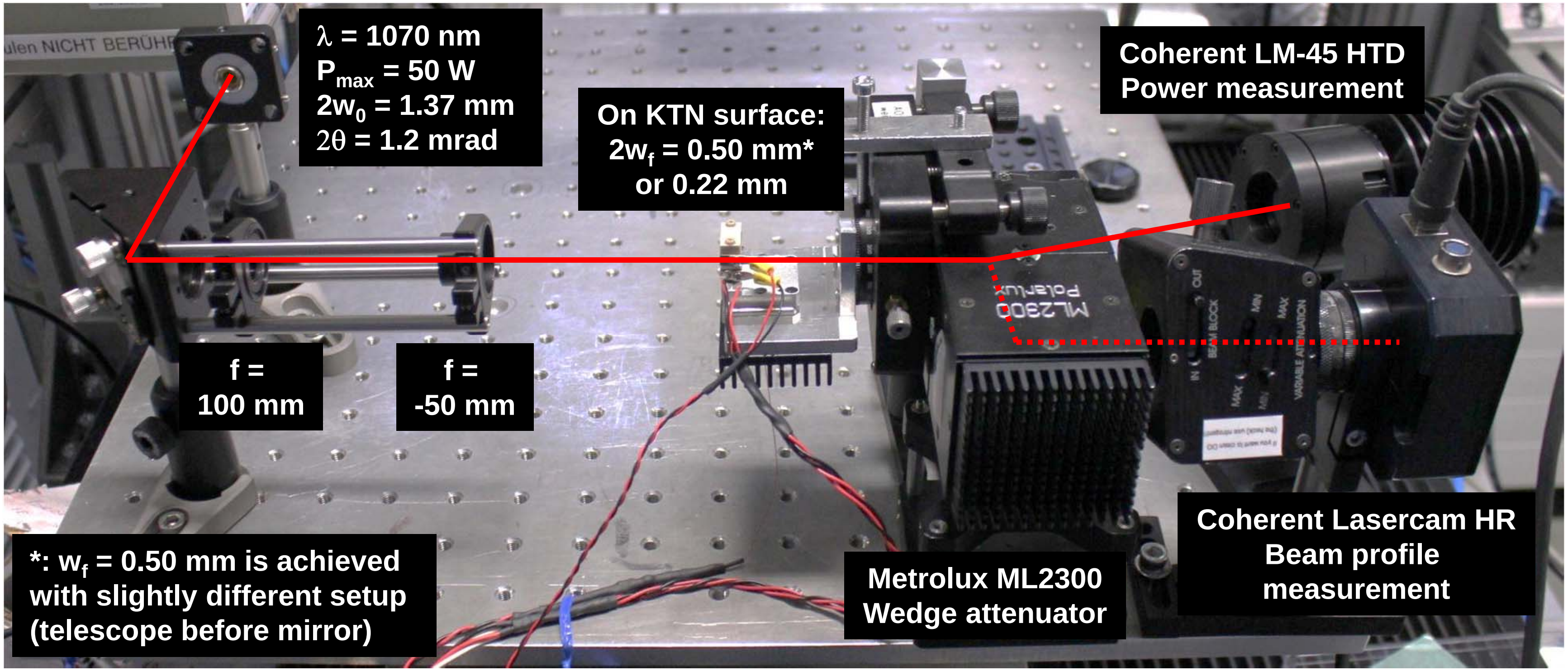
Experimental setup



- Date: 09.01.2015 to 12.01.2015
- Crystal: AOXB19-11-70
- Laser power loss in KTN (reflection, absorption): 2.4% +/- 0.7% (N = 7)
- Laser power loss in wedge attenuator: 7.7% +/- 0.5% (N = 7)
- ➢ Laser power incident on KTN crystal = 111% Measured laser power

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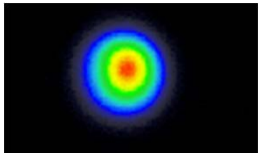
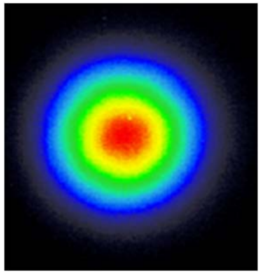
Beam profile and TEC PWM duty cycle references

Setup for $2w_f$ = 0.50 mm



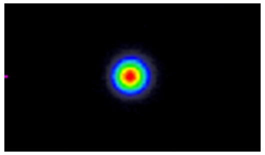
Camera in position
of first KTN surface



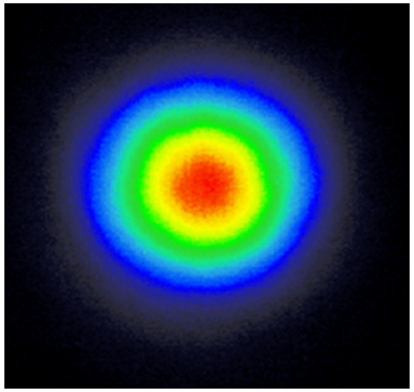
Camera in
measurement position:
280 mm behind first
KTN surface
(2w = 0.96 mm)

