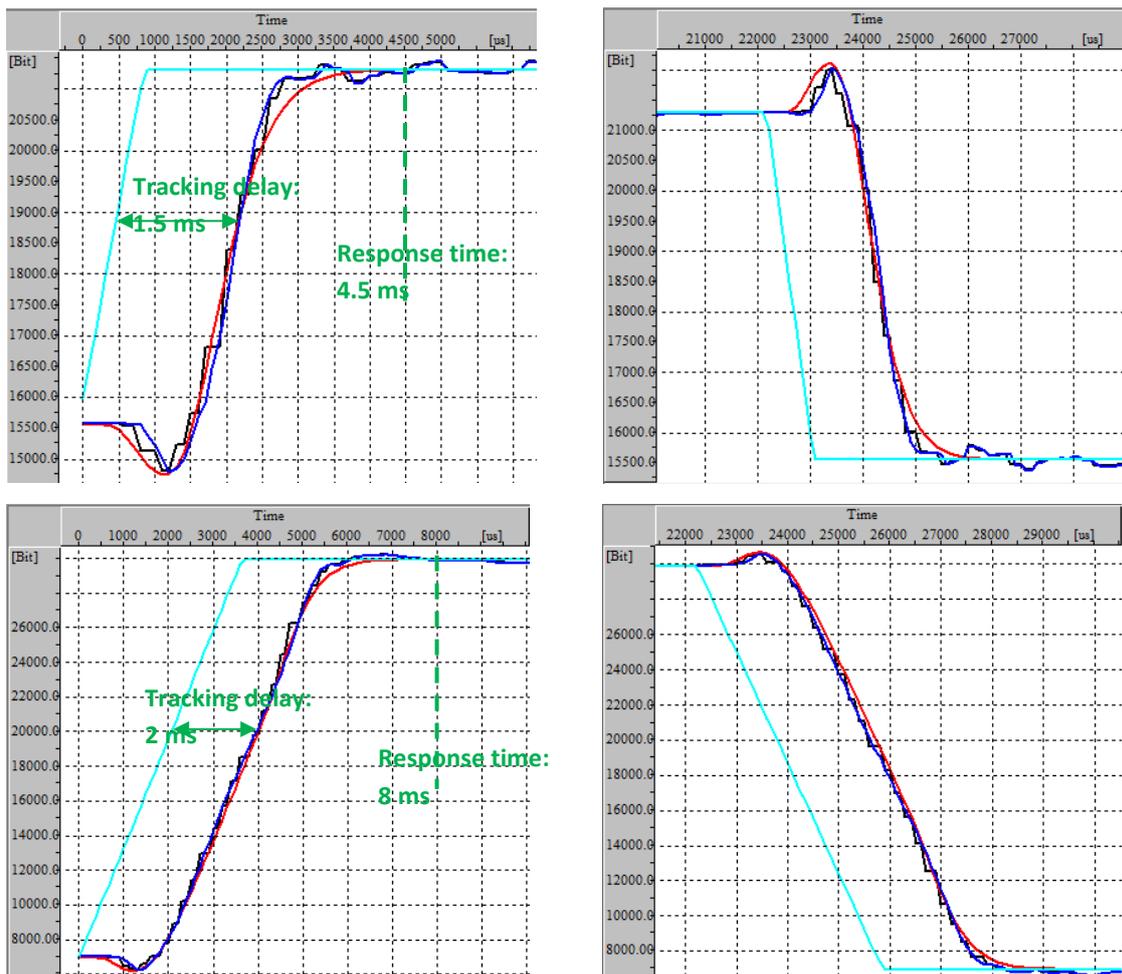Update: 19.03.2020

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Figure 9: Response time of the EL-10-42-OF lens controlled with the Optotune-DSD board for different step sizes (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 Optotune-DSD board. Both falling and rising edge show a very similar response time.
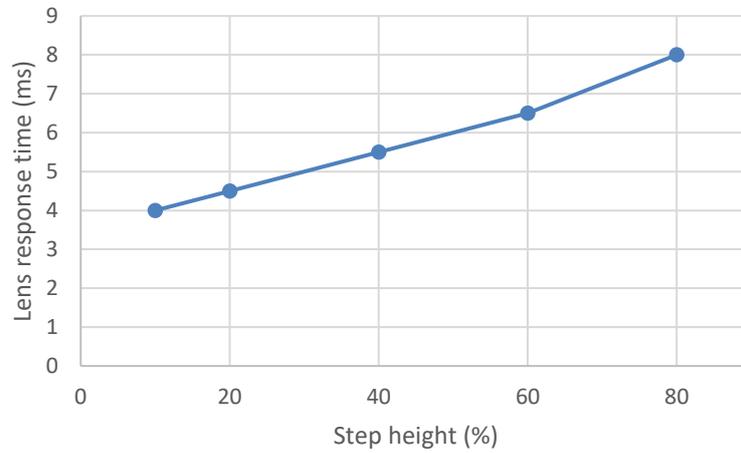

