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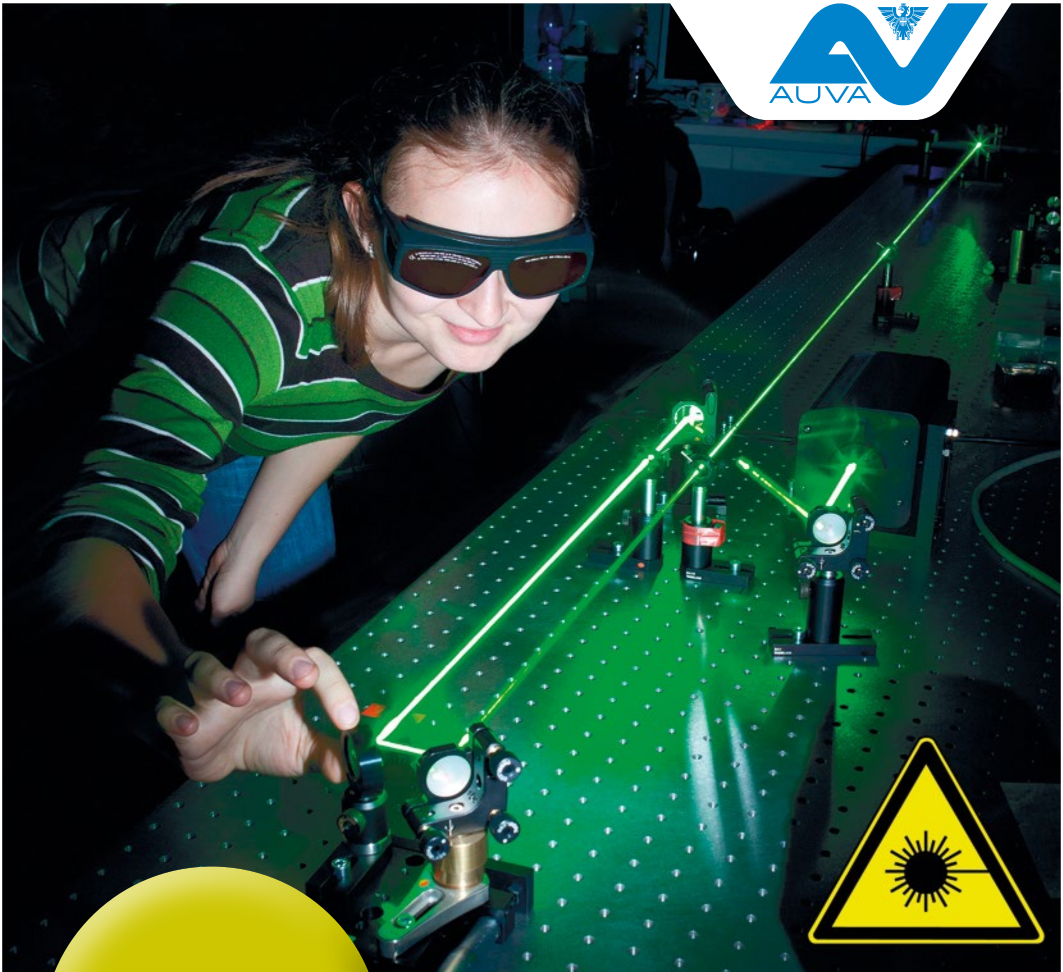

English Version
2017

Basic Laser Safety

www.auva.at

Copy Deadline: 01. February 2017
Edition: July 2017

Content

1 Preliminary remarks

The present text is the English version of the AUVA-leaflet M 080 “Grundlagen der Lasersicherheit”. Both leaflets are available electronically at www.auva.at/merkblaetter. It is aimed at institutions with numerous foreign employees and researchers, and explains laser safety rules in general and the specific Austrian laws for occupational safety and health when using lasers in the workplace.

Laser radiation that affects the eyes may cause cataracts or damage to the retina and cornea. Damage to the retina is irreversible and may result in permanent blindness. The skin is less vulnerable to radiation than the eye. Therefore, only high-powered lasers typically cause damage to the skin and in this case, skin burns are the most common injuries suffered.

When it comes to lasers of a certain power, proper protective measures are essential. Intensive training is a prerequisite for the safe use of lasers, especially if the user may be endangered as a result of laser-radiation exposure during their work.

The leaflet at hand is applicable to all laser uses and should serve to make you aware of the properties, effects, and hazards of laser radiation. Moreover, this manual describes practically tested general protective measures necessary for many laser applications in order to fulfil the legal requirements of occupational health and safety. The VOPST (Verordnung für optische Strahlung: Ordinance on Optical Radiation) demands a risk assessment and protective measures based on this assessment. The exposure limits must be adhered to in accordance with the VOPST. When it comes to laser radiation, the laser class (which must be cited on the device) can be used to evaluate a potential hazard.

Usage-specific hazards, as well as the resulting appropriate protective measures, are described in AUVA leaflets (e.g. M 140 – Lasersicherheit in der Medizin (Safety of Lasers for Medical Purposes), see list below). Evaluation aids may be found at www.eval.at.

Note: The limits for eye or skin exposure to radiation outlined in VOPST from 2010 are referred to as “exposure limits” (Expositionsgrenzwerte), abbreviated here as EGW. In the laser standards manual EN 60825-1, the values are referred to as “MPE-values” (Maximum Permissible Exposures), here MZB values. The numerical data should, in theory, be identical because both standards are derived from the ICNIRP limits.

This, however, is not necessarily the case, especially following revisions. Therefore, should there be a discrepancy between exposure limits, i.e. between "EGWs" from VOPST and "MZB" values stated in EN 60825-1, the exposure limits from VOPST should be used.

Supplementary documents (for additional standards and documents, please see section 12)

- VOPST, Verordnung optische Strahlung (Ordinance on Optical Radiation)
- The ZAI manual regarding Künstliche optische Strahlung; Evaluierung der biologischen Gefahren von Lampen und Lasern ("Artificial optical radiation: Evaluation of the biological hazards of lamps and lasers") are valid for all documents
- ÖNORM S1100-1 Laserschutzbeauftragter – Teil 1: Verantwortlichkeiten und Zuständigkeiten (Laser Protection Officer – Part 1: Responsible individuals and responsibilities)
- DIN EN 60825 supplement 14, 2006 (German translation IEC TR 60825-14: 2004); currently not published as ÖNORM
- AUVA leaflet M 140 Medizinische Anwendung des Lasers (Lasers for Medical Purposes)
- AUVA leaflet M 081 Lasersicherheit bei optischem Richtfunk (Laser Safety for Optical Directional Radio)
- AUVA leaflet M 082 Lasersicherheit bei Lichtwellenleiterkommunikationssystemen (Laser Safety for Optical Fibre Communication Systems)
- AUVA leaflet M 087 Sicherheit bei der Lasermaterialbearbeitung (Safety for Laser Material Processing)
- AUVA leaflet M 088 Sicherheit bei handgeführten Laserbearbeitungsgeräten (Safety with Handheld Laser Processing Devices)

2 Introduction

The word "LASER" is an acronym, which stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.

When we talk about "light," we are really talking about infrared (IR), visible (VIS), and ultraviolet (UV) optical radiation. The use of the term "light" is rather incorrect here, because this term should be reserved for light we can see. To simplify the explanation, however, this term will nevertheless be used in this manual to describe light from the UV and IR ranges of the spectrum as well. Lasers exist in all three spectral ranges. Lasers, however, not only differ in wavelength, but also in the power of the light they emit and the manner in which they emit this power. Wavelengths, light power, and operating mode are the three factors that determine a laser's area of application.

