Heraeus

OPTICAL CONCEPTS FOR UV LAMPS AT LONG WORKING DISTANCES

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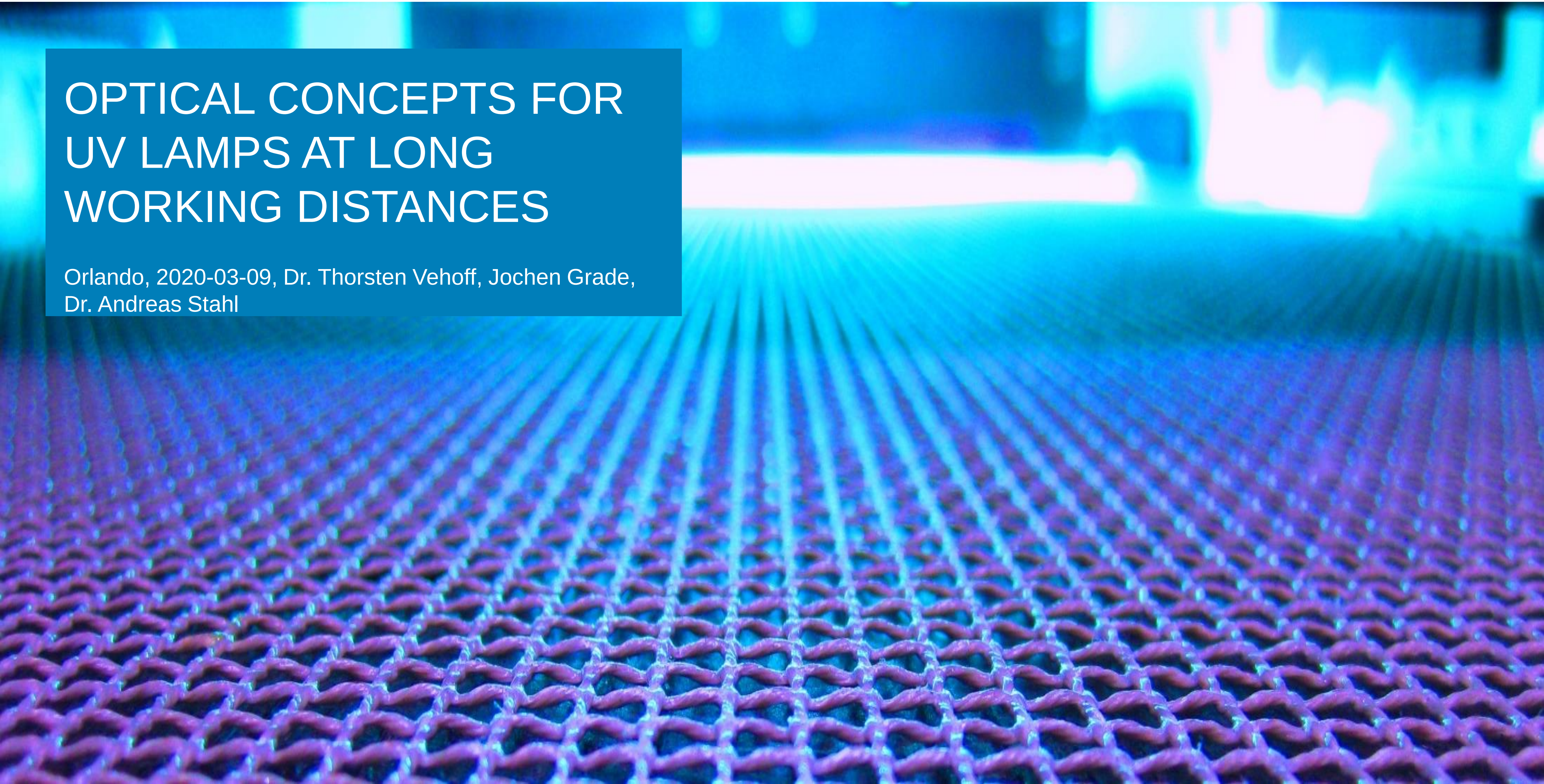

INTRO

Today's agenda

Wording: peak intensity, power, energy

The inverse square law

Optical concepts

- **Differences between conventional and LED lamps**
- **Primary optics**

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Key characteristics of UV LED lamps

Peak intensity I [W/cm²]

One of the most sought-after properties of UV LED lamps is the peak intensity measured in W/cm². It depends highly on the working distance between lamp and substrate and can be substantially increased at specified distances by use of corresponding optics.

Total power P [W]

Total power refers to the total optical (not electrical) power generated by all LEDs in the lamp. It can be approximated by the amount of LEDs multiplied by the optical power of each one at a given current. This is an oversimplification, however, since the available power outside the lamp is reduced by reflection and absorption inside the lamp. Since lamps of the same type are often available in different lengths, the unit W/cm is commonly used to compare lamps of different sizes and power classes.

Total energy E [J]

The total energy is often also referred to as dose. $E = Pt$, i.e. energy ***E*** equals power ***P*** multiplied by time ***t***. Thus the energy seen by the substrate depends on the duration of the UV exposure. Most industrial processes automatically move the paper below the lamps with a given line speed ***v***. Clearly, the time underneath the lamp is proportional to the inverse speed $t \sim 1/v$. However, in contrast to popular opinion it also depends on the working distance (due to losses at high and low angles) and the illuminated area (which defines the angles still hitting the paper).

Peak intensity vs. working distance

Inverse-square law

One of the very fundamental laws of physics states, that the (light) intensity generated by a **point-source** is proportional to the inverse square of the distance away from that point source:

$$I \sim \frac{1}{r^2}$$

The reason is illustrated on the right. The area hit by the light rays increases by **r²** as the distance from the source increases, thus there are less rays or photons per area and hence less intensity. This relation is **not true** very close to two-dimensional or mulitple light sources or when using optics.

- For an LED lamp with the LEDs arranged in a 2D matrix the inverse-square intensity loss of one LED point source will be partially compensated by the intensity generated by the neighboring LEDs.
- The inverse-square law intrinsically assumes a uniform light distribution generated by the point source (Lambertian emission). For an extended light source with optics this is no longer true and the light can for example be focused at certain distances.

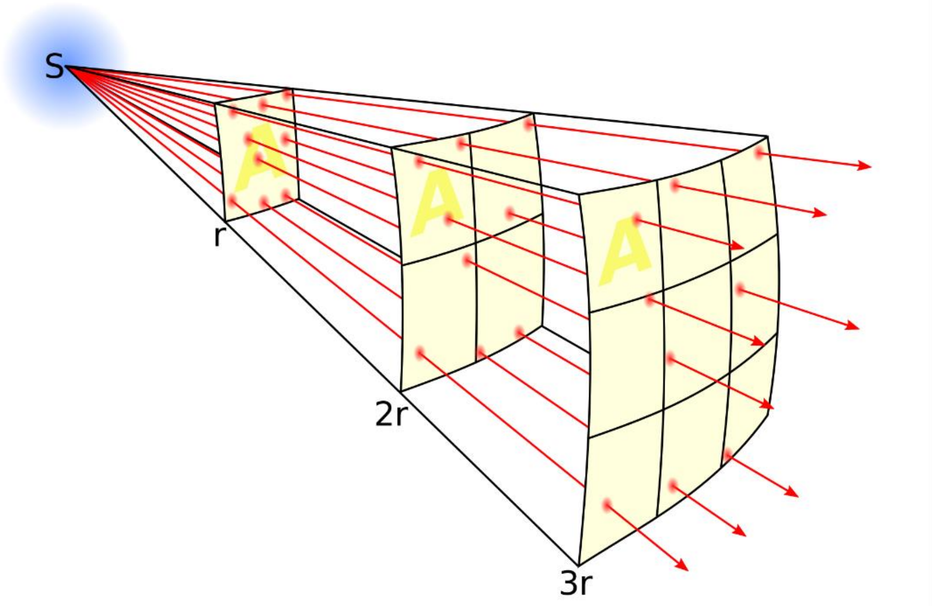

Fig. 1: Reasoning behind inverse-square law.
https://en.wikipedia.org/wiki/Inverse-square_law

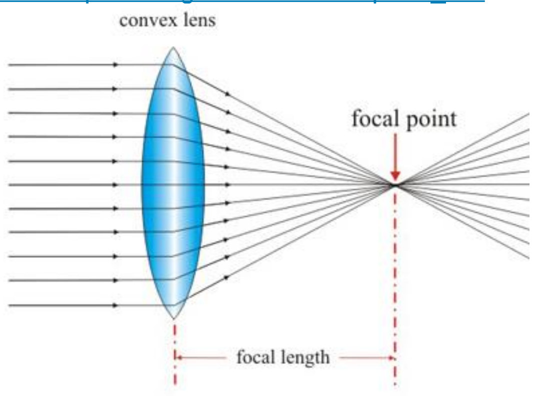

Fig. 2: Effect of convex lens
https://physics.stackexchange.com/questions/117370/interference-at-the-focus-of-a-convex-lens-or-a-concave-mirror

OPTICAL CONCEPTS

UV LED vs. conventional UV (e.g. Hg) lamps

Conventional UV lamps

Conventional lamps such as low or medium pressure lamps based on mercury are tube lamps. All reflector concepts are extremely similar and mainly focused on reflecting the light emitted backwards or reducing the intensity drop at the edges of the lamp. Fancy optical concepts are almost impossible to implement due to the large size of the lamp and the extreme heat near the actual light emission.