Figure 10: Response time of the EL-10-42-OF lens controlled with the Optotune-DSD board for different step sizes

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Appendix 3: Integration example with f-theta lens

Figure 11 shows an integration example of a compact laser marking system built at Optotune. The EL-10-42-OF is small such that it can just be mounted in the empty space between the laser output and the galvo head (see Figure 12). The mechanical holder for the EL-10-42-OF lens is required and should make sure that the laser beam, the EL-10-42-OF lens and the aperture of the galvo head are coaxial.

Figure 11: Laser marking system using Optotune's electrically focus tunable lens EL-10-42-OF for fast z-axis focusing.
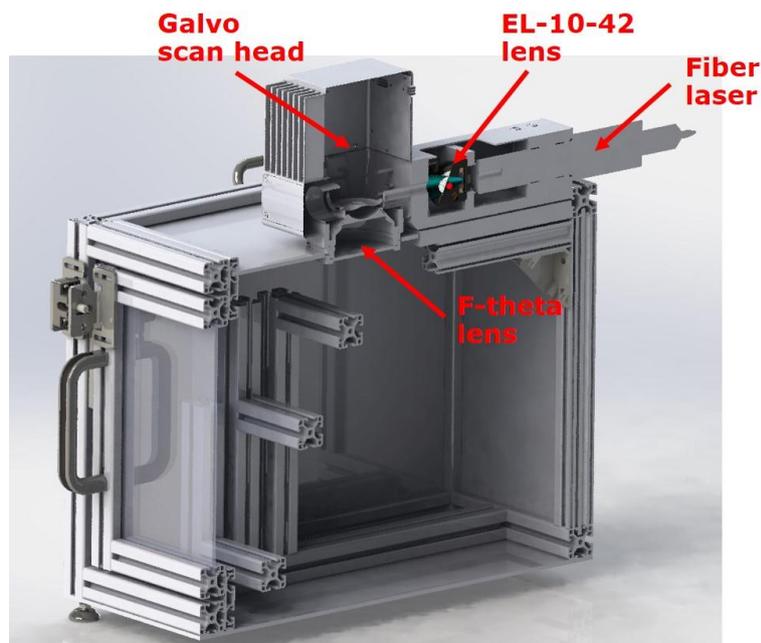

Figure 12: Schematics of Optotune laser marking demo setup. Optotune electrically focus tunable lens EL-10-42-OF is placed between laser head and galvo mirrors, indicated by the arrow.

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The following table summarizes the main specifications of the demo marking system.

Basic Specifications

Outer measures	400 x 400 x 300	mm
Weight	approximately 15	kg
Marking field at central position	100 x 100	mm
Laser class	1 (with housing)	
Laser vendor	IPG / Nufern	
Maximal laser power	20 / 50	W
Laser wavelength	1064	nm
Typical spot size	approximately 70	µm
Beam quality M^2 (IPG specs)	< 2	
Focal length f-theta lens	160	mm
Typ. Jump speed	6000	mm/s
Z-tuning range	100	mm
Software	SCAPS SAMLight	

The following laser marking test result is achieved with the presented system (see Figure 11 and Figure 12) is shown in Figure 13. 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.
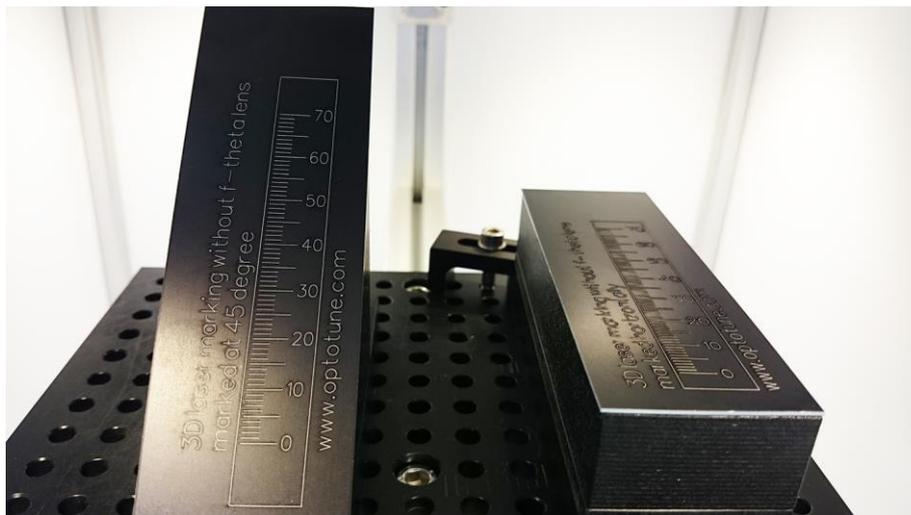