The continual advancement of laser technology and the materials used has given rise to lasers as finely scalable sources of energy enabling wide-ranging laser applications.

Production technology	Cutting, engraving, welding, ...
Medicine	Laser surgery, laser acupuncture, ...
Entertainment	CD players, laser shows, laser displays, ...
Measurement technology	Measurement, spectral analysis, ...
Trade and industry	Laser printers, laser scanners, ...
Traffic	Flight warning systems, distance measurements, ...
Communication	Telephone systems, free-space optical communication, …

3 What is light?

3.1 The electromagnetic spectrum

From a physical perspective, light is an electromagnetic wave characterised by its wavelength. A wavelength is the distance between two maxima of wave. It is abbreviated with the Greek letter lambda (λ) and is denoted in units of nanometre (nm)[1].

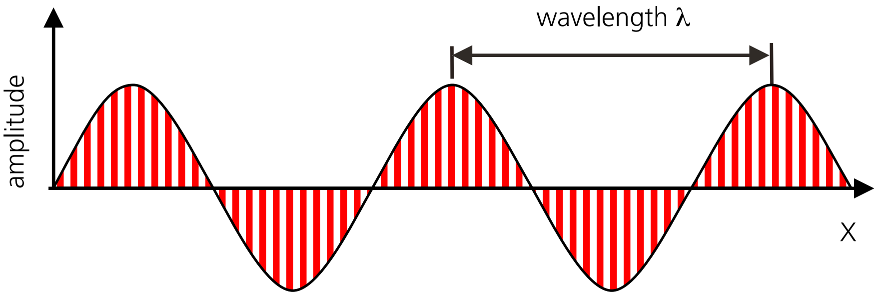

Fig. 1: An electromagnetic wave is composed of the combination of electric and magnetic waves. Electric waves are used as a reference quantity, which explains why only the sinusoidal electrical wave is plotted in the diagram.

If all wavelengths are represented on an axis, the result is the so-called electromagnetic spectrum (see fig. 2). The radiation of various wavelength ranges has different properties. These properties determine the usability as well as the effect on the human body. Radio waves, for example, can penetrate the human body without causing damage, whereas microwaves enter the body and cause an increase in temperature. Human beings can only perceive a very small part of the electromagnetic spectrum as visible light: The range from roughly 400 nm to 700 nm – see Appendix A. The various wavelengths of visible light are perceived as colours.

[1] 1 Nanometer = 10^{-9} m = 0,000 000 001 m.

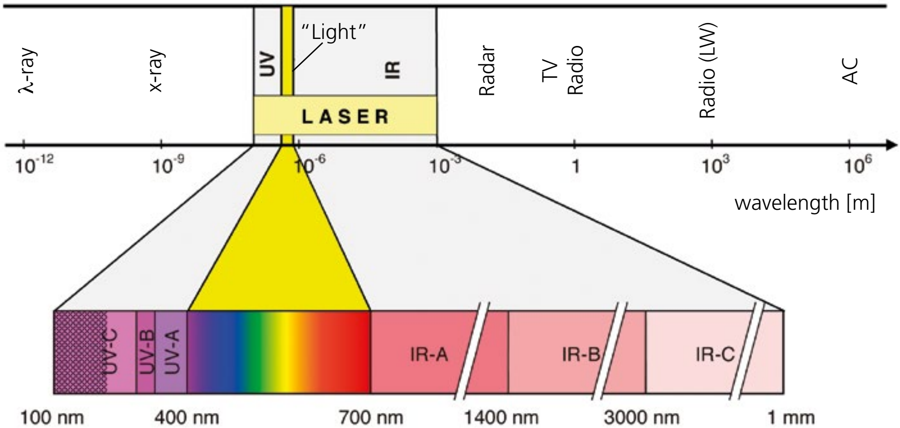

Fig. 2: The electromagnetic spectrum

The so-called "optical spectral range" is composed of ultraviolet radiation (UV), visible light, as well as infrared radiation (IR) and extends from 100 nm to 1 mm. This range is highlighted in fig. 2 because laser beams exist in each of these ranges.

3.2 Characteristics of laser beams

Wavelength

One characteristic of laser beams is that the beam itself only exhibits one single wavelength. Therefore, laser light has only one colour; it is monochromatic. Laser material and configuration/adjustment are two factors that determine which of the possible wavelengths a laser actually exhibits[2]. In contrast, every other light source emits "broad spectrum" beams, containing many wavelengths.

[2] There are exceptions, for example, of white-light (multi-light) lasers or Argon-Ion lasers emitting beams with numerous wavelengths at the same time.

Propagation

Every source of light, with the exception of lasers, disperses light in all directions. See fig. 3. Laser light, on the other hand, is emitted in a single direction, which is why it is referred to as "bundled" or "collimated" light. Even several metres distance from an exit aperture, a well-collimated laser beam will have lost hardly any of its intensity. This characteristic means that laser light is better than any other type of light when it comes to focusing.

With the help of optics, a laser beam can be shaped, e.g. forming anything from a circular beam to a straight line using a cylindrical lens.

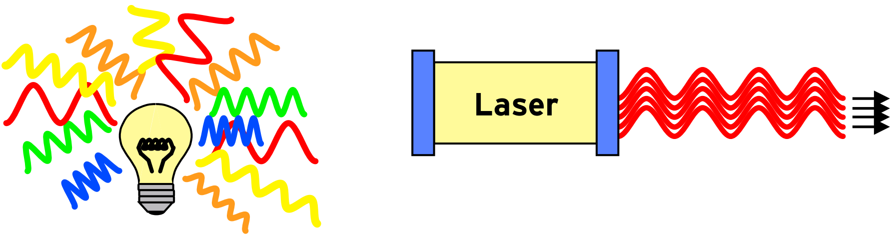

Fig. 3: The difference between broadband radiation and laser light

Coherence

A laser beam's coherence means that there is a fixed phase relationship between the oscillations in the light at different spatial points or at different times. This coherence means that lasers can produce interference patterns (alternating bright and dark regions in space or time). In contrast, wave packages of natural light sources are random to each other.

Polarisation

Polarisation exists when the majority of the light waves oscillate in a preferred plane. The laser type and the design of the laser determine whether a beam is polarised or not.

4 Structure and function of lasers

Light amplification is made possible by the process of stimulated emission. In order to take advantage of this process, energy is pumped into a laser medium, putting it into an excited state for the period of time required to generate a beam. Pumping energy into a medium, however, is not sufficient to create a laser amplifier. As with electrical amplification, the principle of feedback is applied. This principle states that a portion of the output power is routed back as input, forming a continuous loop. The amplifier then becomes an oscillator, whereby the system automatically oscillates after it is switched on. Fig. 4 shows the basic components from which a laser is built. The “heart” of the laser is the laser resonator consisting of a laser medium and mirrors. The laser medium determines the wavelength (‘colour’) of light that the laser radiates and gives the laser its name. The energy source may be electric, optical or chemical in nature.