UV LED lamps

UV LEDs just as VIS LEDs are tiny light sources emitting into the half sphere in front of them. This along with the fact that they are fairly cold and can easily be cooled on the backside allows the use of tiny reflectors or optics directly above them. Heraeus presently uses spherical micro optics made of a special silicone focusing the light into a 60° emission angle. We are also developing cylindrical quartz lenses.

Silicone optics	Quartz optics
+ Extremely precise surfaces	+ Excellent UVC transmission
+ Flexible design	+ Longevity (no cooling required)
- Cooling required	- Limited design options

Fig. 1: Heraeus Steribelt amalgam lamp.

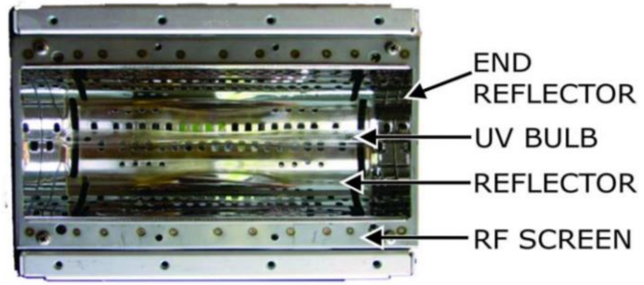

Fig. 2: Heraeus I600M Reflectors.

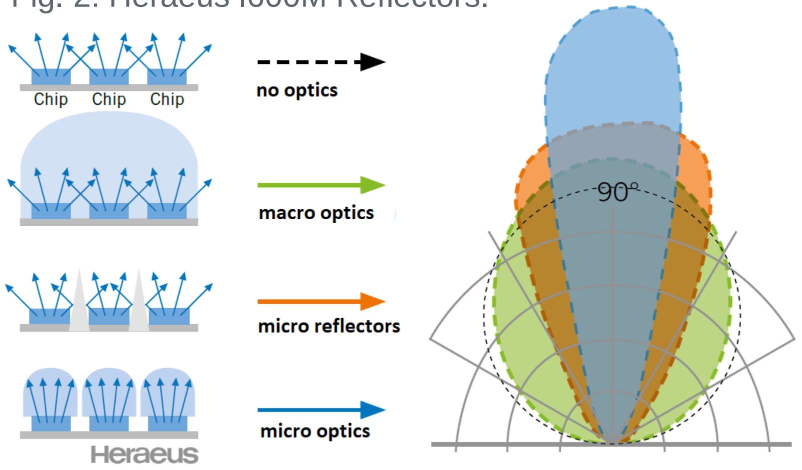

Fig. 3: Concepts for LED primary optics.

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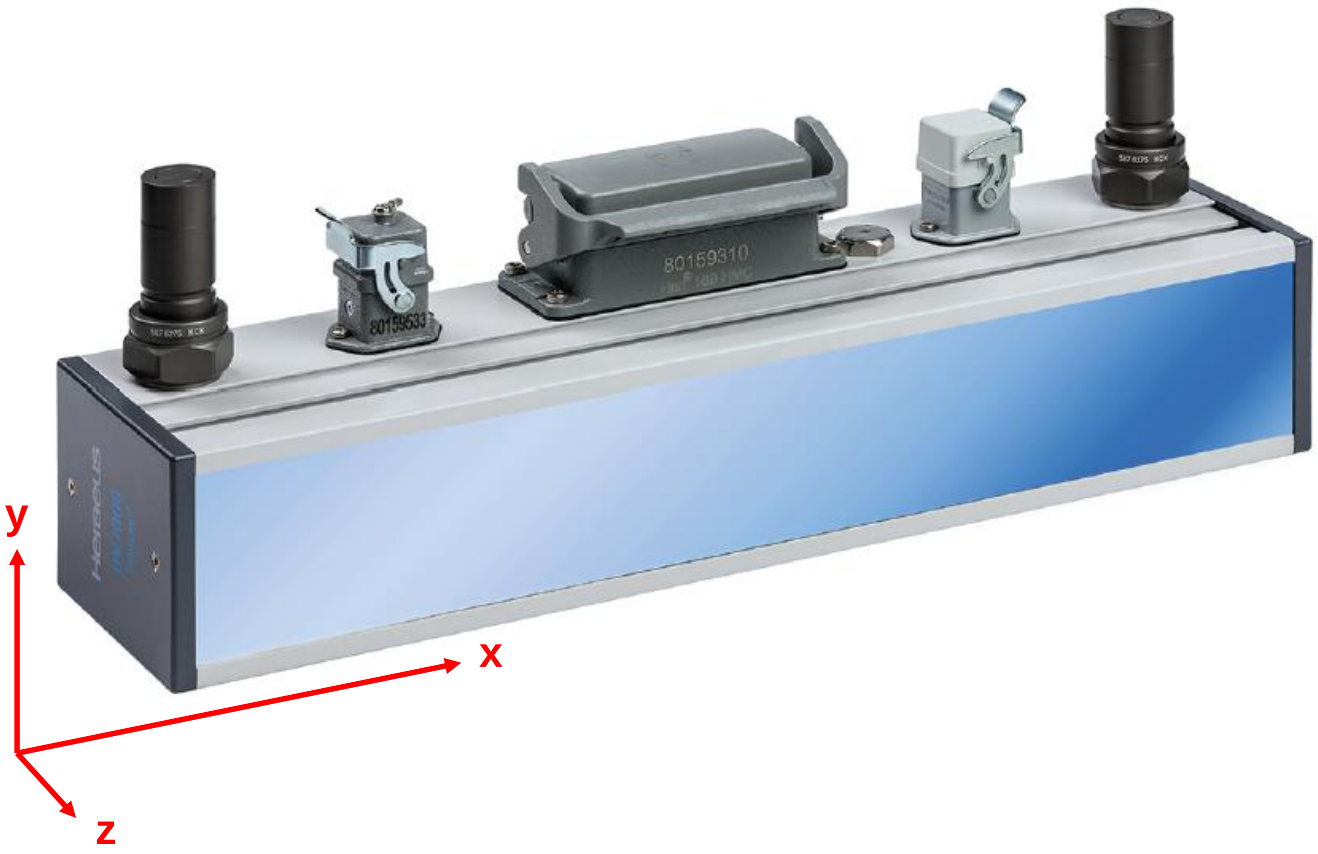
Nomenclature

Coordinate system

x → length of the lamp and the quartz window, width of substrates, used for uniformity calculation
y → width of the lamp and the quartz window, direction of substrate motion (line speed), integral yields W/cm
z → height of the lamp, direction of emission, working distance



OPTICAL CONCEPTS

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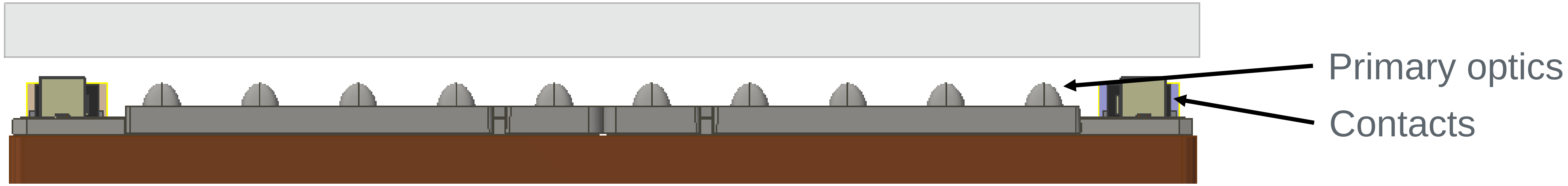
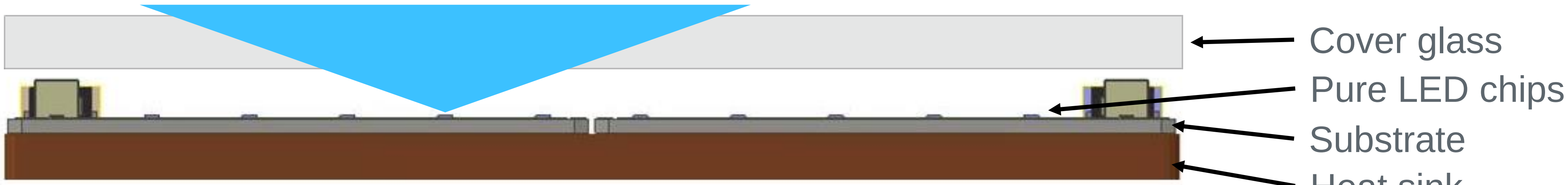
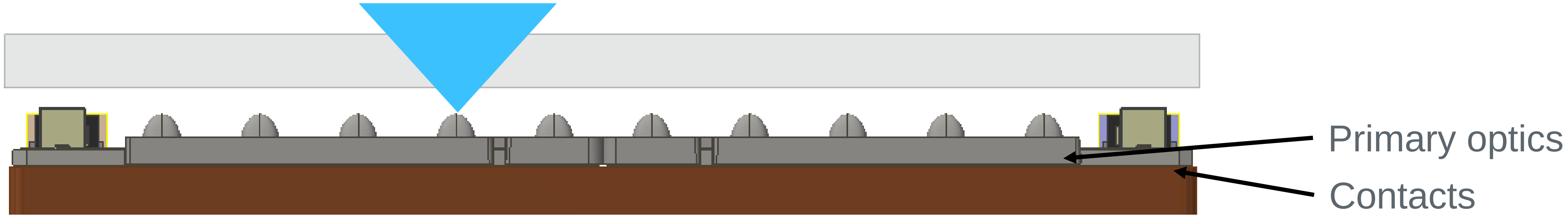


OPTICAL CONCEPTS



Light path without optics.