1 mm

Setup for $2w_f$ = 0.22 mm

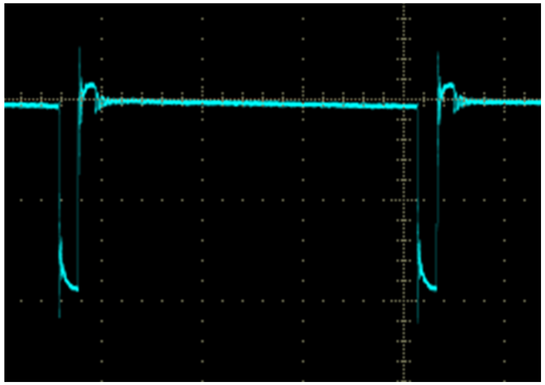


Camera in position
of first KTN surface



Camera in
measurement position:
250 mm behind first
KTN surface
(2w = 1.37 mm)

1 mm

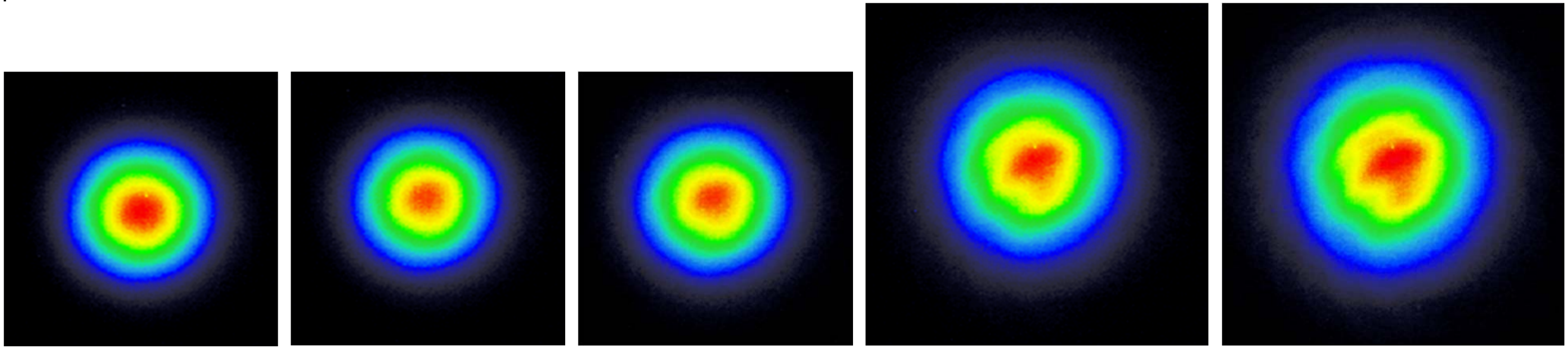


TEC PWM duty cycle:
Measured by detecting radiation close to
TEC cable
f = 14 kHz
Duty cycle at room temperature: ~ 6.2%

Experiment I: No HV

- UV LED switched on for 10 sec prior to measurements
- P_m: Average power incident on KTN
- $2w_f = 0.50$ mm

1 mm



P_m =	2.0 W	7.6 W	18.9 W	41.3 W	50.4 W
TEC duty =	6.1%	6.0%	5.6%	4.8%	4.4%

- ➢ No unexpected beam deformation (comparable to beam without KTN)
- ➢ TEC duty decreases linearly with increasing laser power: Constant, linear absorption in KTN

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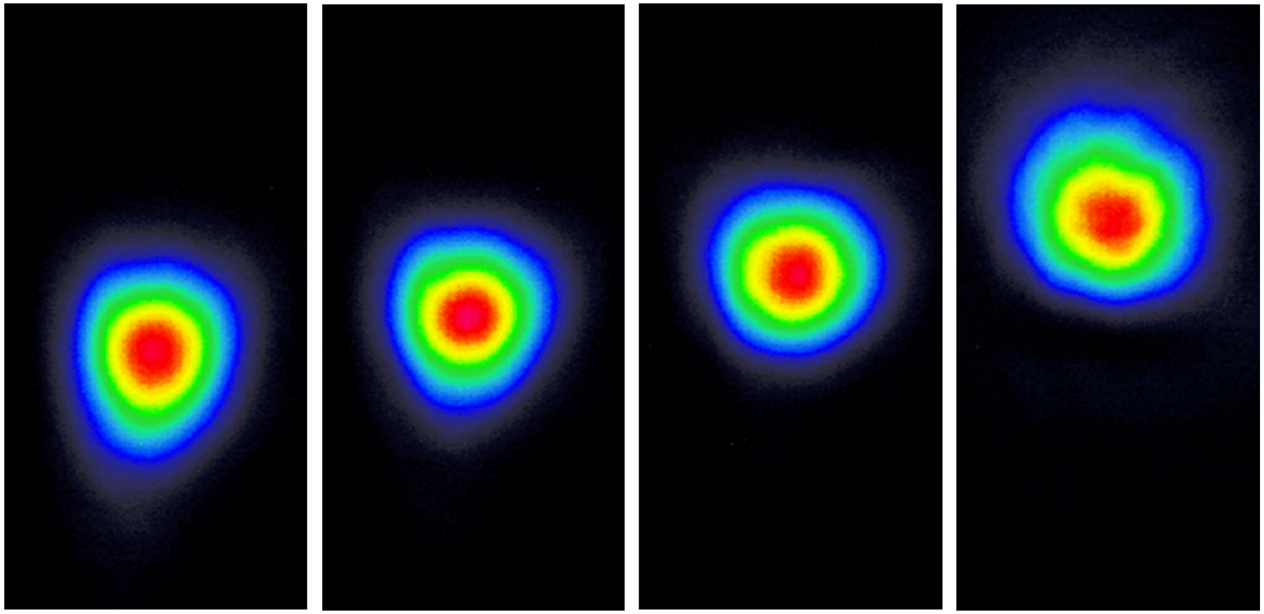
Experiment II: Constant HV