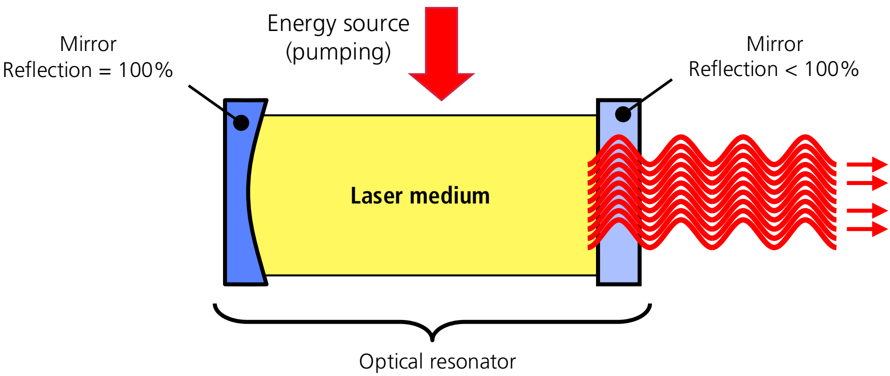

Fig. 4: Schematic laser design

Light feedback is achieved using two parallel mirrors that enclose the laser medium. One mirror reflects 100% of the axial dispersing light waves back into the laser medium. The output coupler mirror, depending on its transparency, lets through 5-40% of the light power. This output of 5-40% forms a laser beam for practical application.

4.1 Laser types

The laser medium can be gaseous, liquid or solid, resulting in the following types of lasers: gas lasers, dye lasers as well as solid-state lasers and semiconductor lasers. An overview of common lasers is available in **table 1** (chemical lasers, far-infrared lasers (FIR), as well as free-electron lasers are not covered here as they are used less frequently).

	Laser	Typical wavelengths [nm]	Type of operation	Usage examples
Gas laser	Helium–neon lasers (HeNe)	633, 611, 594, 543, …	Continuous wave (CW)	Positioning, div. measurements
	CO_2 laser	10600	CW, pulsed	Materials processing, Laser surgery
	Excimer laser	193 (ArF), 248 (KrF), 308 (XeCl), 351 (XeF)	Pulsed	Materials processing
	Argon Ion laser	488/514	Continuous wave (CW)	Pumping source, holography
	Metal vapour laser	510/578 (copper), 628 (gold)	Pulsed	Photodynamic therapeutics, material processing, photodynamic therapeutics, ...
	"Whitelight" laser	e.g. Ar/Kr mixed gas laser	CW	Laser shows, calibration
Solid-state laser	Ruby laser	694	CW, pulsed	Medical purposes, ...
	Alexandrite laser	710-820 (flashbulb pumped)	CW, pulsed	Hair and tattoo removal, dentistry, spectroscopic analysis, ...
	Nd:YAG laser	1064	CW, pulsed	Pumping source, material processing, laser surgery
	Er:YAG lasers	2940	Pulsed	Medical purposes
	Ho:YAG lasers	2100	Pulsed	Medical purposes
	Ti:Saphire lasers Laser	695-950 (flashbulb pumped) 700-1000 (Ar^+ CW pumped)	CW, pulsed	Photochemistry, LIDAR surveying, isotope separation spectroscopy
Semi-conductor lasers	InGaAlP GaAlAs InGaAsP	635 to 680 670 to 890 900 to 1800	CW, pulsed	Laser pointer, positioning, material processing (welding), communication engineering, compact disc players, various measurements ...
Dye lasers[3]	Coumarin 120 Coumarin 102 Rhodamin 6G Rhodamin 6G	441 (Excimer laser pumped) 495 (Ion laser pumped) 581 (Excimer laser pumped) 593 (Ion laser pumped)	CW, pulsed	Spectroscopy, photodynamic therapeutics ...

Table 1: Laser types.

[3] Listed wavelengths correspond to the maximum of fluorescence.

Gas laser (e.g. CO_2 laser): Because they are easily cooled, gases make powerful lasers. Energy is supplied electrically via gas discharge.

Solid-state laser (e.g. Nd:YAG laser): The laser medium is a crystal and light provides the energy source (flash bulb, semi-conductor laser). While classic solid-state lasers use a crystal rod as a laser medium, disk lasers use a thin layer of crystal and fibre lasers use fibre. Utilising these designs, improved efficiency and higher output is possible.

Semi-conductor lasers (e.g. GaAs lasers): Semi-conductor lasers are actually solid-state lasers, but because they are stimulated electrically, they are classified separately. Their wavelengths are located in the visible and near infrared ranges.

Dye lasers: The laser-active mediums are dyes dissolved in liquids. Lasers have been documented in more than 100 dyes in aqueous and organic solutions.

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4.2 Type of operation

Laser radiation may be continuous or pulsed. Lasers that continuously emit radiation are referred to as **continuous wave lasers (abbreviated CW).**

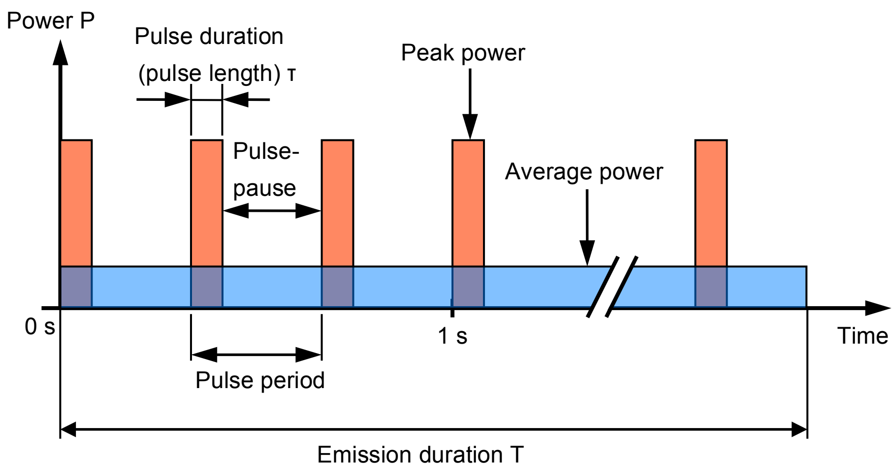

Fig. 5: Pulse parameters

Pulses can be emitted regularly, irregularly, or in pulse bundles and may be produced in various ways, e.g. via electronic control or via flashing. This allows for pulse durations in micro or even milliseconds to be achieved. By means of optical switches within the resonator, one can obtain a so-called **Q-switched solid-state laser** that emits high-energy pulses of very short durations, i.e. just a few nanoseconds. Even shorter pulse lengths, in femto and picoseconds, can be achieved using the **mode-locking** method.

The pulse repetition **frequency f** is a measure of the frequency of pulses per second and is described in hertz (Hz). 1 hertz is 1 pulse per second. Currently, pulse frequencies of several 100 MHz are possible.

Emission burst duration T is any period of time in which the laser beam is enabled. This is applicable to continuous and pulsed lasers. The pulse duration (pulse length) τ indicates how long a single pulse lasts. This is specified using the FWHM (Full Width at Half Maximum) method.