Light path with primary optics.

PRIMARY OPTICS

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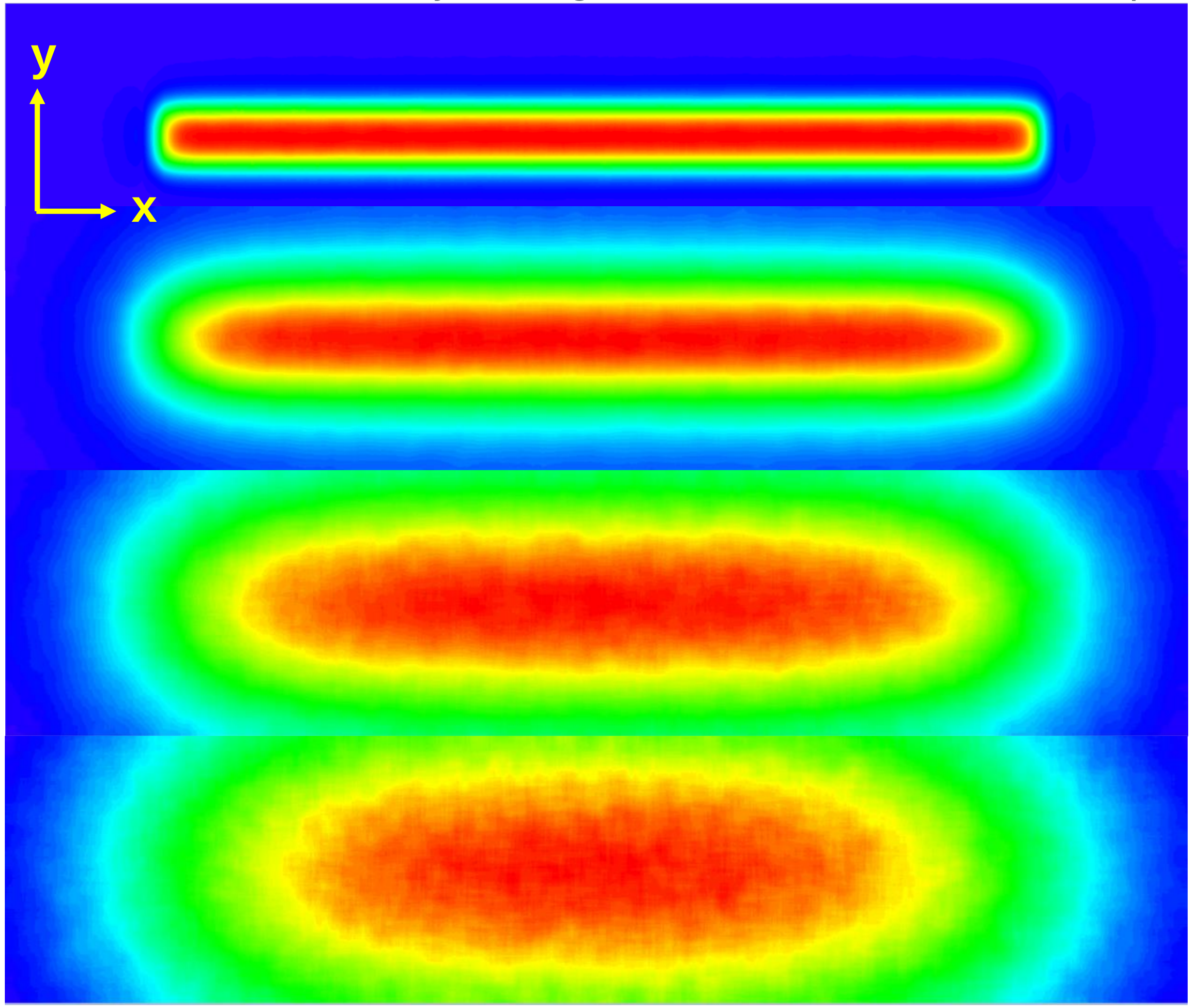
Semray UV7000 without optics

Intensity distributions at different distances (z)

All data is based on ray-tracing simulations of a UV7000 lamp with 395 nm chips.



z = 0 mm (at the quartz glass window)

z = 20 mm

z = 50 mm

z = 80 mm

Description

The initial distribution outlines the window of the lamp. At 20 mm the peak already widens and the edges become blurry. At 80 mm the distribution becomes elliptical, even further away it looks like that of a point source (as all light sources eventually do).

Peak intensity

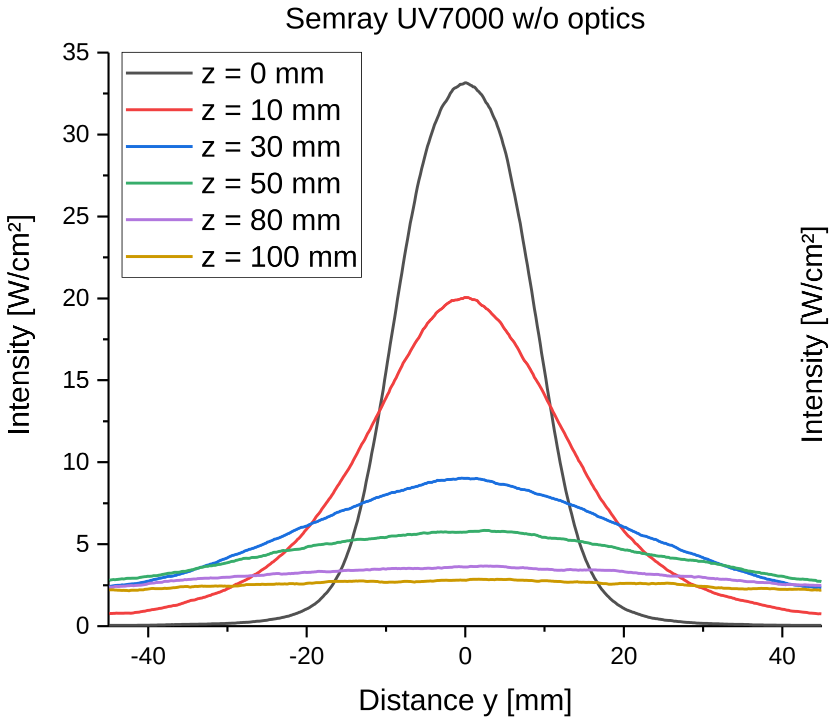
The peak intensity [W/cm²] given in data sheets is the maximum value of the intensity distribution shown on the left. It is almost constant along a central line, which is never quite as long as the lamp's cover glass and whose length decreases with working distance.

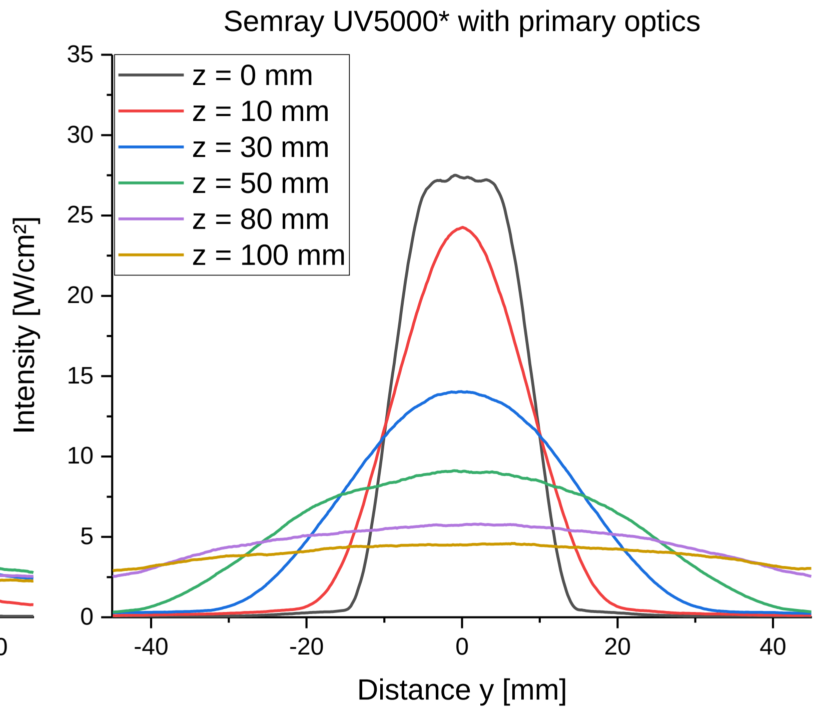
PRIMARY OPTICS

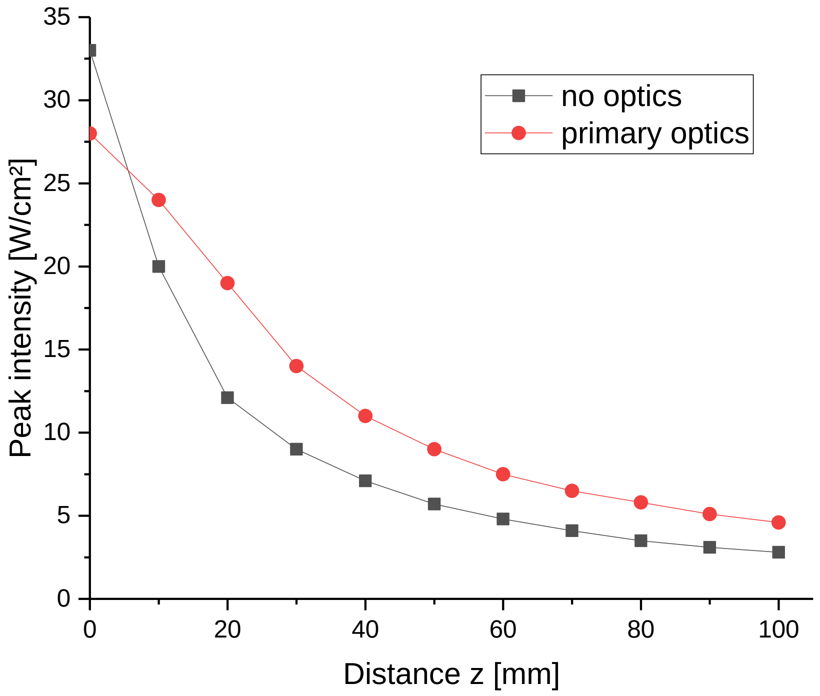
Semray UV7000 with primary optics

Peak intensity in y- and z-direction for systems with and without primary optics

The primary optics are cylindrical quartz optics in the following.







