

Lasers in Manufacturing Conference 2021

# Non-contact focus spot and focus shift measurement of high-power lasers in the manufacturing of differential gears

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## Abstract

The higher the power and energy density in the focus of the laser beam, the more efficient is the process in terms of traverse speed, hardness increase, deformation and other effects. Even a minimal focus shift or an imprecisely adjusted tool center point (TCP) shows extremely negative impact on the quality of the weld. Traditional measurement methods are too complex to capture the focus shift or to quickly check the focus position. The non-contact beam profiling technology developed by MKS Instruments eliminates limits in terms of power, and the measurement takes only seconds. Especially for 24/7 industrial use, the company developed Ophir® BeamWatch® Integrated laser measurement system, a fully automated, robust device with an easy-to-use operating interface.

Keywords: high power lasers; power density; focus shift; focus position; non-contact beam profiling;

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## 1. Introduction

Using laser systems in macro machining is common in today's automotive production sites and the number of applications is continuously growing. It is not only about welding car bodies, as bolts have been replaced by laser welds in the production of powertrains and differential gears. In all those industrial processes, high throughput rates are mandatory to enable economic manufacturing while at the same time, high product quality must be maintained, especially with safety relevant parts. Ensuring reliable laser parameters in the focus of the beam eliminates the "wasting" of valuable production time. This paper focuses on key parameters of laser beam measurement technologies and discusses fully automated, integrated solutions that enable the flexible measurement of different laser beams in one automated production cell.

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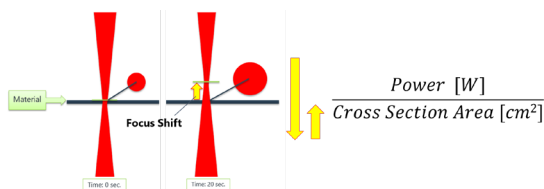
## 2. Why power density

Laser power and laser quality have significantly increased over the years, while cost of ownership and maintenance have generally decreased. However, lasers are made of physical matter and the beam delivery systems with multiple optics degrade over time or components may become contaminated. As a result, laser power at the focus decreases, the spot size changes, or the location of the focus spot drifts. To avoid the worst – production of bad parts or a slow and expensive process – it is crucial to measure the key parameters of the laser system such as:

- Laser Power
- Beam Diameter at Focus
- Focus location (X, Y, Z)
- Focus Shift / Focal Drift
- Beam Profile in Focus
- Divergence, M<sup>2</sup>, BPP, K
- Power Density

The last parameter – power density - is one of the most relevant measures that needs to be monitored at the work plane. Power density is calculated by dividing the power by the cross-section area of the focused beam and is expressed in “Watt per centimeter squared”. As soon as one measure changes, the laser interacts differently with the material and the process silently suffers; once a component within the beam delivery system degrades, there will be a loss in laser power at the work plane and thus the numerator of the equation decreases.

Even a stronger impact on the power density can be seen with thermal effects in the following example: An improperly cooled lens or a dirty protective window causes a thermal effect on the lens, the focus of the beam shifts and the diameter of the beam – which is squared in the denominator - triples. As a result, the power density at the work plane is divided by 70.



Example:	
<u>Without Focal Shift</u>	
Power: 100 W	
Cross Section Area: 0.3 cm <sup>2</sup>	
	$\frac{100 \text{ W}}{0.3 \text{ cm}^2} = 144 \text{ kW/cm}^2$
Diameter multiplied by 3	Power density divided by 70
<u>With Focal Shift</u>	
Power: 100 W	
Cross Section Area: 2.5 cm <sup>2</sup>	
	$\frac{100 \text{ W}}{2.5 \text{ cm}^2} = 2 \text{ kW/cm}^2$

Fig. 1: Relation between beam diameter and power density

As a higher power and energy density in the focus of the laser beam results in a higher process efficiency in terms of traverse speed, hardness increase, and less scrap, it becomes obvious why it is essential to measure laser beam parameters. Even a minimal focus shift or an imprecisely adjusted tool center point (TCP) shows extremely negative impact on the quality of the weld. With the focus position moving out of the desired position it can - depending on the parts geometry - either lead to weak joints or the destruction of parts under process.