- UV LED switched on for 10 sec prior to Precharges
- Precharges: -200 V 10 sec and +300 V 10 sec
- DC Offset: -240 V
- $2w_f$ = 0.50 mm

1 mm



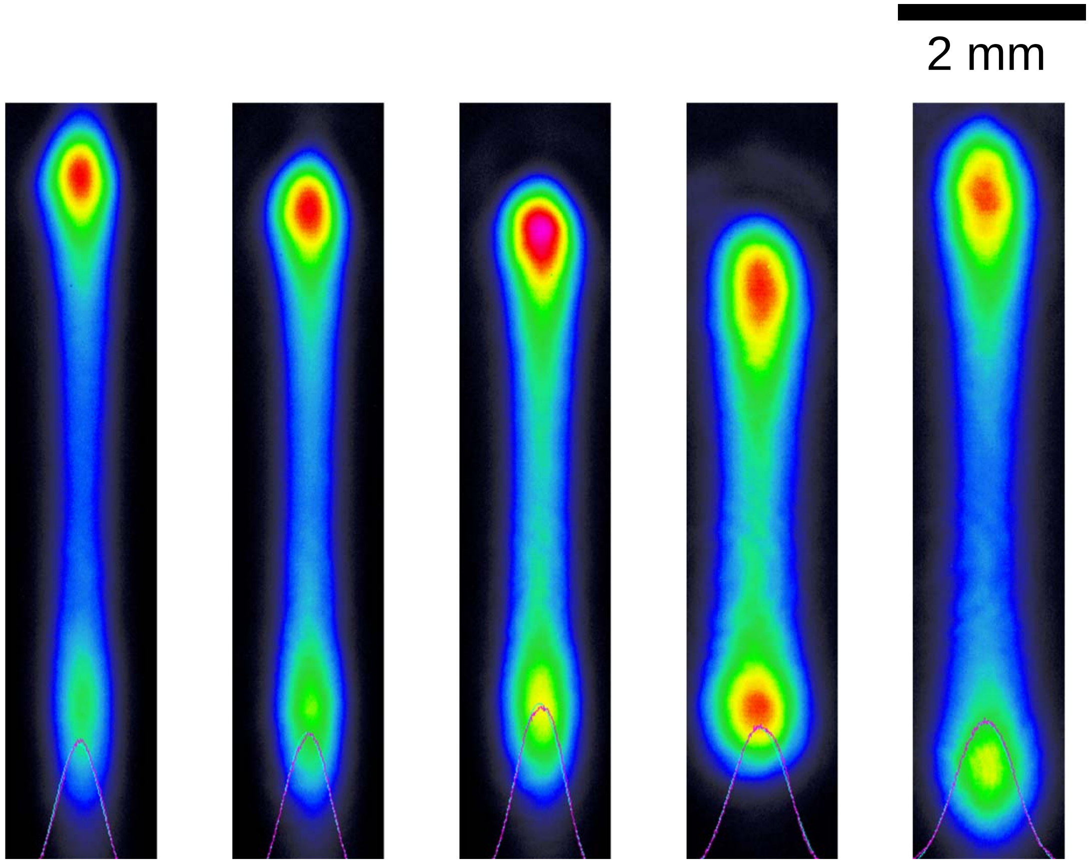
P_m =	2.0 W	7.6 W	18.8 W	40.7 W
TEC duty =	6.0%	5.8%	5.3%	4.6%
Defl. angle =	13.0 mrad	12.4 mrad	11.8 mrad	11.0 mrad

➢ Less deflection with increasing laser power (KTN temperature constant at 26.0°C)

Experiment III: AC HV 0.50 mm

- UV LED switched on for 10 sec prior to Precharges
- Precharges: -200 V 10 sec and +300 V 10 sec
- DC Offset: -240 V
- AC: 1 kHz, 360 V_{pp}
- $2w_f$ = 0.50 mm

➢ Again, reduced deflection angle for increasing laser power
➢ Varying energy distribution with increasing laser power