Effects of primary optics

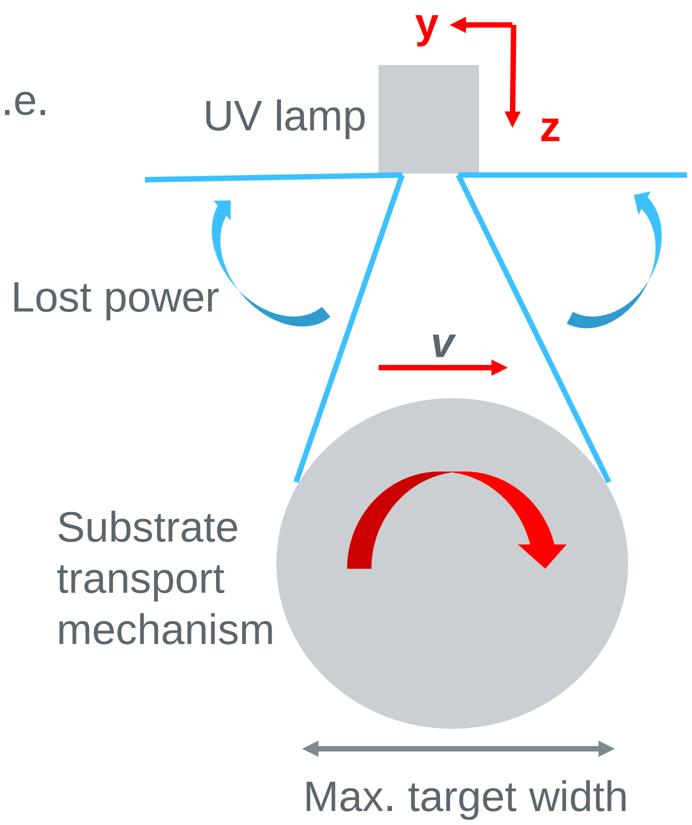
The primary optics create a plateau at 0 mm distance due to focusing each LED row on its own, thus here the peak power is lower than for the system without optics. After that the peak power drops rapidly without primary optics, while the peaks of the primary optics merge resulting in a much slower decline in peak power.

PRIMARY OPTICS

Semray UV7000 with primary optics

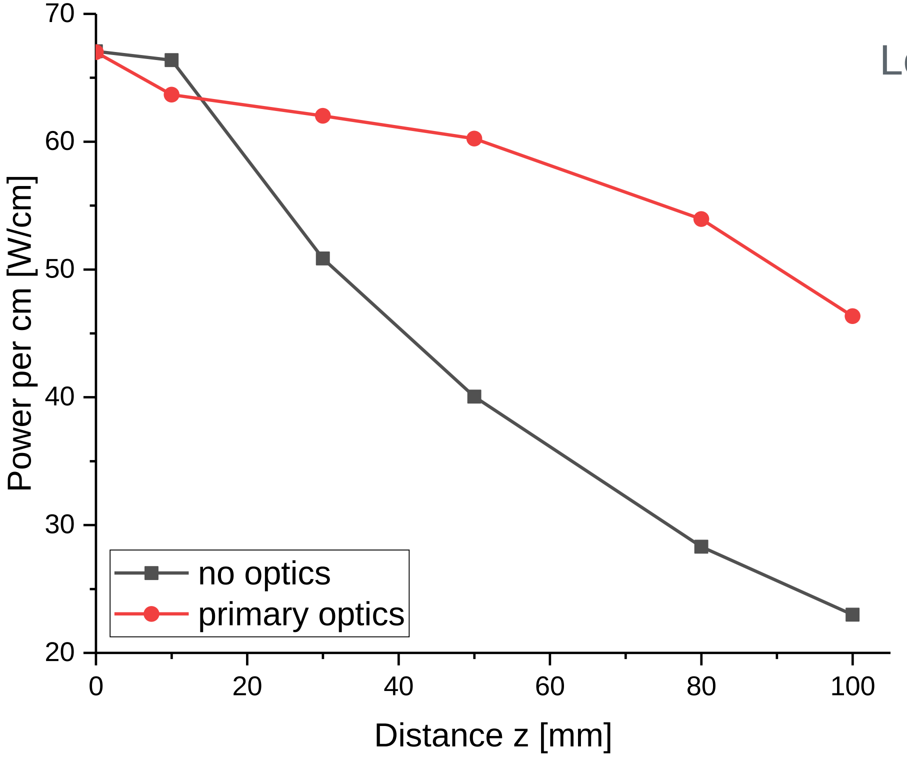
Total power / energy for systems with and without primary optics

To be relevant for an industrial process the optical power generated must arrive at the substrate. Depending on the setup, a lot may be lost in the high and low emission angles. For sheetfed offset printing, a realistic maximum target width is somewhere between 20 and 40 cm. But to obtain a greater effect let us assume that we have a process where this width is merely 9 cm, i.e. from y = -4.5 cm to 4.5 cm of the center (y = 0 cm) of the lamp.



Results

Expected power at z = 0 mm by oversimplified calculation:
12 x 9 LEDs per substrate, width of substrate ~ 2.5 cm, ~1.6 W optical power per LED
→ 12 x 9 x 1.6 W / 2.5 cm ~ 69 W/cm².
Based on this assumption, the power actually hitting the substrate drops dramatically without primary optics and substantially slower with optics. Nevertheless 10 cm away, the power drops by almost 30% (with optics) or 70% (without). The useful power (energy / dose) can strongly drop with distance depending on optics and surroundings of the lamp.