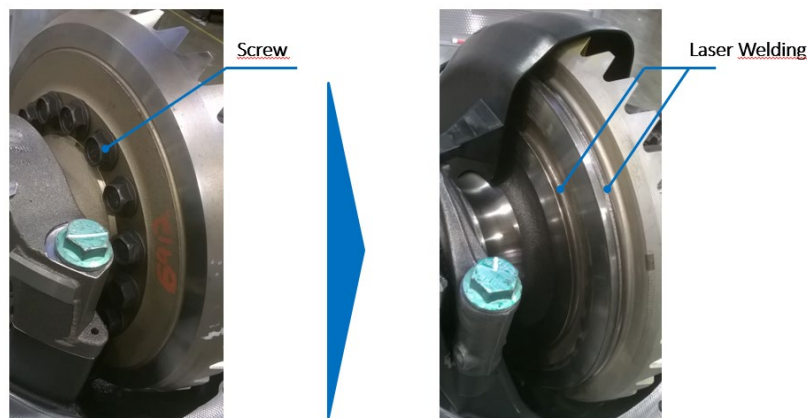


Fig. 2: Screws have been replaced by welds in the powertrain differential gear with Daimler Trucks

### 3. Which measurement strategy

Being fully aware of this impact is one thing. Applying this knowledge about laser systems to industrial production processes is another. In-situ laser measurement in processes such as differential gear manufacturing prove to be very challenging. Since bolts have been widely replaced by welds to save a significant percentage of weight for each part, laser processing enables smaller parts, cleaner surfaces and minimizes the time needed to rework parts. For once, the engineers had to design completely new welding machines to combine different materials and deliver high-end technical solutions. The complexity of a production cell may include multiple laser beam technologies such as welding with and without feeding wire. On the other hand, the production process itself should be optimized and digitized which – to a large extend – depends on the laser beam parameters that need to stay consistent to assure quality results. Based on the key findings about power density, the integrated measurement of the laser beams as part of the ongoing process control significantly gained relevance boiling down to three main challenges:

1. Quality – Thermal effects on the focal position should be detected
2. Time - Laser beam measurement was supposed to be performed within loading/unloading
3. Flexibility – One device to measure different types of laser beams used in one production cell

To gain all relevant laser beam parameters of the focused beam, the measurement process itself cannot be performed during the process, but needs to be performed during the loading and unloading of parts. In-process measurement during the application of the laser could only interpret secondary effects and would not necessarily avoid bad parts. By measuring between the cycles, the production of bad parts can be avoided.

### 4. What measurement technology

Traditional beam profiling methods are too slow to quickly check the focus position and to capture the focus shift. This is where the non-contact measurement of the laser beam enters the production floor. Non-contact beam profiling is based on the Rayleigh scattering, a physical property of light that describes the scattering of electromagnetic waves by particles that are smaller than the wavelength of the radiation. The

highly concentrated light around the laser's beam waist is scattered off nearby air molecules; this phenomenon is captured by a camera from the side using a telecentric lens. This technique allows for analysis of the laser's beam waist without ever touching the beam. The measurement technique itself needs no water cooling, has no moving parts, and there is no upper limit on the power of the laser to be analyzed. And, since the technology is camera-based, it provides data up to 15 times per second, allowing the laser technician to see more time-based characteristics of the laser system. In addition, specially-designed software provides size measurements of the laser focus (beam waist), the location of the focus over time, as well as other features. Thus, the user can measure and graph how much – and how quickly – the focus shifts, which in turn leads to better characterization of the laser system. In non-contact beam measurement, the camera coupled with the telecentric lens observes the laser's Rayleigh length, which besides the focused spot also encompasses the beam path above and below it. Developed by MKS, this beam profiling technology used in the Ophir BeamWatch laser measurement series eliminates limits in terms of power, and the measurement takes only seconds. Using the very accurate, integrated software, beam and beam-quality parameters can be calculated according to ISO 13694 and ISO 11146 standards, including – but not limited to – focus diameter, focus position, divergence, ellipticity,  $M^2$  (1/k) and beam parameter product (BBP).