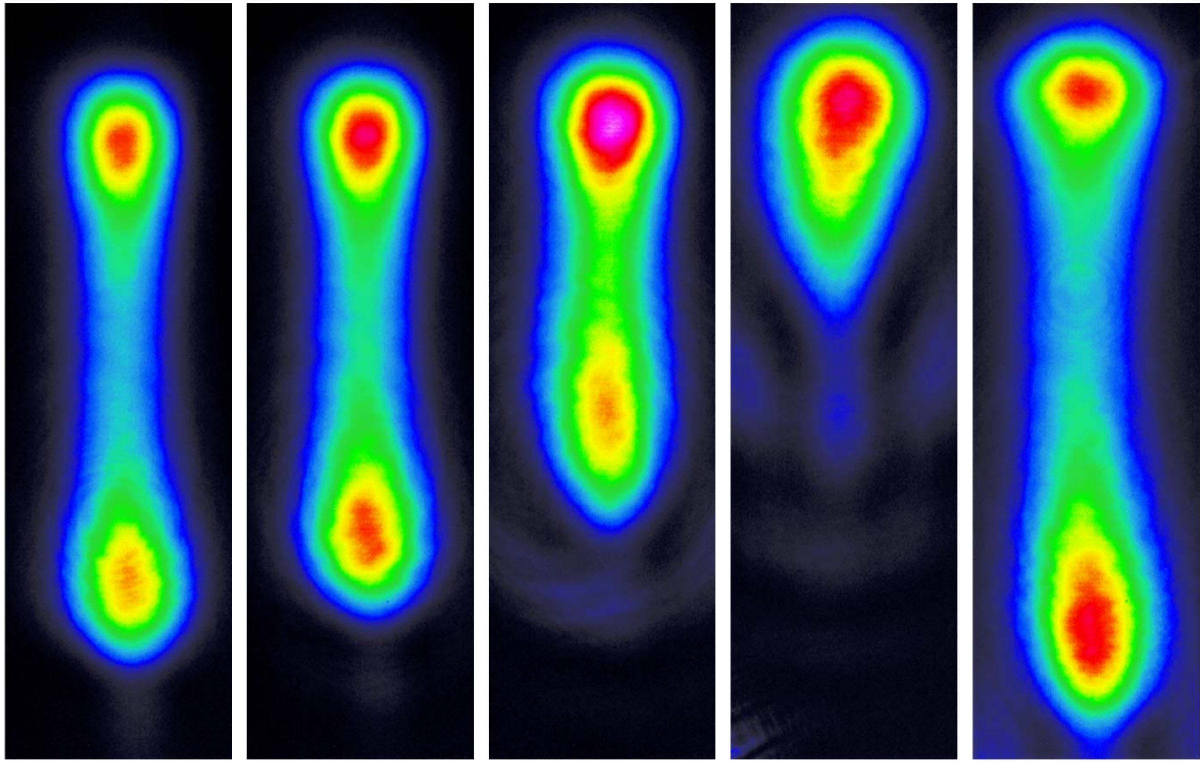
P_m =	2.0 W	7.6 W	18.9 W	50.3 W	50.2 W
TEC duty =	5.8%	5.4%	4.8%	3.7%	3.4%
Defl. angle amplitude =	20.2 mrad	18.7 mrad	18.1 mrad	15.8 mrad	21.3 mrad
					500 V_{pp}

Experiment IV: AC HV 0.22 mm

- UV LED switched on for 10 sec prior to Precharges
- Precharges: -200 V 10 sec and +300 V 10 sec
- DC Offset: -240 V
- AC: 1 kHz, 360 V_{pp}
- *$2w_f$ = 0.22 mm*

➢ Much stronger deflection angle reduction at increasing laser power due to smaller beam diameter
➢ Changing energy distribution with increasing laser power
➢ Increased impact of higher V_{pp} at max. laser power

2 mm



P_m =	1.9 W	7.4 W	18.2 W	48.8 W	48.8 W
TEC duty =	4.7%	4.6%	4.2%	3.0%	2.7%
Defl. angle amplitude =	18.7 mrad	16.8 mrad	11.9 mrad	~1.5 mrad	22.7 mrad
					600 V_{pp}