5 Beam parameters and propagation

5.1 Energy and power

The well-known term "solar energy" is a reminder that light is a form of energy. Lasers emit light and therefore energy. For pulsed lasers, **pulse energy** is often stated in addition to power. Pulse energy is expressed in **joule (J)**.
A continuous-beam laser emits energy continuously. Once the energy transmitted is related to the time over which it is delivered, we can begin to speak in terms of power. The **variable P** is used for power and stands for the rate at which the laser emits energy (energy per unit time). Power is expressed in **watts (W)**. The conversion between power (watt) and energy (joule) is as follows:

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

$$1\ \text{watt} = \frac{1\ \text{joule}}{1\ \text{second}}$$

For CW lasers, the maximum beam power is the most important parameter in addition to the wavelength. Consider, for example, a 100 W Nd:YAG laser. The power of the laser beam would be a maximum of 100 W. This value should not be confused with the device's electrical power rating, which is much higher. With pulsed lasers, one normally states the energy contained in a single pulse. The meaning of power, however, can vary greatly. While the **peak power** of a pulsed laser is often very high, the attainable **mean power** can be relatively small – see fig. 5 and fig. 6. The peak power is the maximum achievable power during a pulse. Because power is energy per second, pulse energy's peak power depends on the pulse duration:

$$\text{Peak power} = \frac{\text{Pulse energy}}{\text{Pulse duration}}$$

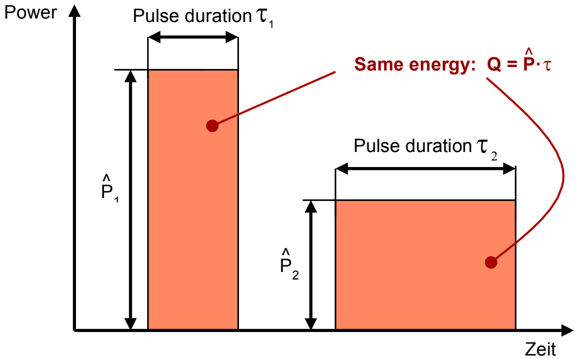

Fig. 6: Pulses with a different peak power but the same energy.

When the same energy is emitted in ever-shorter pulses, the peak power is increased. Fig. 6 illustrates an example of two pulses. The energy of both pulses is of equal size, though the peak power is different due to the difference in pulse duration. Intuitively, the effect of this pulse on the skin or on a material is different.

The mean power is the power over a longer period of time (see fig. 5, blue bar), which is why it has no bearing on the peak power of a pulsed laser! The average power can be much smaller than the peak power.

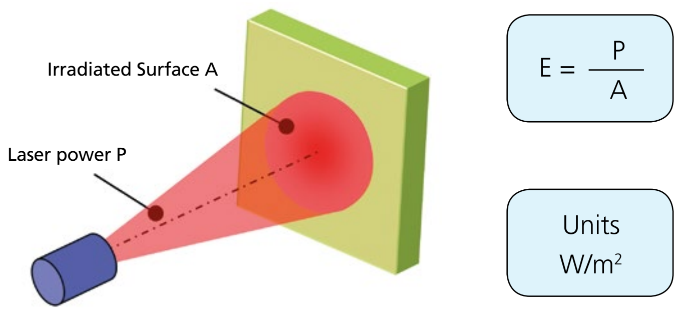

Fig. 7: Definition of irradiance

When it comes to the interaction between laser beams and material, the achievable effect depends on the size of the irradiated surface at a given energy or power. Clearly, whether or not a certain light power is spread across a square metre or a focal point using a focusing lens will have a different effect.

Depending on whether a laser is pulsed or continuous, the energy or power is applied to the irradiated surface. This is how we define **radiant exposure H [J/m²]** and **irradiance E [W/m²]. Energy density** or dose are commonly used terms for H, and **power density** or intensity are commonly used for E.

5.2 Reflection and transmission

In order to estimate the potential hazard from a laser beam, it is necessary to take into account possible reflections from objects or transmission, e.g. windows in the room.

If a light beam hits the surface of an object, the object will absorb a portion of the beam and the rest will be reflected back into the room. If, on the other hand, this object is a transparent medium for the arriving wavelengths, a corresponding portion of the light waves will pass through.

Unless the surface has undergone anti-reflection treatment for the wavelengths in question, a certain portion of the arriving radiation will be reflected. A pane of glass is used for illustration: 4% of the radiation is reflected on the front side. Because the reverse side also reflects 4%, a total of around 8% of the light is reflected.

Surface structures on objects can reflect incident light in different ways – fig. 8 shows the three possibilities. If the surface is absolutely smooth, a **specular reflection** may occur. Specularly reflected laser beams have the same risk potential as direct laser light. When it comes to such types of reflection, the hazard can literally "go around the bend".

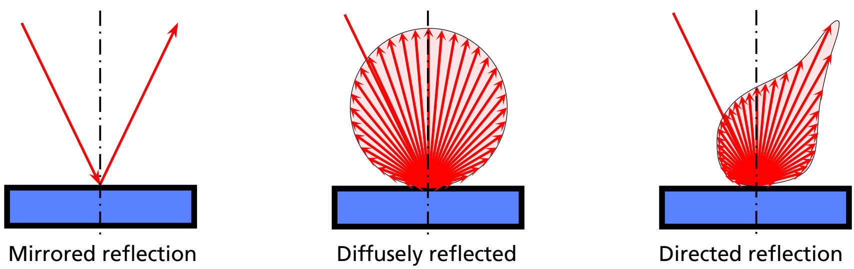

Fig. 8: Types of reflection

On the other hand, if the surface has a homogeneous, rough surface structure, the reflection is equally distributed throughout half the space. The laser beam is **diffusely reflected**, which means that the light output is distributed in half the space. As a result, the irradiance decreases dramatically with increasing distance. In many cases, a combination of both reflection types occurs, which is referred to as a **directed reflection**. It is important to note that a beam in the far infrared range (e.g. 10.6 µm) may be reflected by rough surfaces in a specular way. Lenses or freeform surfaces such as those of tools or vices can also focus a beam or make it diverge – see fig. 9.

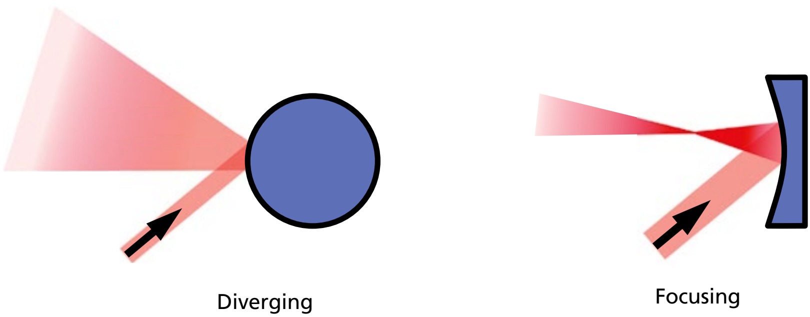

Fig. 9: Focusing and diverging effects of curved surfaces

5.3 Beam parameters

5.3.1 Beam quality

Beam quality depends on the energy distribution of a cross section of a laser beam. Depending on the design of the resonator, various energy distributions are formed. These are **transversal electromagnetic modes**, or **TEM_{pl} modes** for short (see attachment B), whereby indexes p and l serve to denote the modes. The lowest mode is the **fundamental mode TEM_{00} (Gaussian mode)**. A beam with this base mode can be concentrated on the tiniest possible focal point. As a result, the achievable power density increases. This is decisive for every type of processing, as it determines the “sharpness” of the laser beam.

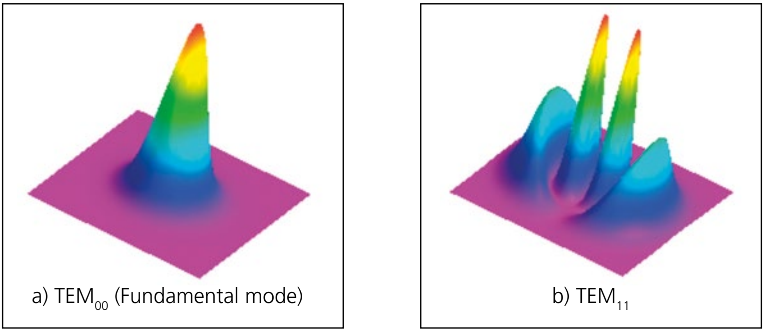

Fig. 10: Two examples of TEM modes

The relationship between the given energy distribution and the ideal base mode is a measure of beam quality and is described as the so-called **K-factor**[4]. It is a measure of how much the observed beam quality differs from the ideal base mode. Instead of K, M^2 (M squared) often stands for **beam quality**. Both ratios have the following relationship to one another:

$$K = 1/M^2.$$

5.3.2 Beam radius

Because a beam doesn't have an edge, the radius must be defined mathematically. In fig. 11, two radii are defined. For beams with a Gaussian intensity distribution, $1/e^2$ decrease from the maximum power density at the centre of the beam is often used as the radius for laser applications. This is defined as w_{86}, because approx. 86% of the power is concentrated within this radius. However, within the context of laser safety, one tends to rely on the definition of 1/e decrease. The corresponding radius is defined as w_{63}, because approx. 63% of the power is concentrated within this radius.