## 5. How to integrate

While the non-contact measurement technology delivered a solution that ensures the quality of the laser beam including parameters such as the focal shift that is delivered to the workpiece, there was still the need to integrate the measurement solution into the production process without prolonging the production cycle. To achieve this goal on the hardware side, it needed to be combined with a power measurement that can measure high power beams up to 30 KW and function as a beam dump within the application. To enable the fully automated operation of the measurement in industrial product lines and to ensure all data can be stored, a network interface was a prerequisite. Summing up those findings, MKS took the non-contact measurement technology to the next level and developed Ophir BeamWatch Integrated. The integrated measurement device combines the non-contact measurement of the beam profile with a 10 KW power sensor (30 KW available on request) and adds industrial data interfaces such as Profinet, Ethernet/IP, CC-Link, GigE. As the measurement device is relatively compact it can be easily and permanently integrated in the production cell.

Additional flexibility is gained, as the non-contact measurement can accommodate many different laser types, power levels and welding head designs. The software can store up to ten different laser profiles to compare measurements to the target parameters established the process.

This functionality is extremely helpful, when it comes to the welding of differential gears and two laser processes need to be integrated in one production cell: The welding process using the wire needs a different laser beam than the one without it. To ensure the parameters of both laser beams are in spec within the process, the measurement device needs to be located in a part of the cell where it can be reached by both welding heads. This way, the laser beam measurement of both welding heads can be taken while loading and unloading the machine and cycle times are not affected at all.

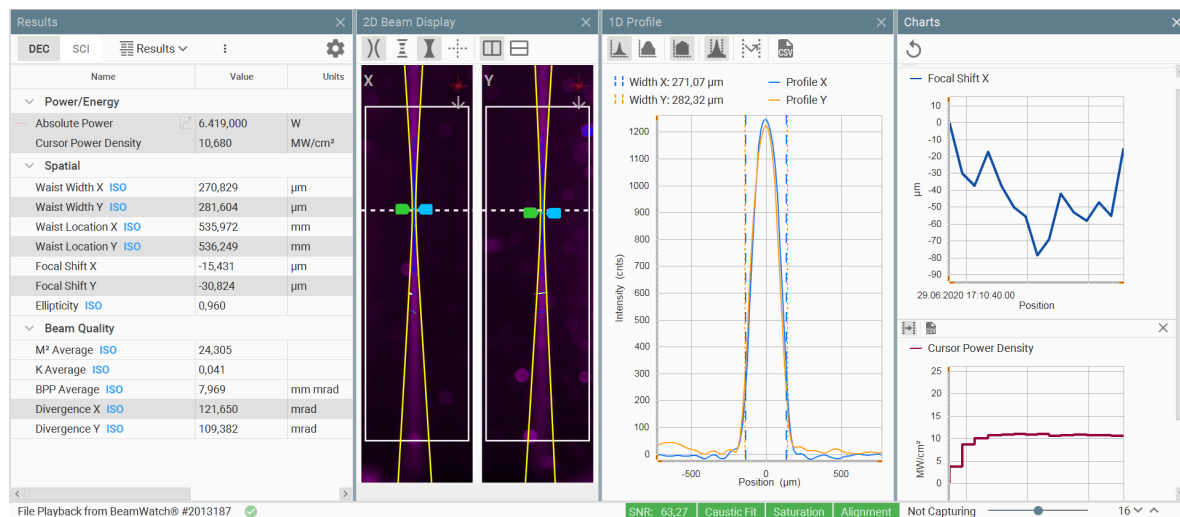


Fig. 3: BeamWatch Integrated Non-Contact Beam Profiling: Optic 1 at 6.5 kW for 15 seconds