PRIMARY OPTICS

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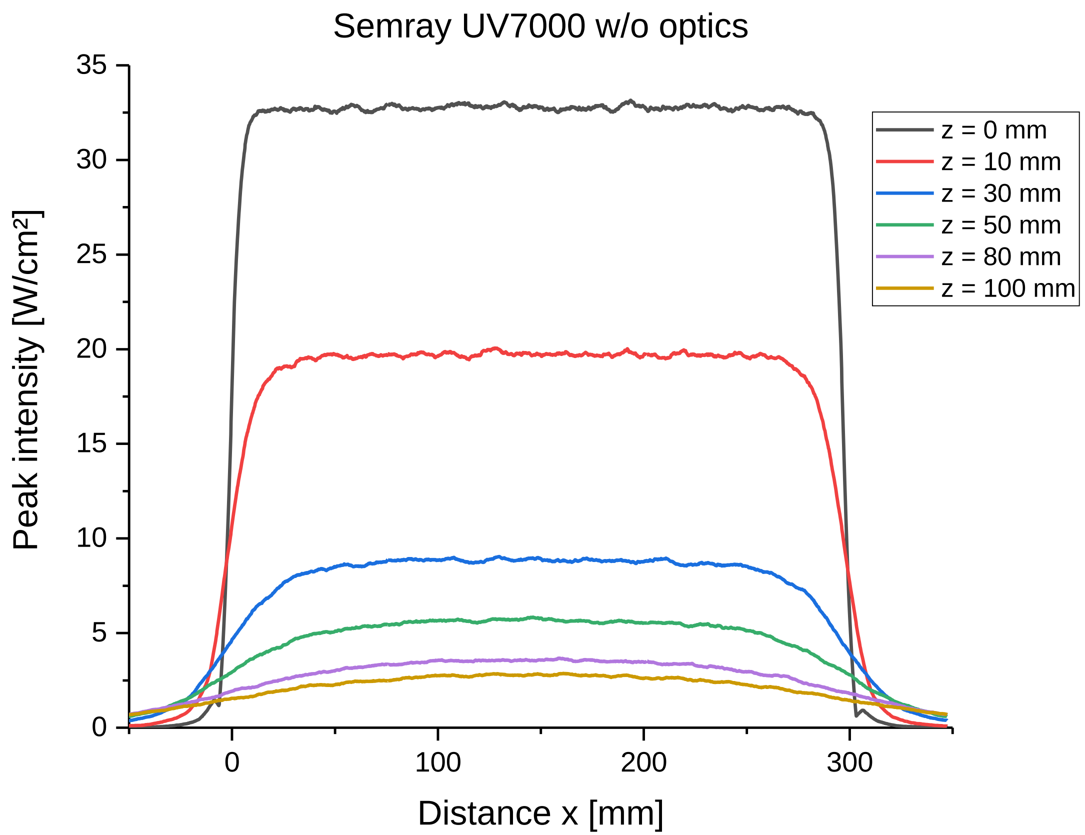
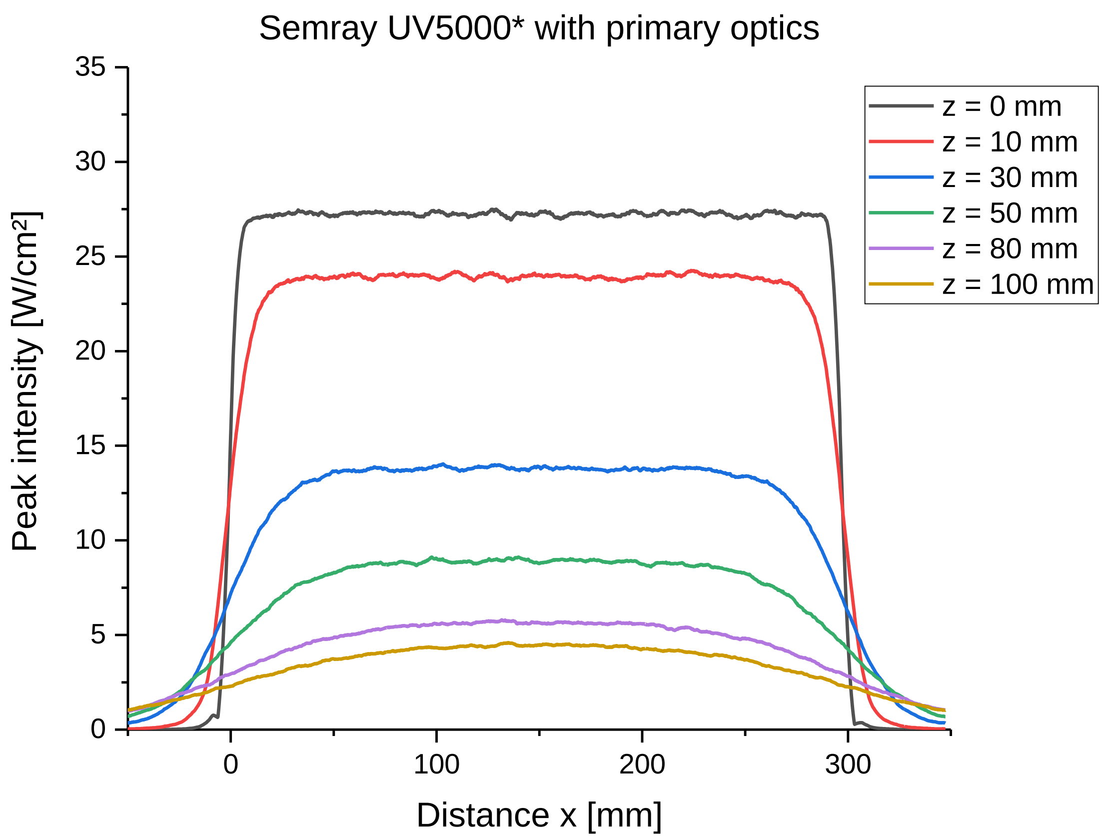
Semray UV7000 with primary optics

Peak intensity in x-direction for systems with and without primary optics



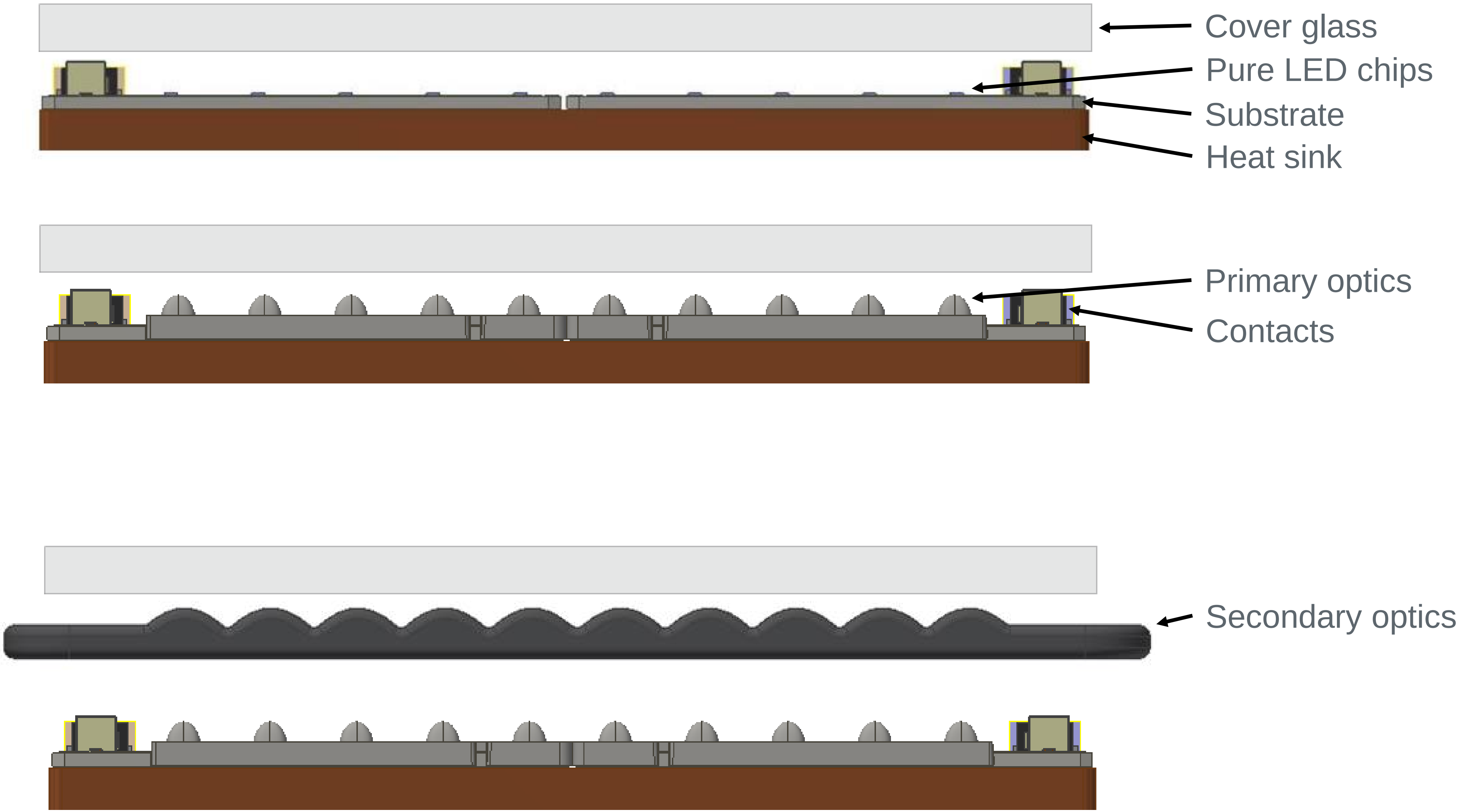


Results

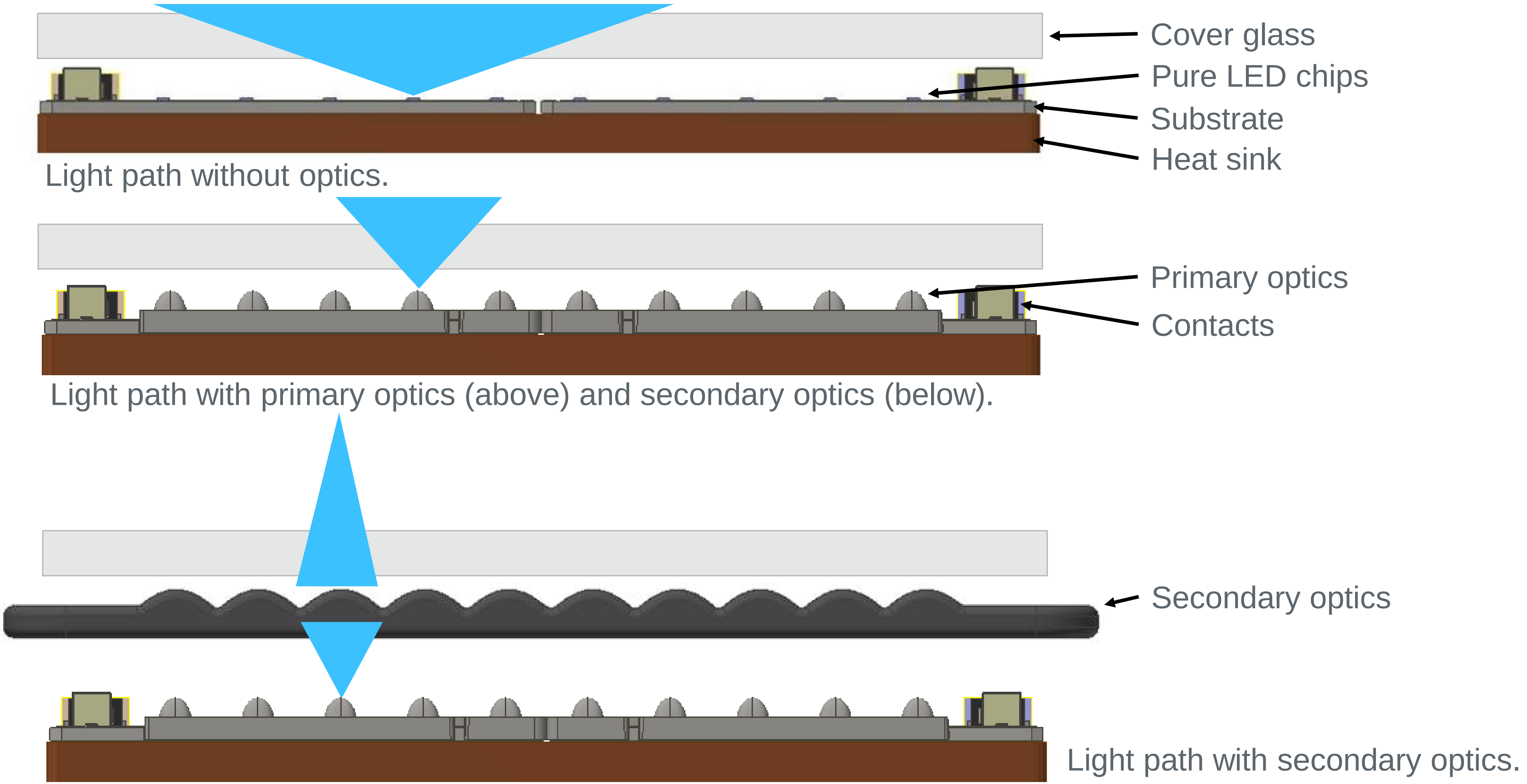
The uniformity is close to perfect for both systems. The peak intensity drops more quickly without primary optics again. The edge drop smoothens with increased distance in a similar fashion.