[4] The value of K is between 0 and 1. In case of an ideal Gaussian beam K gets 1. When the divergence increases, the beam quality decreases and K gets smaller

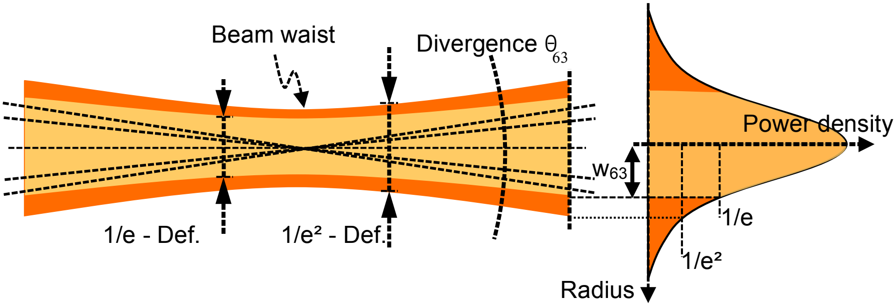

Fig. 11: Radial distribution of power/energy in a Gaussian beam

For power distributions that exhibit an unstructured beam profile due to the interference of a variety of modes, the 4σ method is typically used, which is based upon the second moment of the intensity cross section of power of the beam.

5.3.3 Beam expansion

Contingent upon diffraction and construction, a laser beam is not 100% parallel. The diameter of the laser beam increases with distance from the beam waist – see fig. 11. This expansion is called divergence Θ and is expressed in radian [rad]. ("radian" is a technical unit of angular measure. Conversion from degree to radian: 360 [°] = 2*π [rad][5]. The divergence of laser light is an order of magnitude of just a few milliradians. A small divergence means that the laser beam can still pose a hazard, even from far away. As soon as the raw beam is focused through a fibrous glass or focusing lens, the beam expands rapidly from the optical element, thereby shrinking the laser hazard area.

Example:
1 mrad corresponds to an expansion of the beam diameter by 1 mm per metre of distance! (1 mrad ≈ 0.057°)

[5] 1 radian ≈ 57.3 degrees, 1 degree ≈ 0.017 radian

6 Interaction Laser - Tissue

6.1 The human eye

The eye is the most sensitive organ when it comes to laser radiation. Fig. 12 shows a cross-sectional view of the human eye. Vision is made possible by the refraction of light that passes through the **cornea** and the lens to the retina. When we see, the **retina** receives the image that the cornea and the lens focus on and transforms this image into electrical impulses that are carried by the optic nerve to the brain.

The cornea is the clear, transparent front covering of the eye, which admits light and begins the refractive process. It acts as a convergent lens, sending light to the **iris**. The hole at the centre of the iris is the pupil, which appears black and functions as the aperture of the eye. Like the aperture stops of a camera, the diameter of the pupil varies depending on the level of the ambient light. The next component in the beam path is the lens of the eye. The most important function of the lens is to provide sharpness aided by the optical **accommodation**. The lens, by changing shape, functions to change the focal distance of the eye so that it can focus on objects at various distances, allowing a sharp image to be formed on the retina. The **vitreous body** is the largest part of the eye and is the supportive frame for the retina.

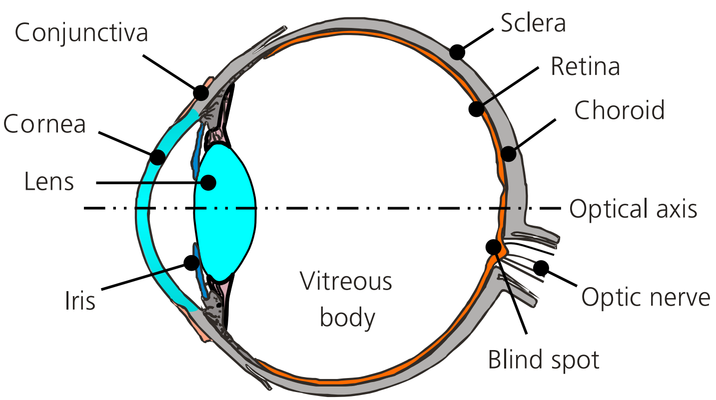

Fig. 12: Structure of the eye

6.2 Biological effects

The effect of certain wavelengths on irradiated tissue primarily depends on the penetration depth of this radiation as illustrated schematically in figs. 13 and 14 for both the eye and the skin. Because the majority of retinal damage is irreparable, the wavelength range that can be focused on the retina is especially dangerous. This range, however, is not limited to the visible portion of the spectral range. It extends **from 400 nm to 1400 nm** and includes the near infrared range.

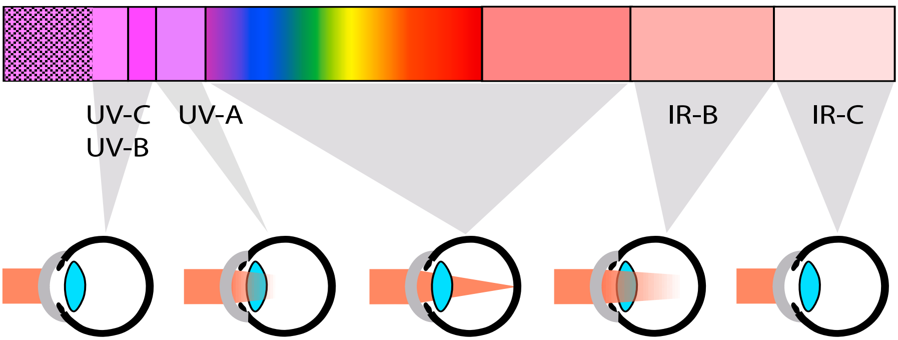

Fig. 13: Absorption of optical radiation by the eye

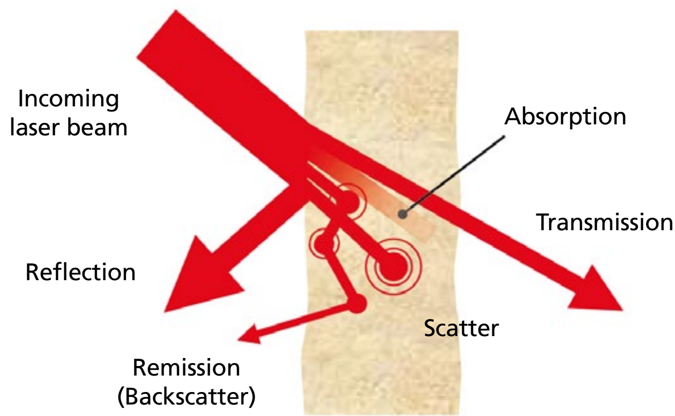

Fig. 14: Absorption of optical radiation by the skin

Mechanism of action

With respect to the biological effects of laser radiation, there are two different types of mechanisms of action. In the shorter wave range (UV, blue), **photochemical processes** determine the damage thresholds. In the longer wave range (red, infrared range), damage is primarily caused by **thermal processes**.

