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Influence of the beam diameter on the resistance of laser guards to green laser radiation

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Abstract

To protect operators from laser radiation, laser machines must have a protective enclosure. The requirements for laser protective shielding are defined in the current standard EN 60825-4. According to this, extensive case-related laser stability tests must be carried out on the protective material. These case-related tests make it difficult to compare and select suitable materials and thus considerably increase the effort for manufacturers. Therefore, the SALSA project is taking a different approach: The influence of the beam diameter and the irradiance on the laser resistance of common protection materials is systematically investigated and the relationships found are expressed in simple mathematical formulas. This should enable manufacturers to use exemplary laser stability measurements to extrapolate service lifetimes for any operating conditions. The study describes the relationships found using green laser radiation, since laser radiation in the visible wavelength range is currently of particular importance for applications in e-mobility.

Keywords: laser safety; machine safety; laser guards; laser resistance; beam diameter dependence

1. Introduction

Currently, there are two European standards that define the requirements for laser guards. EN 12254 addresses the standardisation and testing of laser guards using a beam diameter of 1.0 mm. Although not intended for machine enclosure protection, it is frequently applied in practice by manufacturers and certifiers for that purpose. In contrast, EN 60825-4 pertains to application-specific guards used as protective equipment for machinery. It involves complex, case-dependent testing procedures, which has limited its practical adoption.

Under realistic operating conditions, laser faults often result in beam diameters significantly larger than 1.0 mm impacting the guard. Consequently, the application of EN 12254 in such scenarios is not permissible. However, the results of the BAuA project F 2335 by Urmoneit et al., 2015 and 2016 demonstrate that the laser beam diameter exerts a substantial influence on the resistance of filter materials. Since the same and similar filter materials are also used for cabin windows, a corresponding correlation is likely.

The objective of the SALSA research project is to investigate the influence of the beam diameter on the laser resistance of commonly used protective materials. It also aims to describe the relationships between irradiance, which leads to failure of the guard after a specified time and beam diameter using mathematical descriptions that are as fundamental as possible and may be material-dependent. To ensure the comparability of test results, a standardized testing box was developed and constructed within the scope of this project by Zirkelbach, 2023, Schadow, 2023 and Büttner, 2024. The design prioritises simplicity and accessibility by utilizing readily available materials and measurement technologies to facilitate replication and global adoption by testing laboratories and manufacturers. The results of the project aim to enable the prediction of a critical power density or more precisely, a critical irradiance for any application, i.e. for any beam diameter, thereby eliminating the

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need for case specific testing. The insights gained will support the further refinement and enhancement of testing standards EN 60825-4 and EN 12254.

The SALSA project encompasses the testing of various product groups and materials at different laser wavelengths. The use of various testing lasers in the visible (VIS) and near-infrared (NIR) spectral ranges is essential for the successful implementation of this project. Extensive investigations have been carried out over the past three years in the NIR range at a laser wavelength of 1030 nm and 1070 nm. These investigations have been published in part by Alam et al., 2024 and List et al., 2025. The present study investigates the influence of beam diameter on laser resistance using green laser radiation at a wavelength of 515 nm. This wavelength is currently of growing significance for applications in e-mobility.

2. Experimental Setup

Three laser guards made of special plastics were used to systematically investigate the resistance to green laser radiation. These laser protective shielding materials are based on polymethyl methacrylate (PMMA). The PMMA1 laser safety filter is available in 3 mm and 6 mm thicknesses, with an identical chemical composition. Another laser guard made of 6 mm thick mineral glass was also tested. An overview of the tested laser safety products can be found in Table 1.

Table 1. An overview of laser guards that were tested using green laser radiation (515 nm).

Laser guard	Material	Plate thickness
PMMA1 3-mm	PMMA	3 mm
PMMA1 6-mm	PMMA	6 mm
PMMA2 3-mm	PMMA	3 mm
GLASS 6-mm	Mineral glass	6 mm

A frequency-doubled disc laser TRUMPF TruDisk 3022 operating at a wavelength of 515 nm was used in continuous wave mode for the investigation of laser resistance. The beam caustics were determined using a Primes FocusMonitor FM+, and the focus distances required to obtain the desired beam diameters were verified using pinhole apertures in accordance with ISO 11146-1. This procedure was repeated at different laser powers to account for the focus shift, i.e. the power-dependent drift of the beam waist. This method enabled systematic laser exposure tests to be carried out with a beam diameter d_{86} of 1 mm to 100 mm using green laser radiation. The experimental setup is shown in Fig. 1 (a).