*The peak power is almost identical for UV5000 & UV7000, merely the width of the distribution along the y-axis and hence the contained energy differs significantly.

OPTIC CONCEPTS



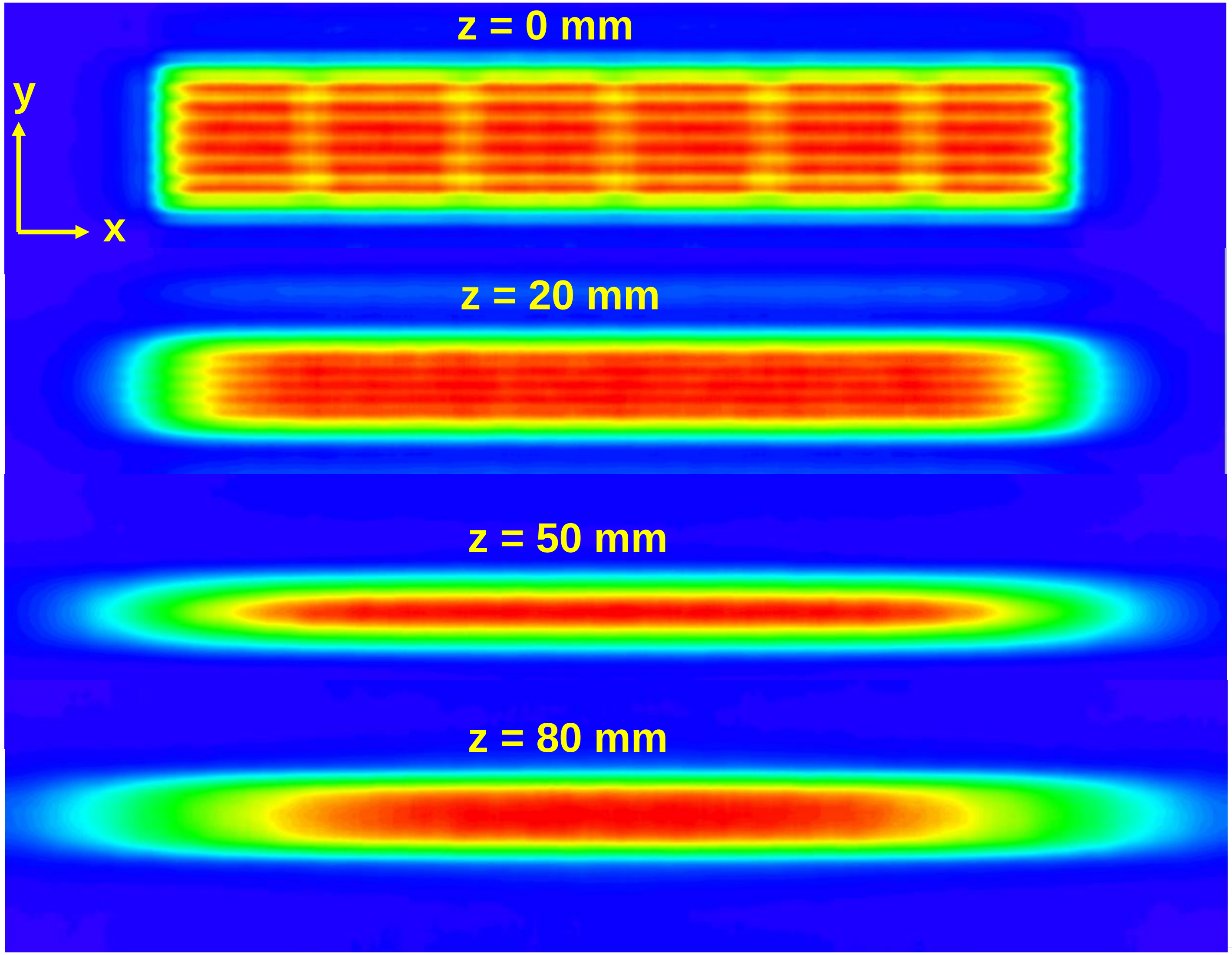
OPTIC CONCEPTS



SECONDARY OPTICS

Semray UV5000+ with secondary optics

Intensity distributions at different distances (z)



Effect of secondary optics
The primary optics focus the light onto the secondary optics, which in turn focus it at a given distance (here ~ 60 mm). Each row of LEDs itself is focusing at this distance, but peaks of the rows also converge.
As can be seen each row produces its own peak at z = 0 mm. At 50 mm all these peaks have converged into one combined peak. At 80 mm the combined peak begins to blur out again.
Optimization
The farther away the focal point of a lens, the larger the diameter of the lens has to be. The closer together the LED chips, the higher the light intensity. Thus an optimum has to be found for the spacing of the chips and the size of the corresponding lenses above them.

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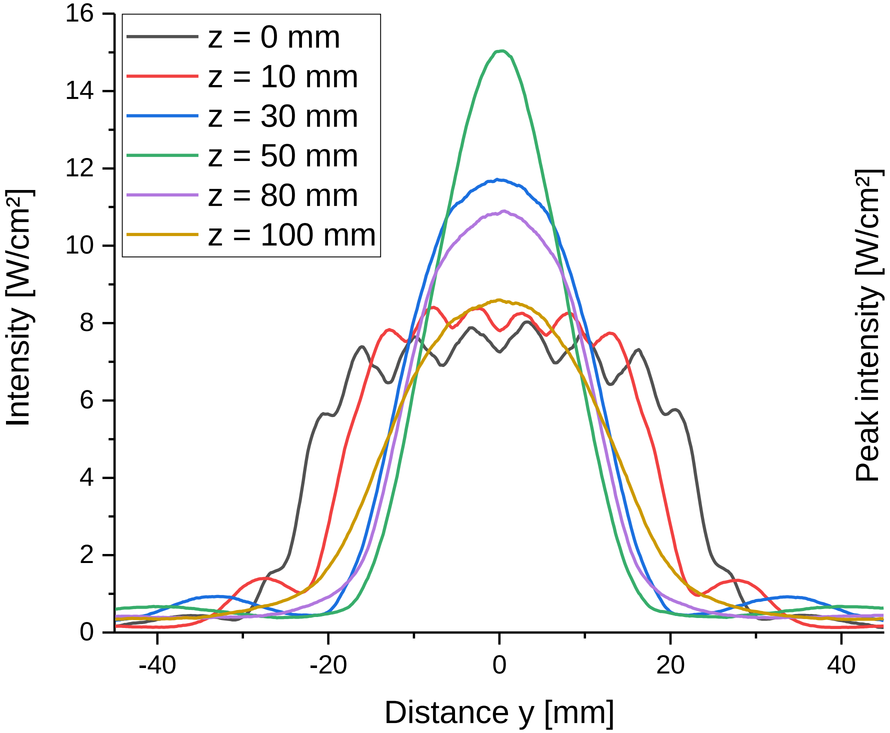
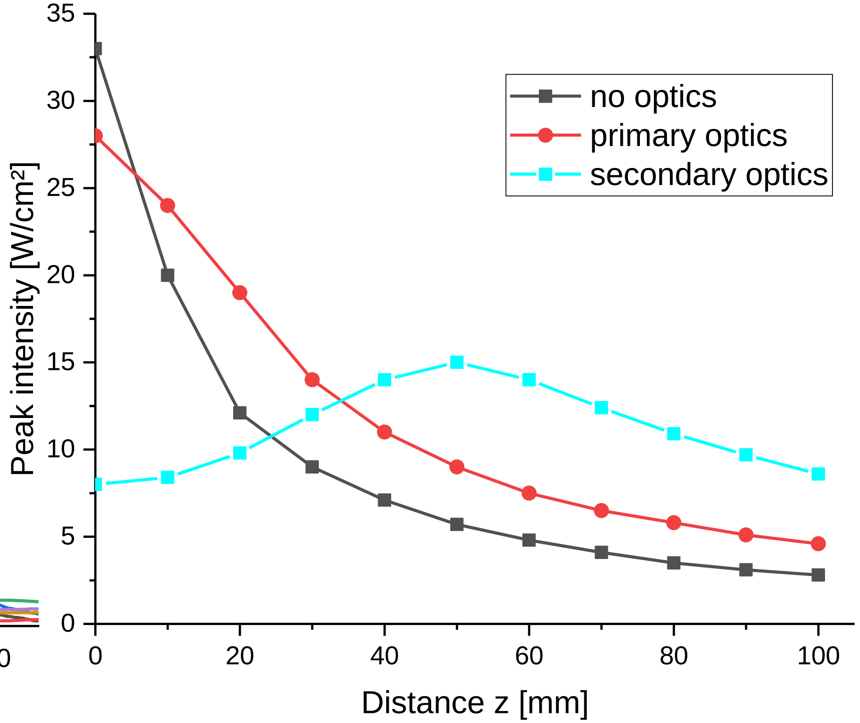
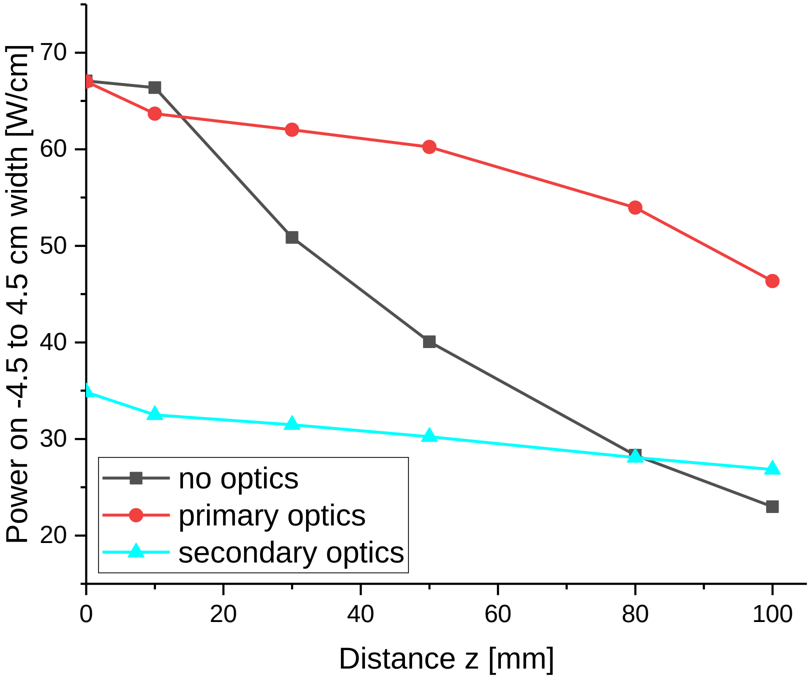
Semray UV5000+ with secondary optics