Photochemical damage: This is the result of specific absorbance through molecules, whereby a chemical reaction is triggered. In particular, UV or blue-light radiation may irreversibly damage the skin, the lens, and the retina. For photochemical damage, the size of the irradiated surface has no influence on the effect.

Thermal damage: Heating results when incident power is non-specifically absorbed. In contrast to photochemical damage, the size of the irradiated surface is important as it plays a role in the heat dissipation process. The effects of the rise in temperature on the tissue depend upon the temperature reached. No irreversible damage should be expected up to 45°C. At 60°C, coagulation occurs. Tissue is carbonised at 150°C, and at over 300°C, the tissue begins to vaporise.

The extent of a laser's effect is dependent upon the optical and thermal properties of the irradiated tissue. These properties determine how much of the introduced energy is absorbed and in which form this energy is transferred. One of the most significant parameters for tissue in this context is the spectral **absorption coefficient**, which is a measure of how much of the energy is absorbed when penetrating a certain layer of tissue.

6.2.1 UV range

UV-A: 315 nm – 400 nm. The lens of the eye absorbs the majority of this radiation, contributing to the forming of cataracts.

UV-B: 280 – 315 nm. This spectral range leads us to the most well known form of light damage: sunburn. In comparison to the threshold values of UV-A radiation, the threshold for sunburn is approximately 200 – 300 times lower. In the eye, this radiation can lead to an inflammation of the cornea and the conjunctiva.

UV-C: 100 – 280 nm. For practical reasons, 180 nm can serve as the lower threshold, because UV radiation below this level cannot be transmitted through the air (vacuum UV). Due to UV-C radiation's short wavelength, it is the most energetic form of UV radiation, representing the highest risk of inflammation to the cornea and conjunctiva.

6.2.2 Visible light

Due to natural defences (aversion response), the eye is protected from light powers up to approx. 1 mW in the visible range. These defences (including blink reflex time) allow us to assume that the eye may be exposed inadvertently to a visible laser beam for 0.25 seconds. Damage to the retina cannot be ruled out, however, if the exposure time exceeds 0.25 seconds or if the power is higher than 1 mW.

Short periods of thermal exposure or even longer periods of photochemical exposure can damage the retina (blue-light hazard).

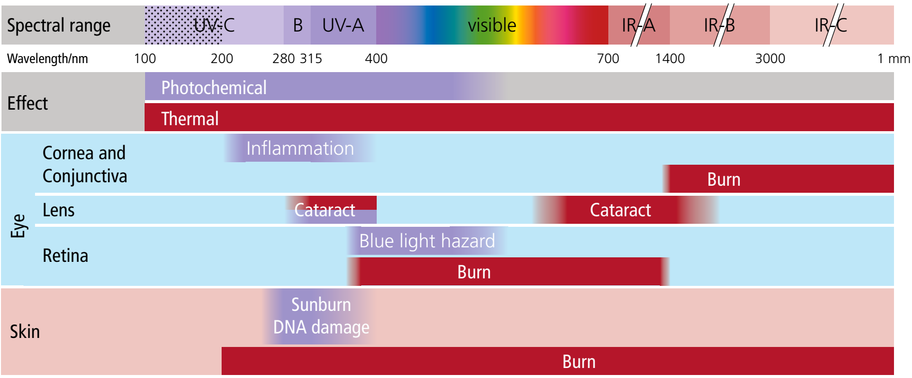

Fig. 15: Overview of possible tissue damage

6.2.3 IR range

IR-A: 700 – 1400 nm. Although IR-A radiation may not be visible, it is **especially dangerous** because it is focused on the retina and **natural defences of the body do not set in.**

IR-B: 1400 – 3000 nm. The penetration depth of this radiation is reduced dramatically at increased wavelengths. The effect of IR-B radiation is of a thermal nature. At sufficient levels of power density, it may cause burns to the cornea or skin.

IR-C: 3 µm – 1 mm. Due to water absorption, the penetration depth remains below 1 mm across the entire IR-C range. Biological effects include increases in temperature and burns. Throughout the entire IR-C range, the exposure limits are equally high.

6.3 Influence of time

In addition to wavelength, exposure time determines the effect of laser radiation. The evaluation of a biological effect is complicated because various processes take place over time. A graphical representation of possible effects on tissue is available in fig. 16.

Thermal effects may take nanoseconds or up to several minutes. If exposure time of the irradiated tissue is long in comparison to the thermal time constant, and if there is only a small difference between energy absorption and dissipation, tissue will increase in temperature in proportion to the irradiated power. The allowable limit will be measured according to the irradiance (power density) and expressed in W/m^2. If the exposure times are short in comparison to the thermal time constant, the effects of radiation are proportional to the irradiated energy.

When working with short-pulse lasers, the tissue may be exposed to a lot of energy in a very short period of time (pico and femto seconds). The observed effects are summarised using the term **non-linear processes** **(photo ablation, photo disruption)**.

Photochemical damage requires significantly longer exposure times in comparison to thermal effects. In the UV range and for a blue-light hazard affecting the retina, the effect of radiation is cumulative, i.e. the individual effects add up over time. As with x-rays, a dose-effect relationship exists. Independent of exposure time, the energy density must be around 1 or above to have an effect on tissue.

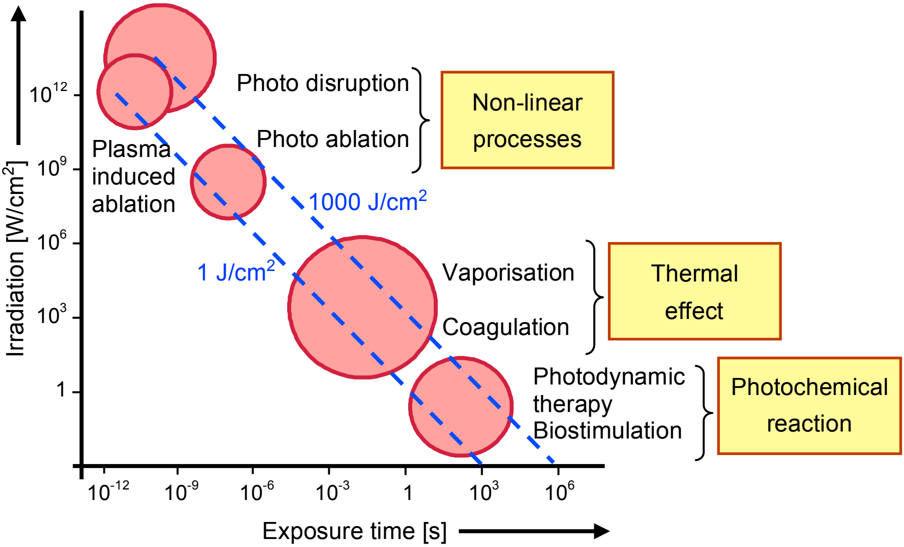

Fig. 16: The impact on tissue as a function of exposure time and irradiance (power density).

7 Maximum Permissible Exposures (MPEs)

As with other chemical and physical exposures, limits have also been defined for laser radiation. In Austria, these limits are referred to as **Maximum Permissible Exposures** (MPEs) and have been defined by the VOPST regulation. There is a complex interdependency between the MPEs and the respective exposure time and wavelength. Values given in VOPST are expressed in units of W/m² (irradiance) or J/m² (radiant exposure) (MZB values in the ÖVE/ÖNORM EN 60825-1 standard are merely informative and must not necessarily be in accordance with those from VOPST).