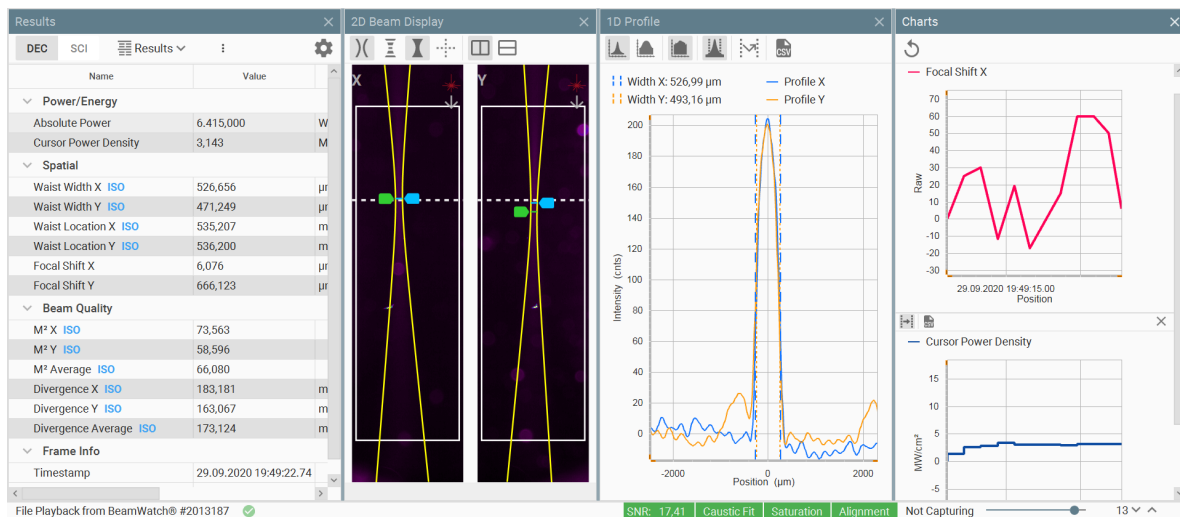


Fig. 4: BeamWatch Integrated Non-Contact Beam Profiling: Optic 2 at 6.5 kW for 15 seconds

Within seconds the measurement is done, and data is instantaneously transferred via Profinet (other industrial interfaces available). The system delivers all individual laser parameters and additionally flags the beam with an OK/NOK (good/bad) output that can be configured by the users based on the chosen limits for the parameters relevant to the process. When parameters drift, the user can be warned upfront and take corrective actions before bad parts are produced (for instance changing the protective cover glass when the focus shift exceeds a certain value). This way the measurement system also serves as a predictive maintenance tool. In addition, the systematically collected measurement data allows for trending and statistical analysis which help to better understand the effect of each parameter and significantly improves the predictability of the results.

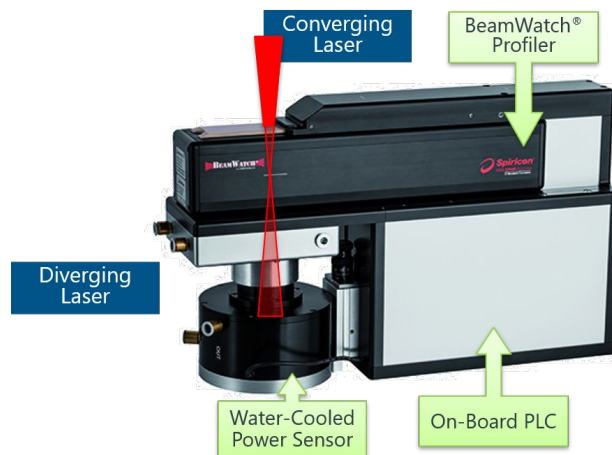


Fig. 5: Ophir BeamWatch Integrated combines different measurement technologies.

## 6. Conclusion

The quality and efficiency of automated laser welding processes is highly dependent on the laser beam at the working plane. In this paper, the production of differential gears serves as an example, but the case stays the same wherever expensive parts are welded in high throughput production and destructive part testing should be minimized. The only technology fast enough to reliably detect the focal shift is the non-contact laser beam measurement. By integrating the measurement technology in the production cell, the laser beams can be frequently monitored, and the production of bad parts can thus be avoided. The additional data collection pays off when it comes to the predictive maintenance of the laser welding systems.

## References

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