Peak intensity in y- and z-direction for systems with secondary optics







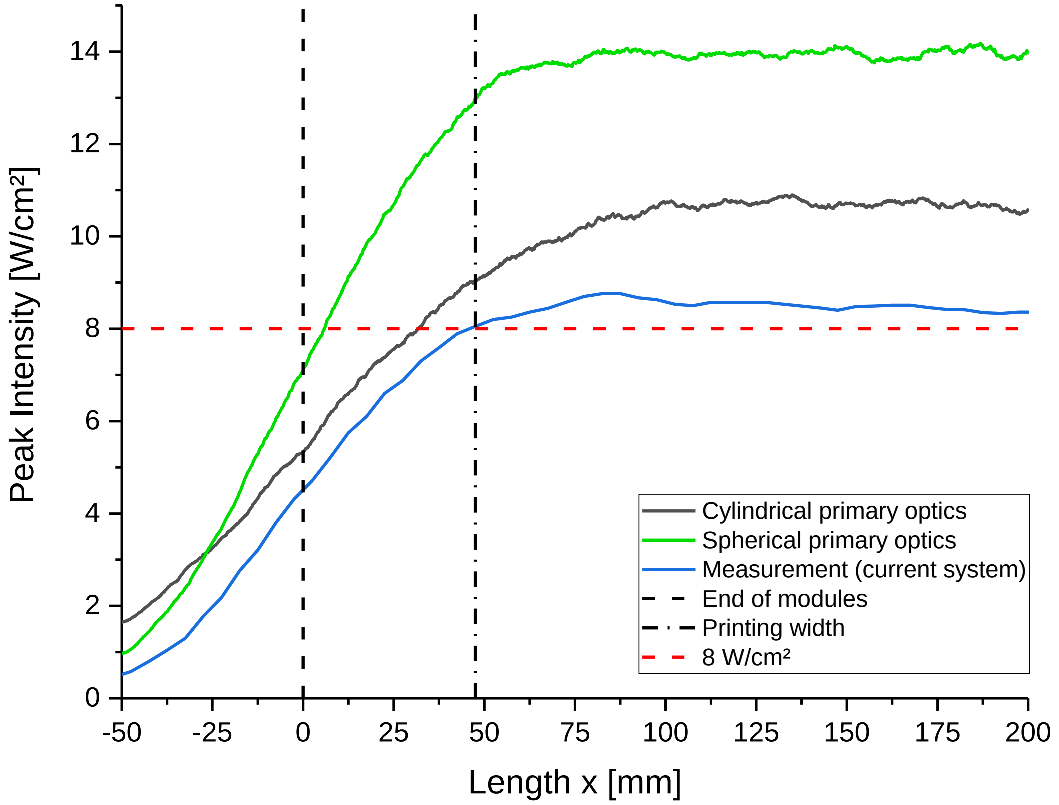
Effects of secondary optics

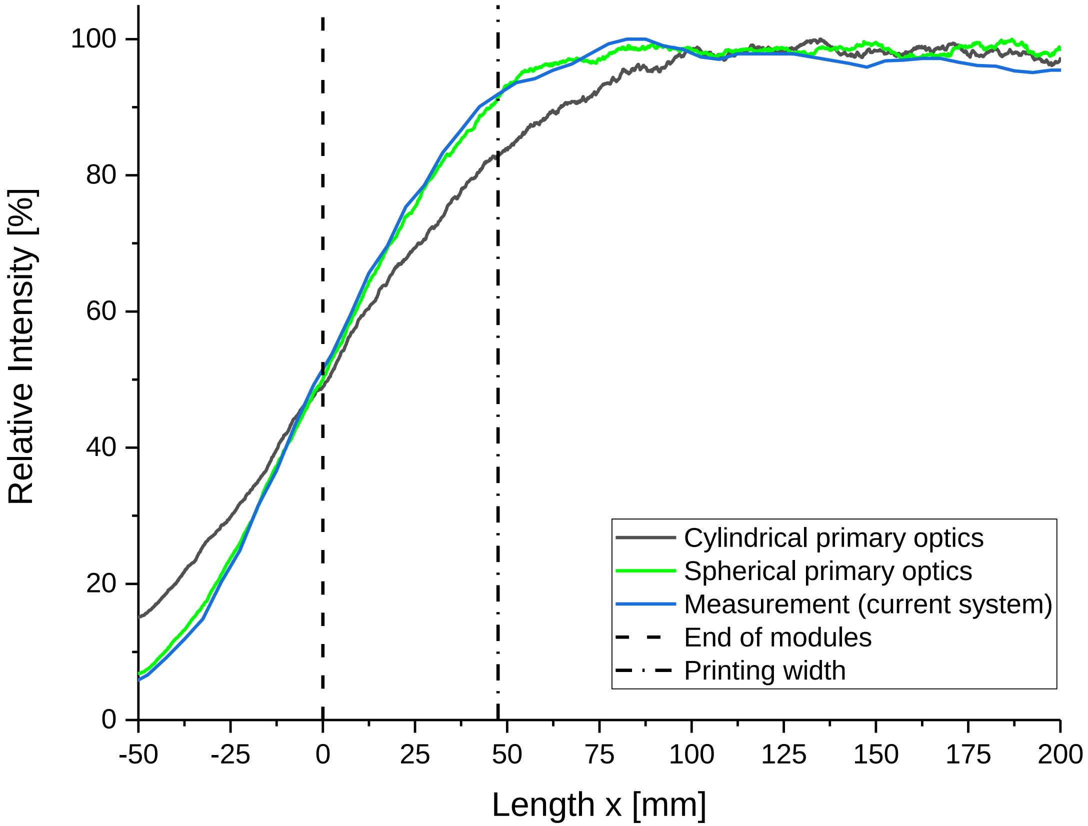
The intensity behaves completely different. At close distances there is no single, distinct peak, but multiple lower peaks. Hence the peak intensity increases with distance for a time until all peaks merge and the intensity begins to drop again. The delivered energy starts quite low, but remains almost constant with distance.