To determine if a given beam is above MPE, the applicable MPE value must be determined, following which the irradiance or radiant exposure must be measured or calculated at the site where a possible hazard may occur. For this purpose, the wavelength of the radiation must be determined and, in addition, a realistic irradiation period estimated.

7.1 Influencing factors

7.1.1 Irradiation period

In order to analyse the assumed risk to the eyes in the visible range, 0.25 seconds are standard if an intentional observation of the source is not planned. In the invisible IR range, an irradiation period of 10 seconds is assumed.

In the UV range, an irradiation period of up to 30,000 seconds (about 8 hours) is considered for the eyes and the skin. For wavelengths larger than 400 nm for the skin and 1400 nm for the eye, an irradiation period of 10 seconds is assumed.

7.1.2 Orifice plates

Orifice plates with a defined diameter are used to measure energy or power. They are placed in front of the energy or power detectors. The diameter of the orifice plates is defined by VOPST under the designation “Grenzblende” (restriction plates). They are dependent upon the wavelength of the laser to be measured, as well as in part upon the irradiation period. Table 2 provides an overview.

Wavelength ranges [nm]	Exposure time [s]	Diameter of orifice plates [mm]	
		Eye	Skin
180-400		1	3,5
400-1400		7	3,5
$1400\text{-}10^5$	$t < 0{,}35$	1	
	$0{,}35 < t < 10$	$1{,}5\ t^{3/8}$	3,5
	$t > 10$	3,5	
$10^5\text{-}10^6$		11	11

Table 2: Diameter of orifice plates

When it comes to measuring energy or power, energy distribution within a beam is not taken into account. A measurement is made of the total amount of energy or power that travels through the orifice plate to the detecting instrument with regard to the distribution area. This means that the irradiance or radiant exposure via the orifice plate is averaged by dividing the measured power by the distribution area of the plate.

Example:
In the visible wavelength range, the diameter of the orifice plate is 7 mm. When measuring a laser beam with a power of 1 mW, whether the beam's diameter is 1 mm or 3 mm makes no difference to the result. Both beam diameters are smaller than 7 mm and in both cases, the orifice plate transmits the entire power of 1 mW.

7.1.3 Pulsed laser radiation

The values in the MPE tables are only directly valid for a single pulse of a certain duration or for continuous radiation. In the case of pulsed radiation, three pulse criteria must be fulfilled. The irradiation per pulse is compared with the smallest calculated MPE value of the three criteria. For wavelengths below 400 nm, only criteria a) and b) may be used.

a) **Single-pulse MPE:** The irradiation (energy density) of a single pulse with a duration τ may not exceed the MPE value of a single pulse with a duration τ.

b) **Average output:** The irradiance (power density) averaged across the pulse repetition duration T may not exceed the MPE value of a single pulse of this irradiation period.

c) **Numerous pulses:** For wavelength ranges larger than 400 nm, the human eye is more sensitive to repeated pulses than to single pulses. This increased sensitivity is dependent upon the number of pulses N within the irradiation period. Therefore, the limit for single pulses decreases by the experimentally demonstrated factor $N^{-1/4}$.

7.1.4 Point source and extended source

In the wavelength range of 400 – 1400 nm, the MPE values are also dependent on the size of the represented laser beam on the retina and therefore the size of the observed apparent[6] (light) source. As a measure of this magnitude, the viewing angle α is used. If α is smaller than 1.5 mrad, then this apparent source is referred to as a "point source". If α is larger than 1.5 mrad, it is called an "extended source". Point sources always represent the worst case. Well-collimated laser beams are normally regarded as point sources.

7.1.5 Multiple wavelengths

In cases where the laser beam in question consists of various wavelengths, the MPE analysis depends upon whether the biological effects behave "additively" depending on the wavelength, or if they function "independently" from one another – see table 3.

If "additivity" exists, the effects of individual wavelengths must be considered collectively. If additivity does not exist, the individual effects of radiation are to be considered separately and the smallest MPE must be used.

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[6] The term "apparent" is used because the radiation field (light) of a laser beam is projected on the eye, rather than a real object. This is why, for example, light from a well-collimated, visible laser beam seems to come from a point far behind the real laser device.

λ₁ / λ₂	180 nm to 315 nm	315 nm to 400 nm	400 nm to 1400 nm	1400 nm to 1 mm
180-315 nm	Eye, Skin	---	---	---
315-400 nm	---	Eye, Skin	Skin	Eye, Skin
400-1400 nm	---	Skin	Eye, Skin	Skin
1400 nm -1 mm	---	Eye, Skin	Skin	Eye, Skin

Table 3: Additivity of various wavelength ranges for the eye and the skin

7.2 Nominal Hazard Zone – Hazard distance

An area where MPE has been exceeded is considered to be a Nominal Hazard Zone. A hazard distance or **NOHD** (Nominal Ocular Hazard Distance) describes the maximum distance at which the irradiance or radiation exposure equals the MPE for the eye.

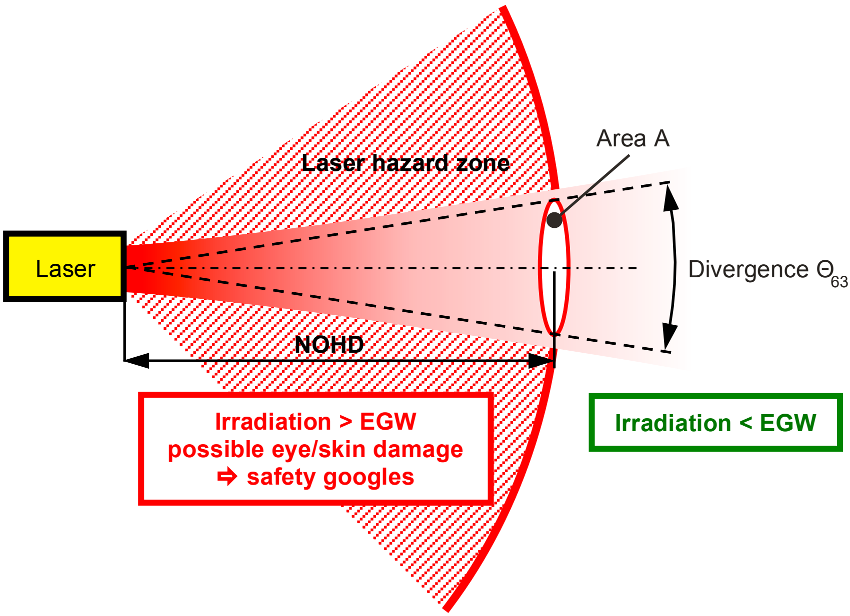


Fig. 17: Laser hazard zone and hazard distance

At a minimal divergence, this distance can be considerable. At a larger divergence, the nominal hazard zone may be limited to just a few centimetres[7].

Because, for example, windows and reflections need to be taken into account as part of the analysis, hazards exist not only in the intended beam direction but also in the immediate surroundings. Therefore, the actual nominal hazard zone is dependent upon the immediate area. It may also be extended via windows into a neighbouring room or even stretch "around the corner" (due to reflections).