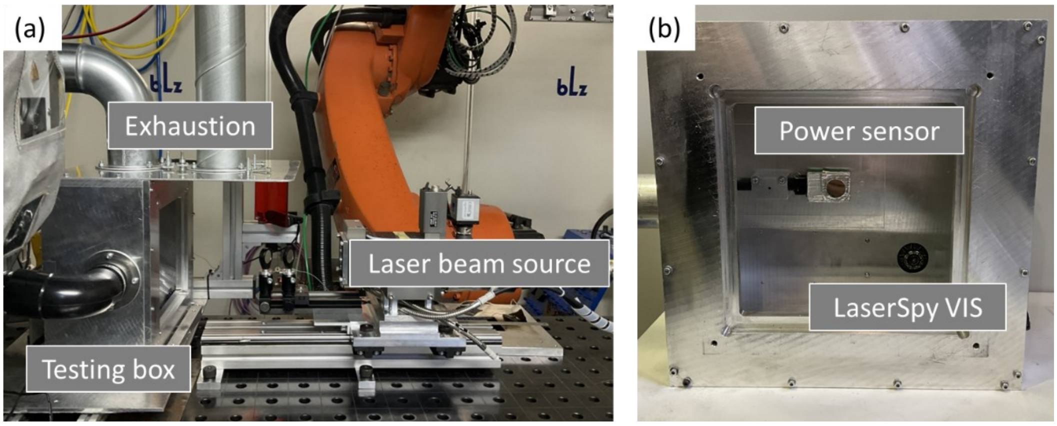

Fig.1 (a): Testing box in the experimental setup for performing systematic laser exposure tests at a wavelength of 515 nm. The testing box is connected to a defined exhaustion. (b) The LaserSpy VIS is integrated into the rear wall of the testing box. A power sensor PD300-3W is used for continuous power measurement.

A standardised laser test stand, referred to as the testing box, was utilised for all laser exposure tests. The initial version of the testing box was developed and used by Zirkelbach, 2023 and Schadow, 2023. Bühring, 2024 and Büttner, 2024 developed an optimised version incorporating a power sensor for laser exposure tests at 1030 nm. For this study, the LaserSpy Sensor Standard 4.0 (NIR) was replaced with a LaserSpy VIS by Werth, 2025, which is suitable for the visible spectrum. The version of the testing box with a LaserSpy VIS can also be connected to a defined exhaust system, see Fig. 1 (a). A LaserSpy VIS was mounted off-centre to the beam axis on the rear wall of the testing box, see Fig. 1 (b). It was integrated into the laser safety circuit and modified to ensure that the laser beam would switch off before the power sensor PD300-W could be damaged. This sensor, positioned centrally along the beam axis, was used to measure laser power throughout the test duration, as shown in Fig. 1(b). The sample size of the laser guards was chosen such that the edge length of the plates was at least three times the test beam diameter d_{86}. As specified in EN 60825-4, six samples were tested for each beam diameter.

In accordance with the testing standards, the resistance time was set at 100 s and then multiplied by a safety factor of 1.5, resulting in a required average resistance time of 150 s. In all laser exposure tests, the resistance time of the laser guards was defined as the interval from laser activation (Laser switch on) to the point at which the failure criterion is exceeded. For shoot-through detection, the failure criterion is based on visible laser radiation of class 2 laser, with a time base of 0.25 s. According to TROS Laser Radiation, this corresponds to a laser power of 1 mW at a wavelength of 515 nm.

3. Results

Laser exposure tests were conducted using a laser operating at a wavelength of 515 nm and a beam diameter ranging from 1 mm to 100 mm on the laser guard. In his bachelor's thesis 2025, Werth examined the laser guard PMMA1 in two different material thicknesses as well as a glass filter. In addition, a further laser guard, referred to as PMMA2, was also characterised for this study. Fig. 2 presents representative samples of laser guards tested with a beam diameter d_{86} of 50 mm.