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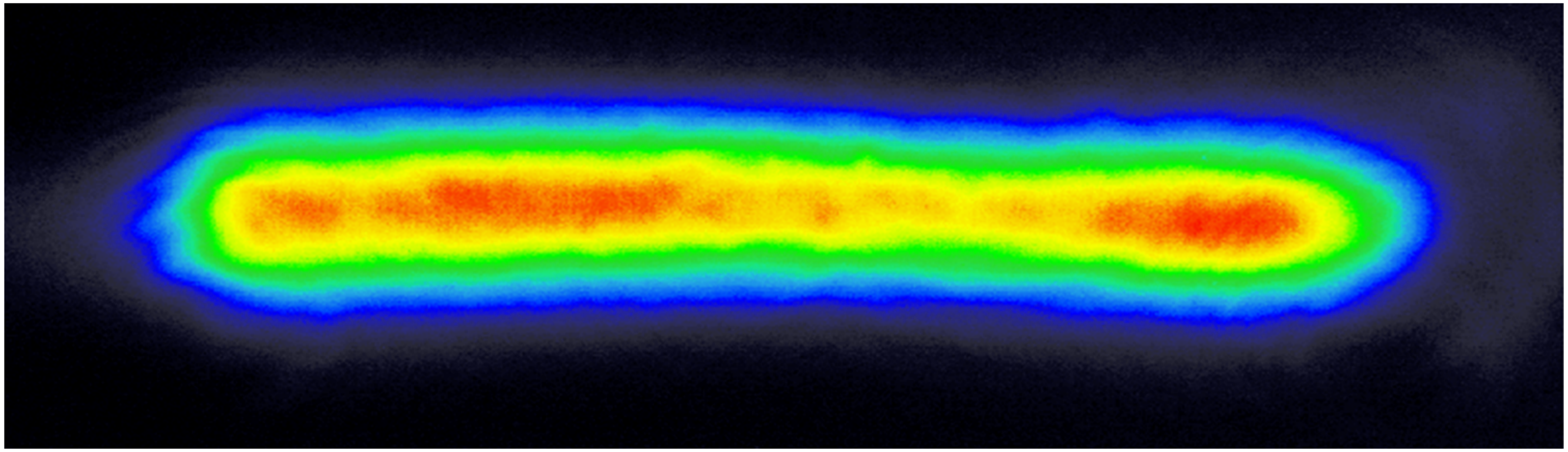
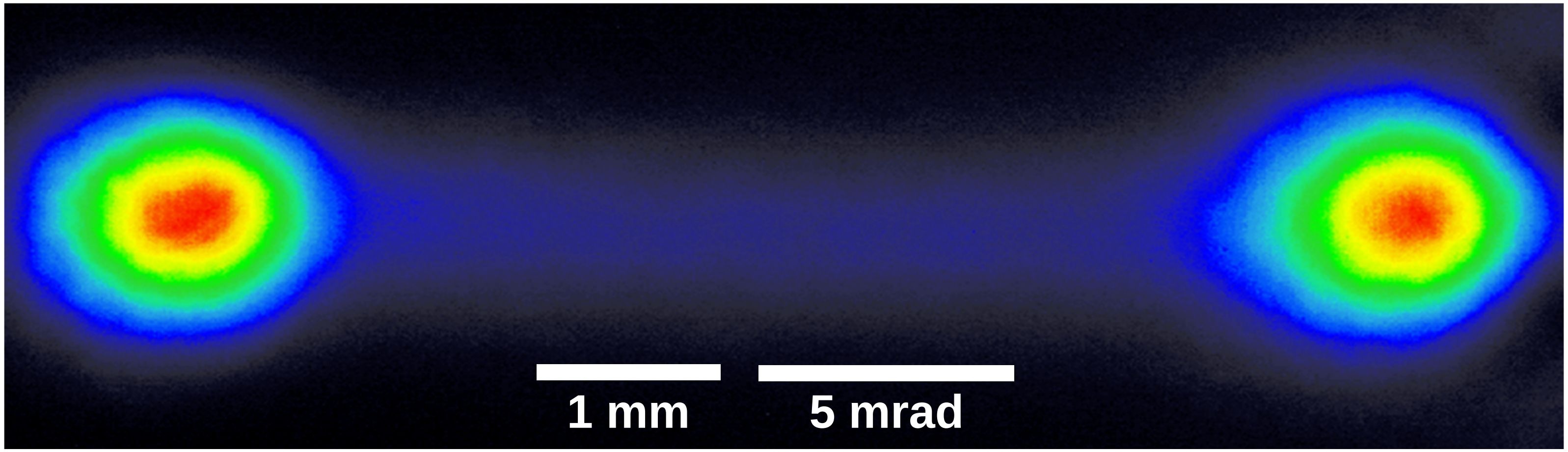
Exemplary demonstrations