SECONDARY OPTICS

Semray UV5000+ with secondary optics

Edge behavior @ z = 8 cm: Intensity





Influence of primary optics on edge behavior

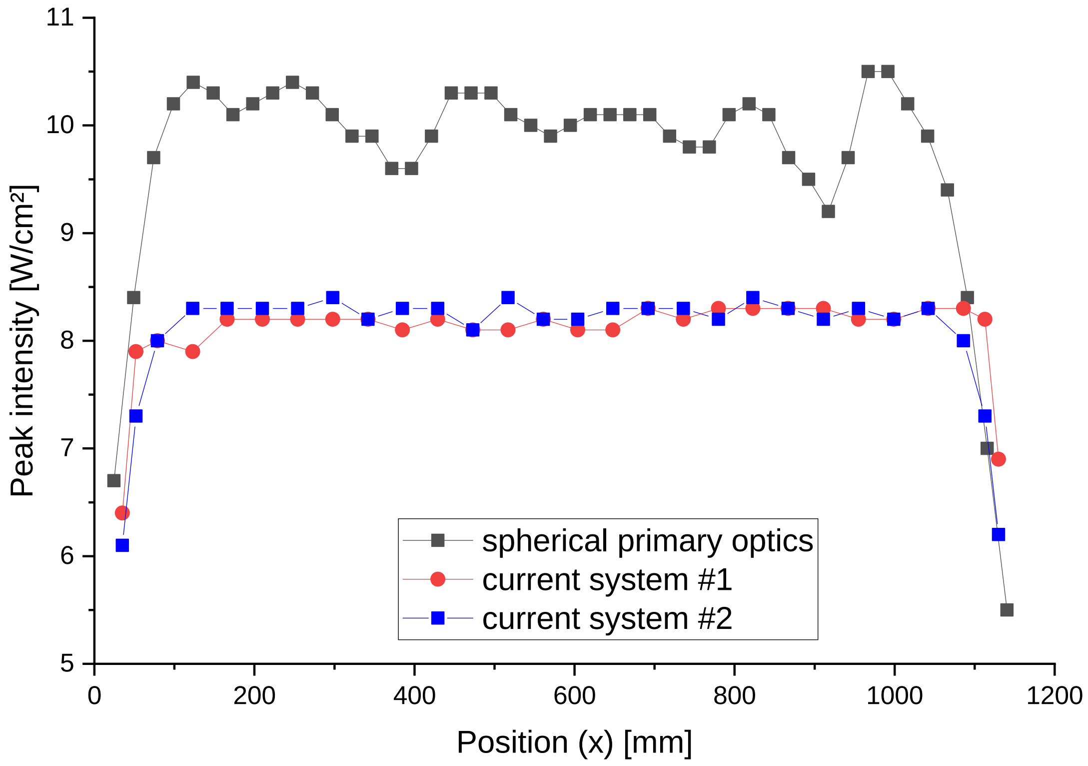
With cylindrical optics the intensity begins to drop 100 mm prior to the edge, while for spherical optics it declines at a much later point (~55 mm), but therefore more drastic. As can be seen when rescaling the graphs, our current system uses spherical optics, since the edge behavior is identical to UV5000+ with spherical optics.

→ Spherical optics reduce the required size of the lamp to reach a given printing width.

SECONDARY OPTICS

Semray UV5000+ with secondary optics (measured)

Edge behavior @ z = 8 cm: Intensity



Details

Comparison of peak intensity uniformity between two current systems and one UV5000+ prototype.

The current system show much lower peak power, but a higher uniformity.

Comparison UV5000+ vs. current system

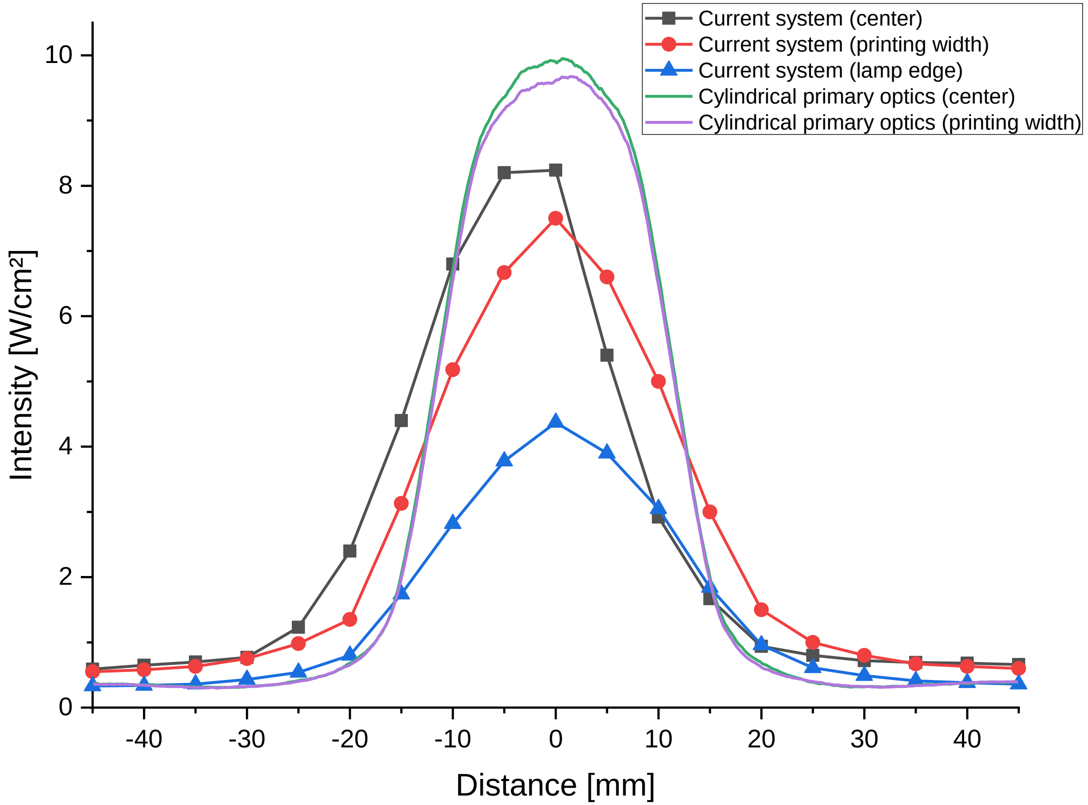
Current system ~ 8 +/- 0.2 W/cm² → UV5000+ ~ 10 +/- 0.5 W/cm²

The fluctuations of the UV5000+ prototype are still below usual offset printing requirements (+/- 10%), but will be reduced significantly in the future on the way to series production.

SECONDARY OPTICS

Semray UV5000+ with secondary optics

Edge behavior @ z = 8 cm: Energy



Details

Energy at different positions:

Current system, center ~ 24.2 W/cm

Current system, printing width ~ 23.7 W/cm

Cylindrical optics, center ~ 25.4 W/cm

Cylindrical optics, printing width ~ 24.8 W/cm

Integration from -4.5 to 4.5 cm.

Data for current system was measured, for UV5000+ simulated.

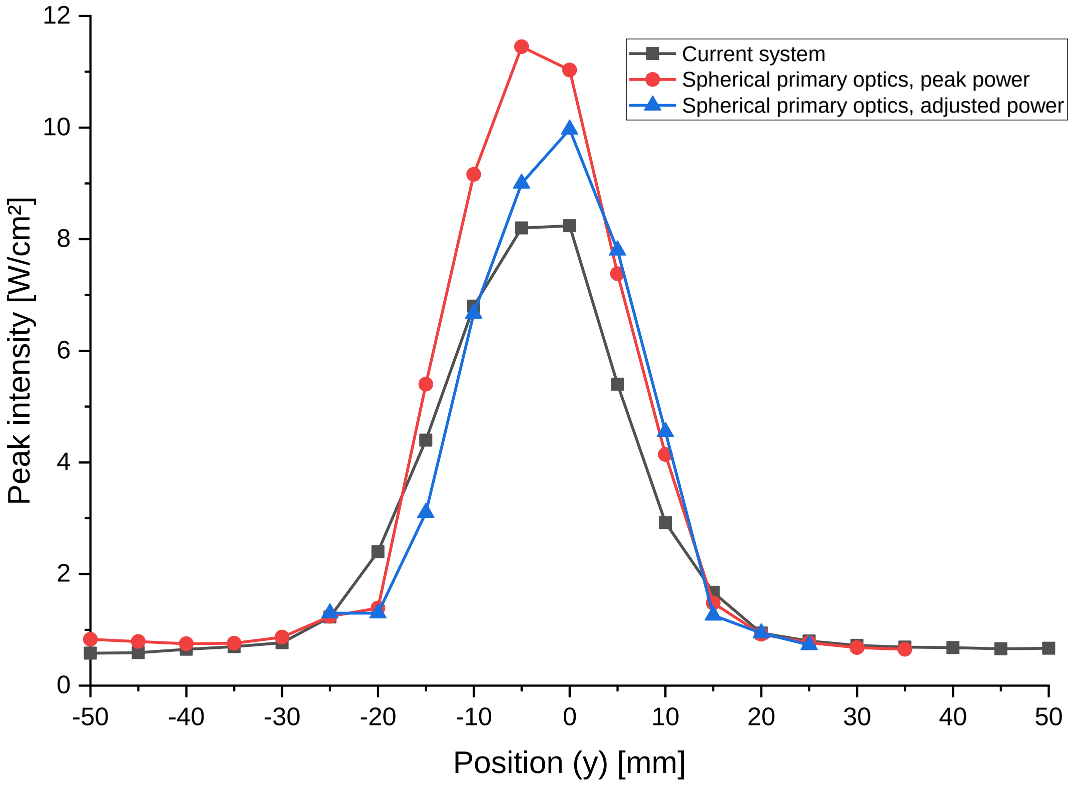
Results

The energy emitted by the system with cylindrical optics drops less between center and printing width and is generally higher than for our current system.

SECONDARY OPTICS

Semray UV5000+ with secondary optics (measured)

Edge behavior @ z = 8 cm: Energy



Details

Initial measurements of UV5000+ prototype vs. current system.

Peak power = maximum possible current.

Adjusted power = partially reduced current to improve uniformity.

All measurements in the center of the lamp.

Results

It was decided to produce the initial version of the new lamp with spherical primary optics after all due to the edge drop.
The results match the expectations in being significantly more powerful than the current lamp.

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THANK YOU FOR YOUR ATTENTION