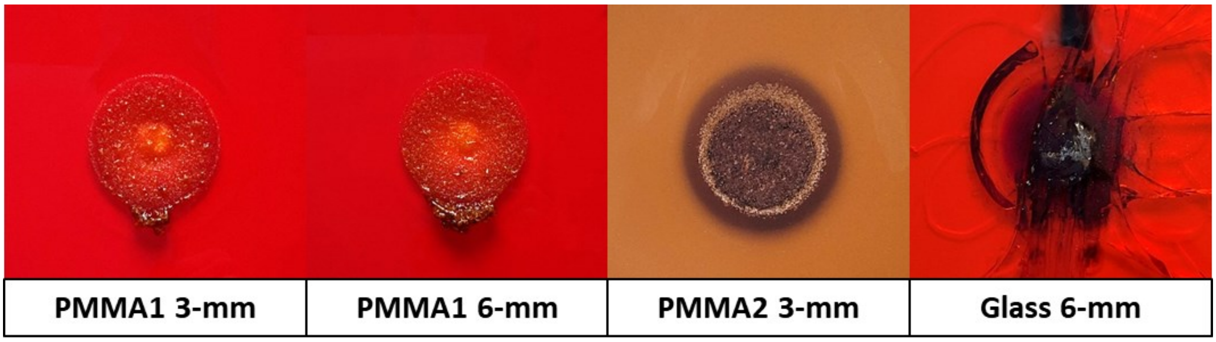

Fig. 2. Examples of laser guards tested with a beam diameter d_{86} of 50 mm at a laser wavelength of 515 nm and a required average resistance time of 150 s.

Fig. 3 illustrates the measured laser powers and the corresponding power densities for the four laser guards across the full range of investigated beam diameters. The glass filter significantly outperforms the PMMA filters. The influence of material thickness is evident in the PMMA1 filter. The PMMA filters with a thickness of 3 mm exhibit minimal variation in performance.

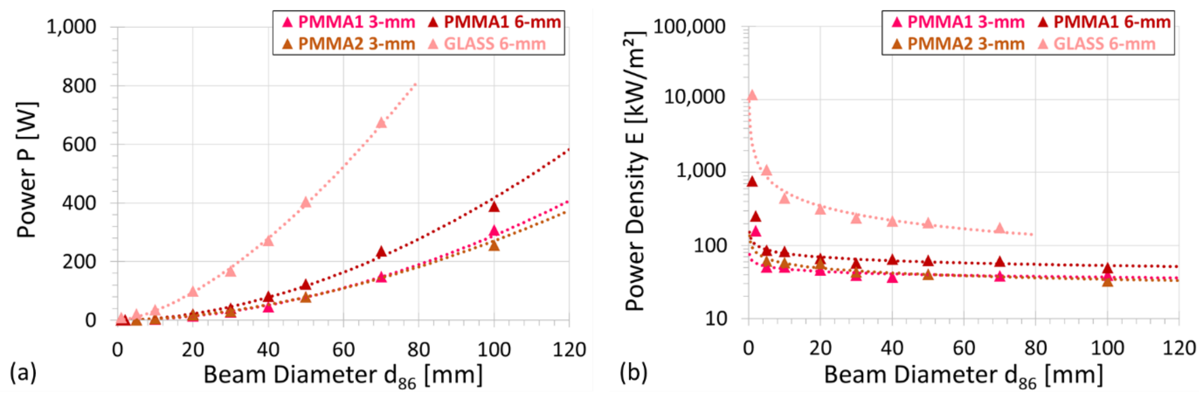

Fig. 3. Measured laser power (a) and power density (b) as a function of beam diameter, for an average resistance time of 150 seconds at a laser wavelength of 515 nm. The glass filter is clearly superior to the PMMA filters.

For all materials, specifying a constant resistance time of 150 s allows the dependence of laser power P on beam diameter d_{86} to be well approximated by a power function with a positive exponent, as shown below:

$$P(d_{86}) = a \cdot d_{86}^{b} \tag{1}$$

The relevant standards use power density when designing laser guards. For all materials, the relationship between power density or more specifically irradiance E and beam diameter d_{86} at a resistance time of 150 s explicitly follows a power law with a negative exponent of the form shown below:

$$E(d_{86}) = a \cdot d_{86}^{-b} \tag{2}$$

The differences in the materials could be defined by the material-specific parameters, the coefficient 'a' and the exponent 'b'.