Figure 13: Real example of the 3D marking capabilities. On the right, a horizontal ruler is marked to illustrate the field flattening capabilities. The left shows a ruler marked on a 45° tilted surface.

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Appendix 4: Integration example without f-theta lens

We implemented the EL-10-42-OF without an f-theta lens in our lab laser marking machine presented in Appendix 3. When removing the f-theta lens, another focusing optics has to be implemented instead, which can be realized with standard 1 inch optics, available from e.g. www.thorlabs.com. A top view of the involved optics is shown in Figure 14. Also note the white Teflon washer between the EL-10-42-OF and the holder plate for thermal isolation.
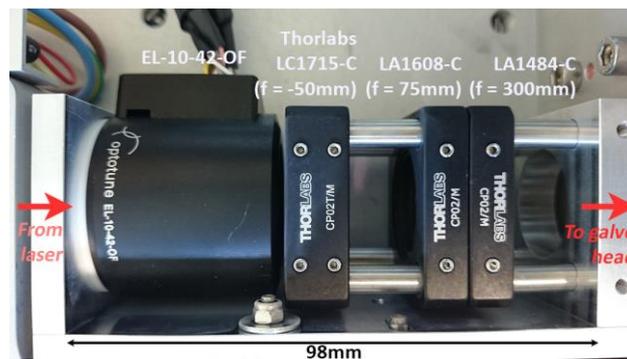

Figure 14: The optical setup for an f-theta free marking system, placed between the laser output and the scanning head.

The corresponding optical layout is illustrated in Figure 15, based on the following idea: the EL-10-42-OF is as the first lens tuning the beam divergence from -2 to +2 dpt. The next two lenses (f = -50 mm and f = 75 mm) serve as a beam expander in order to enlarge the beam size. Finally the beam is focused by the f = 300 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 mm).
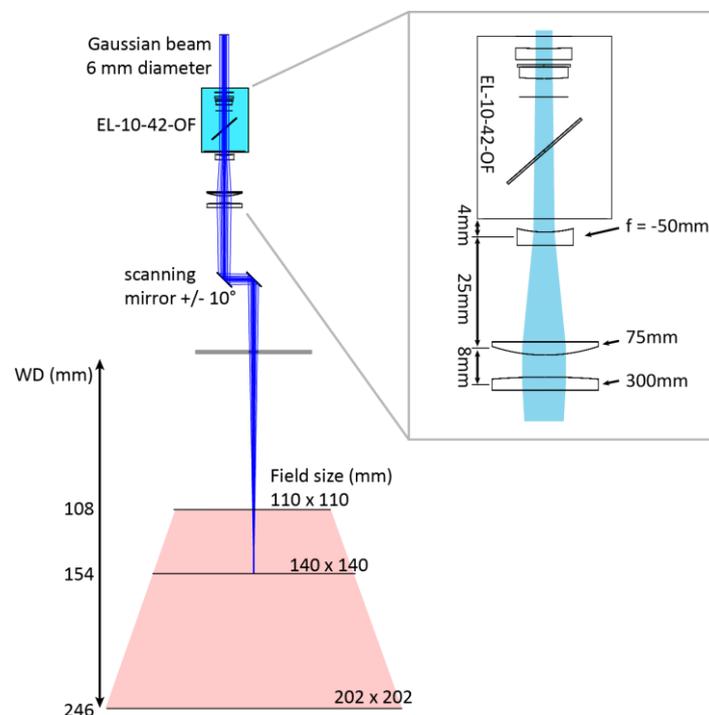

Figure 15: Optical layout of an f-theta free marking system. The schematic on the right shows the involved optical elements. As a first element, the EL-10-42-OF tunes the beam divergence. The f = -50 mm lens diverges the beam further to achieve a beam expansion of about a factor 1.5. The f = 75 mm lens collimates the beam, which gets focused by the f = 300 mm lens onto the working plane.