P_m = 41.1 W
TEC duty 3.6%
Defl. Angle Amplitude: 19.6 mrad

1 kHz triangle waveform
500 V_{pp}

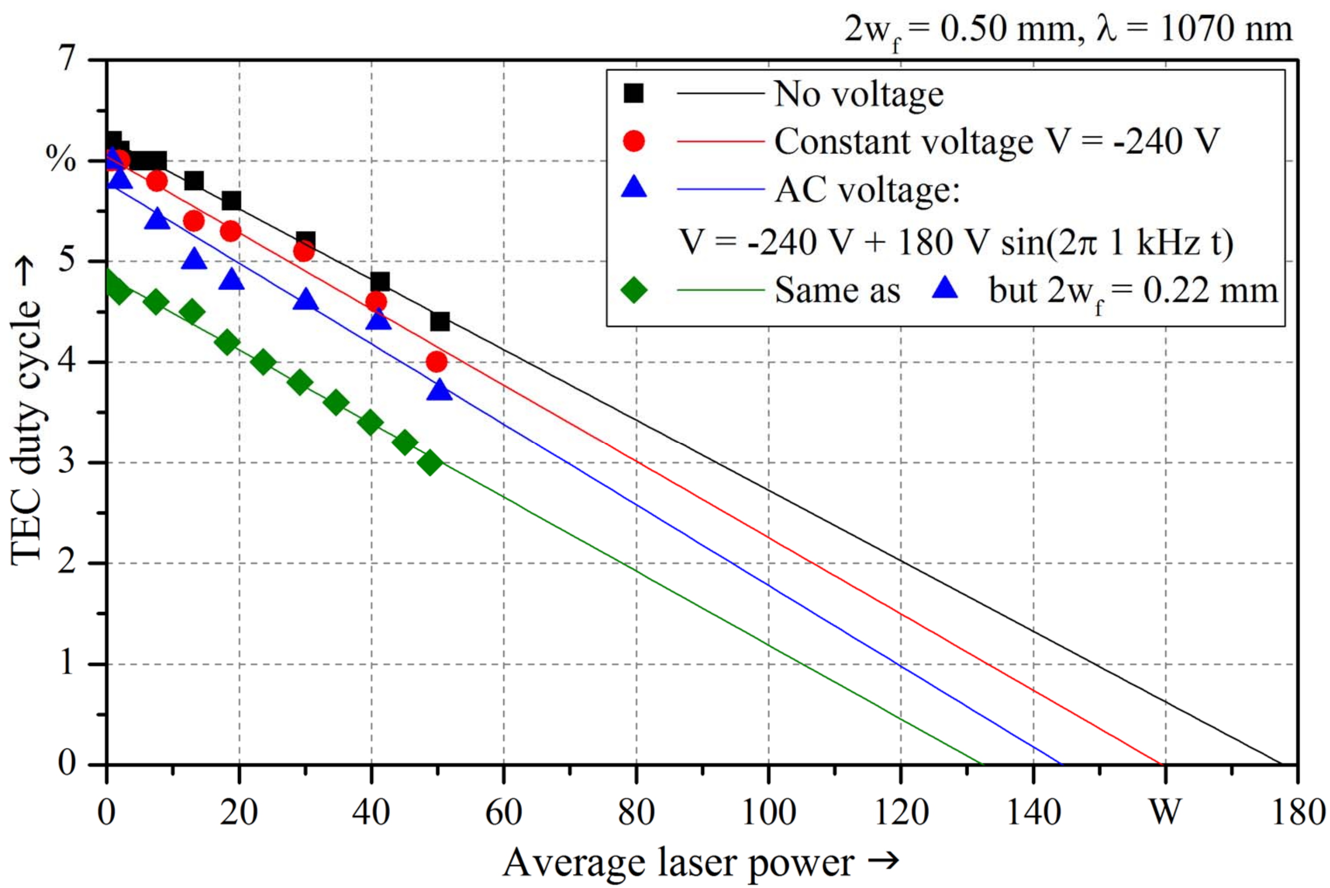


P_m = 22.3 W
TEC duty 3.7%
Defl. Angle Amplitude: 23.0 mrad

1 kHz rect. waveform
480 V_{pp}

Contrast ratio of rectangle waveform: 5.5:1

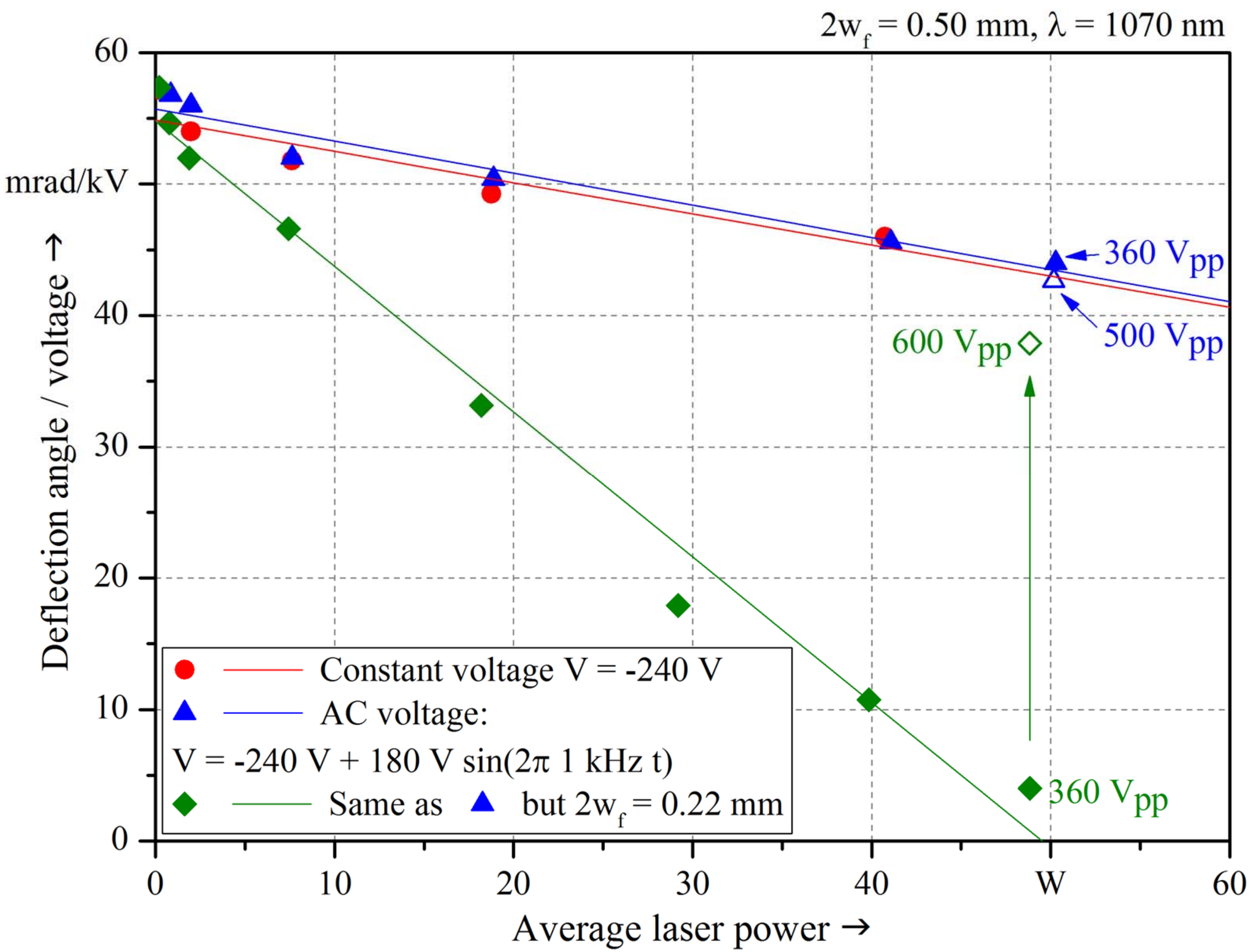
TEC duty cycle over average power



- TEC duty cycle linearly dependent on average power
- Will cross x-axis at approximately 130 W … 180 W