4. Discussion

The PMMA filters in Fig. 3 (b) show only a slight dependence of the power density on the beam diameter d_{86} in the range from 5 to 100 mm. This observation suggests that the dominant damage mechanism is material vaporisation, which occurs after sufficient thermal energy has been absorbed. The onset of vaporisation depends on the material and occurs at a certain power density. The minimal decrease in power density with increasing beam diameter indicates that thermal conduction within the filter material plays a relatively minor role. Unlike the circumference C of a circular beam, which increases linearly with radius, the irradiated area A increases quadratically, see Fig. 4. This leads to greater heat accumulation within the laser spot on the laser guard. Material vaporisation and blister formation are clearly visible. According to Braunreuther, 2014 and Lugauer, 2015, vaporisation initiates at a temperature that is specific to the material's properties. Further increases in power density values do not exceed this temperature. Therefore, a minimum power density value is sufficient to initiate vaporisation. However, at small beam diameters, thermal conduction becomes the determining factor, enabling significantly higher power densities to be achieved. Due to the favourable area-to-circumference ratio of the laser spot on the guard, the introduced thermal energy can be efficiently dissipated into the surrounding material volume.

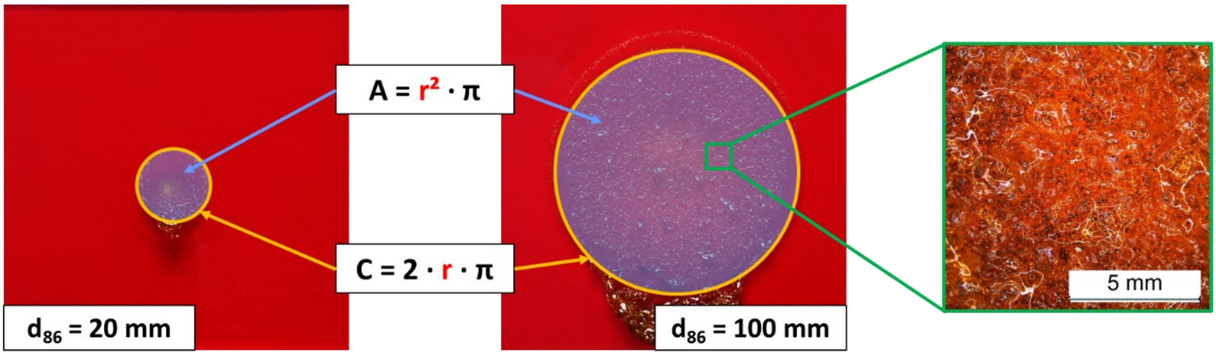

Fig. 4. As the radius of the laser beam increases, the irradiated area A grows more rapidly than the circumference C, leading to increased heat accumulation that promotes material vaporisation. Blister formation resulting from this process can be observed under a light microscope.

As illustrated in Fig. 3 (b), the mineral glass filter exhibits a significantly stronger dependence of the power density on the beam diameter d_{86}. This behaviour is attributed to the inherently higher thermal conductivity and melting temperature of glass compared to PMMA. Consequently, material vaporisation plays a minimal role, and thermal conduction becomes the dominant mechanism. As a result, there is a continuous decrease in the measured power density as the beam diameter increases.

5. Conclusion

This study presents the results of laser exposure tests using green laser radiation, conducted using a standardised testing box. Four filter materials made of PMMA and mineral glass were systematically examined. The results demonstrates that the resistance of the laser guards against the laser radiation decreases with increasing beam diameter. This dependence can be effectively approximated using power laws.

The results were presented to the working groups responsible for revising EN 60825-4 and EN 12254 standards, and will be incorporated into the revisions. In future, these revised standards will incorporate the use of the standardized testing box, along with detailed construction guidelines. Determining the power density, or more specifically the irradiance, for a given beam diameter enables extrapolation to other irradiance values. List, 2025 has already demonstrated this approach for plastic and glass filter materials, independent of material type for a laser wavelength of 1030 nm. The introduction of a material-independent correction function and a safety factor will reliably take the dependence of irradiance on beam diameter into account for many filter materials in the respective test standards. This advancement has the potential to reduce the need for individual case-specific tests, thereby improving the safety, practicality, and cost-efficiency of laser protection systems.

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