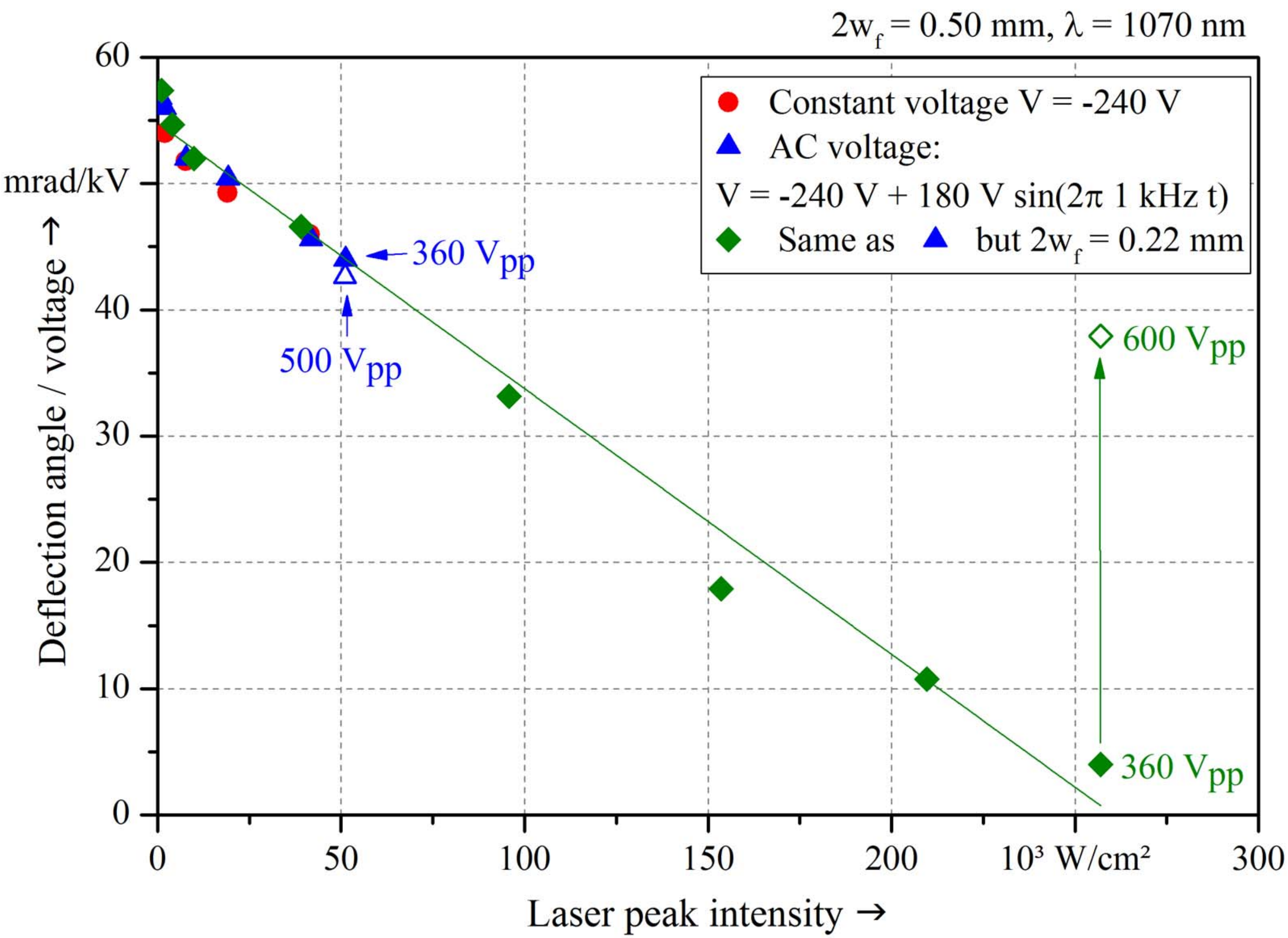
- Increased TEC current at room temperature will allow for higher laser powers
- Active cooling of the surroundings may be beneficial (i.e. lowering TEC duty cycle at 0 W laser power)

Deflection per volt over average laser power



- Deflection decreasing with increasing laser power
  - Crystal is heated up locally, partly loosing ability to deflect the beam (i.e. lateral temperature gradient)
- Severe impact of decreased beam diameter and increased intensity
  - May be compensated by higher deflection voltage (is not the case for lower intensity), compare page 6

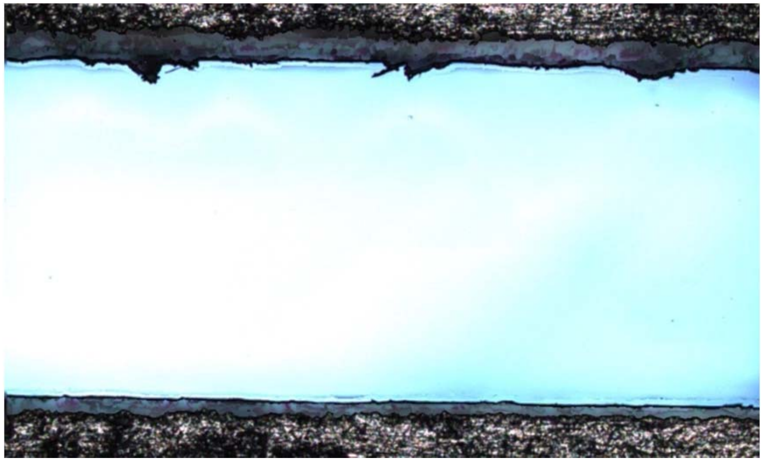
Deflection per volt over laser intensity



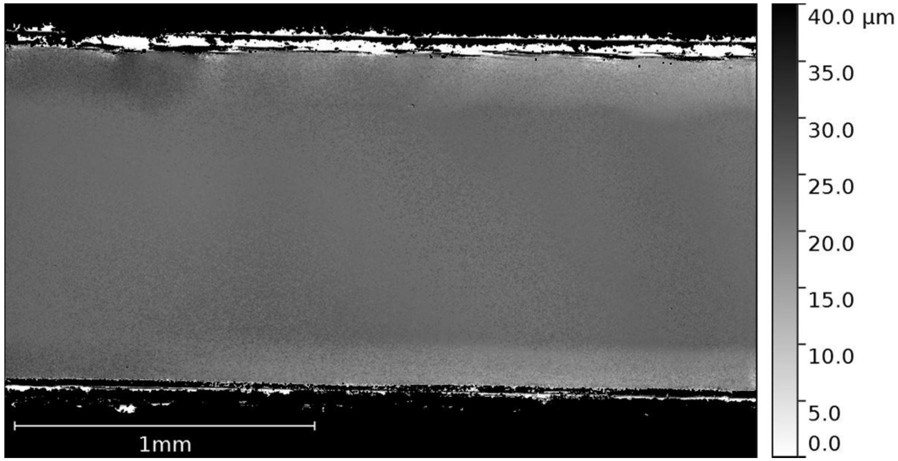
- Beam deflection angle reduction due to lateral temperature gradient is dependent on laser intensity
- Effect may be counteracted by increasing the voltage for higher intensities

KTN crystal topography

Optical microscope

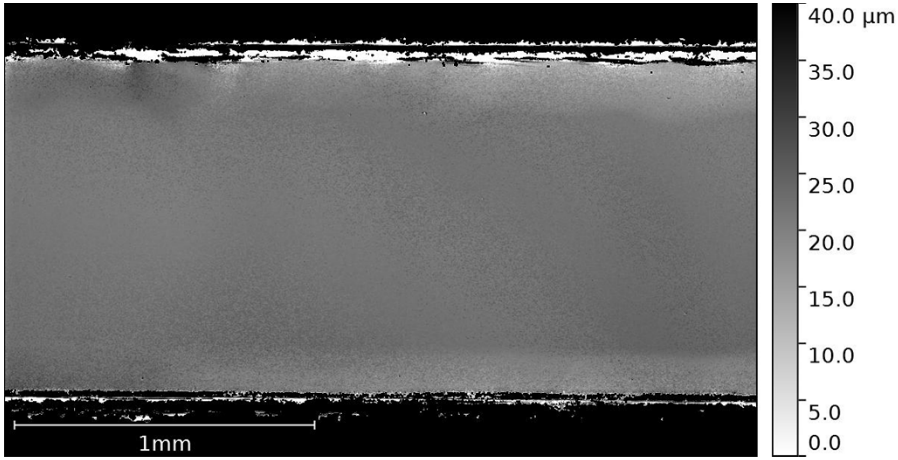


Confocal microscope



Topography before experiments

- There was no observable damage induced during any of the experiments
- The crystal is suitable for cw intensities of at least 2.6 10^5 W/cm^2 (wavelength 1070 nm)



Topography after experiments

Concluding max. applicable laser power

Damage threshold

- The maximum intensity used in these experiments: $2w_f = 0.22$ mm; $P_m = 48.8$ W → $2.6\ 10^5$ W/cm²
- The crystal was not damaged by this intensity (compare page 11)
- Increasing the beam diameter to 0.7 mm will lead to ~0.1 % absorbed laser power (taking the rectangular aperture into account).
- At the same intensity, this would allow for at least 490 W laser power.

Temperature stabilization

- Increasing the TEC duty cycle at room temperature to approximately 20% would allow for ~ 530 W laser power, compare page 8

Lateral temperature gradient

- The deflection angle is halved at around $1.2\ 10^5$ W/cm² and vanishes for $2.5\ 10^5$ W/cm², compare page 10. I.e. at a beam diameter of 0.7 mm this corresponds to 230 W and 480 W. Higher deflection voltages might counteract this effect and allow for increased laser power.

- With slight adaptions (increased beam diameter, increased PWM duty cycle), the KTN crystal would be usable up to at least ***230 W … 480 W*** of laser power.
- With further adaptions (increased aperture) the maximum laser power will even be higher.

Further discussion

- 230 W … 460 W of laser power are enough for efficient welding and selective laser melting.
- The varying beam profile deformation, varying energy distribution and decreasing deflection angle (amplitude) heavily suggest that a closed-loop control will be needed for deflecting high-power cw laser beam with KTN scanners in a controlled manner, compare results on pages 5 and 6.
- Exemplary results on page 7 show the application as semi-simultaneous beam shaping device and semi-simultaneous beam divider.