Example:

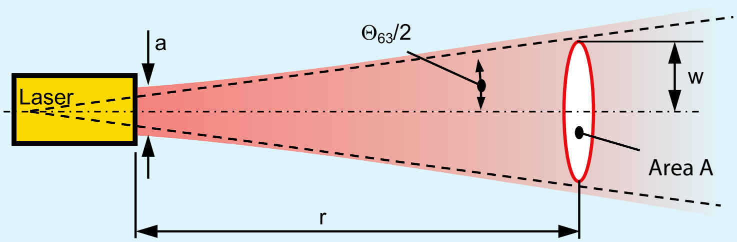
How large is the hazard distance of a CO_2 laser with P_0 = 600 W output power, with a beam divergence Θ_{63} = 3 mrad, which exhibits a beam diameter of a = 2 cm at the exit aperture?

First, we need an expression for the irradiance E. Irradiance is the laser power falling on some kind of surface, divided by the area A of that surface. Consider the surface in the diagram shown below, then:

$E = P_0/A$

To calculate the area A, the next step is to determine the beam radius w at a distance r from the exit aperture of the laser:

$w = r \cdot \tan(\Theta_{63}/2) + \text{beam radius } a/2 \text{ at exit aperture}$



In comparison to the first term in the above equation for w, the beam radius at the exit aperture of the laser is typically small and can be neglected. Furthermore, for very small angles, the term $\tan(\Theta/2)$ can be replaced with $\Theta/2$.

[7] Class 3B or 4 lasers with a small nominal hazard zone (e.g. < 0.5 m) have a significantly lower hazard potential in comparison to lasers with a hazard zone of several 100 m. As a result, fewer safety measures are required.

This simplifies the formula as follows:

$$A = w^2 \cdot \pi = \left(r \cdot \tan \frac{\Theta_{63}}{2} \right)^2 \cdot \pi \approx \left(r \cdot \frac{\theta_{63}}{2} \right)^2 \cdot \pi$$

The result is an irradiance E at a distance of r

$$E = \frac{P_0}{A} = \frac{P_0}{\pi \cdot \left(r \cdot \frac{\Theta_{63}}{2} \right)^2}$$

If E is replaced by EGW E_{EGW}, then r represents the hazard distance NOHD. When solved for NOHD, the above equation results

$$NOHD = \frac{2}{\Theta_{63}} \cdot \sqrt{\frac{P_0}{E_{EGW} \cdot \pi}}$$

The EGW for the eye in the far IR range is: E_{EGW} = 1000 W/m^2. Applying the values to the formula results in a hazard distance of about 291 m! (Taking the beam diameter into consideration results in an NOHD of 284 m)

8 Laser classes

So that the user understands the hazards inherent in using a particular laser, manufacturers worldwide are required to classify lasers into particular groups. This classification is designed to highlight the greatest possible hazard from a given laser beam according to the "worst-case principle". Lasers considered to be non-dangerous are rated as class 1. Those with the highest possible risk are rated as class 4. The classes are defined according to the Laser Safety Standard IEC 60825-1, published identically in Austria and entitled ÖVE/ÖNORM EN 60825-1. **Threshold Limit Values (TLVs) for radiation** are used to define the boundaries of the individual laser classes (GZS in Austria). Similar to MPE, they are dependent upon both time and wavelength.

Class 1

Safe lasers. Class 1 are considered safe, either because the power is so low, or because they possess a protective housing capable of outwardly shielding the laser beam completely during normal intended operation. As a result, class 1 laser products do not have a hazard zone.

Warning: None

Class 1M lasers ("M" stands for "magnifying instruments")

Any laser with a beam considered safe for the naked eye but potentially dangerous when coupled with an optical viewing system (magnifying glass or binoculars) is classified as **class 1M**.

Warning:

Do not view directly with optical instruments.

Class 2

Defined for visible laser beams (400 – 700 nm) only. The eye's natural defences (e.g. blink reflex) are sufficient for low-powered lasers. For point sources, e.g. the majority of laser pointers, 1 mW is the maximum allowable output power for class 2.

Although the time base for class 2 is 0.25 seconds, an exposure to light up to a maximum of 1 mW for somewhat longer than 0.25 seconds is not dangerous. Class 2 lasers are safe, as long as the body's natural defences (aversion responses) are not suppressed (purposely looking at the beam) or affected by the influence of medication, drugs, etc. As a result, class 2 laser products do not have a hazard zone.

Warning:

Do not stare into beam!

Class 2M

Defined for visible laser beams (400 – 700 nm) only. Class 2M lasers are defined as any laser that is safe for the naked eye at an irradiation period of 0.25 seconds but that may be considered potentially unsafe for the eyes when coupled with an optical viewing system (magnifying glass or binoculars).

Warning:

Do not stare into beam or view directly with optical instruments

Class 3A (outdated class)

The potential risks in the visible range may be equated to class 2. They are similar to class 1 for all other wavelength ranges as long as no optical viewing systems are used.

Condition: For power in the visible range up to 5 mW and an irradiance of $E < 25\ W/m^2$. In the invisible spectral range, the laser power may be up to five times higher than class 1.

Warning:

Do not stare into beam or view directly with optical instruments

Note: Since 2001, class 3A has been substituted by classes 1M and 2M, depending upon the wavelength of the laser in question.

Class 3R

Due to the risk of eye injury, class 3R could be considered a transitional classification between (the practically safe) class 2 and the more "dangerous" class 3B. Although class 3R may exceed MPE by a factor of 5, risks associated with short inadvertent radiant exposure and with continuous-wave lasers remain low because safety factors are contained within the MPE values (the classification R may be understood to mean "reduced" risk and reduced safety procedures). Actual risk of damage/injury only results from a radiant exposure lasting several seconds as illustrated by numerous studies and accident reports. For products classified as 3R, a hazard zone can nevertheless be established. Risks associated with short-term radiant exposure cannot be ruled out for some pulsed systems.

It is essential that only individuals trained to recognise the residual associated risks use class 3R lasers. Wearing protective eyewear is only deemed unnecessary when the assumption can clearly be made that the eyes will not be exposed in the hazard zone.

<u>Caveat:</u> 5 x class 2 in visible range (e.g. 5 mW for point sources), 5 x class 1 outside the visible range

Warning:

Avoid direct eye exposure

or

Warning:

Avoid exposure to beam

Special class "3B*" (outdated class)

In the 2001 edition of the EN 60825-1 standard, the special class 3B* was designated "**class 3R**".

Class 3B

Within the hazard zone, associated risks exist for the eyes (and for the skin in exceptional cases). An eye injury can occur even after a short period of exposure. This applies to invisible radiation as well. In general, however, there is no risk for the skin or the eyes from a diffuse reflection.

Warning:

Avoid exposure to beam

Class 4

The following applies to lasers with an output of 0.5 W. Risk exists within the respective hazard zones for the eye and skin. Associated risks, however, arise not only from direct laser radiation but also from scattered laser radiation (which constitutes an additional hazard zone). A fire hazard exists if the laser beam comes into contact with flammable materials!

Warning:

Avoid eye or skin exposure to direct or scattered radiation

<u>Note regarding class 1M and 2M:</u>

Risks associated with the use of optical instruments are higher as a result of more light power potentially reaching the eye. In practice, two types of laser radiation should be considered: Strong divergent beams and beams with a large diameter.

With a magnifying glass, a source can be observed at a very short distance, appearing very sharp upon the retina. Due to the close proximity, correspondingly high radiation is collected by the magnifying glass that would have normally escaped the eye at a normal distance.

Binoculars have a light collecting effect, especially when it comes to larger beam diameters. With its large diameter, the binoculars' lens acts as a collector.

The entire beam power that reaches the lens can reach the eye as well. For classes 1M or 2M lasers featuring a well-collimated laser beam, the nominal hazard zone may be expanded (ENOHD or Enhanced Nominal Ocular Hazard Distance).

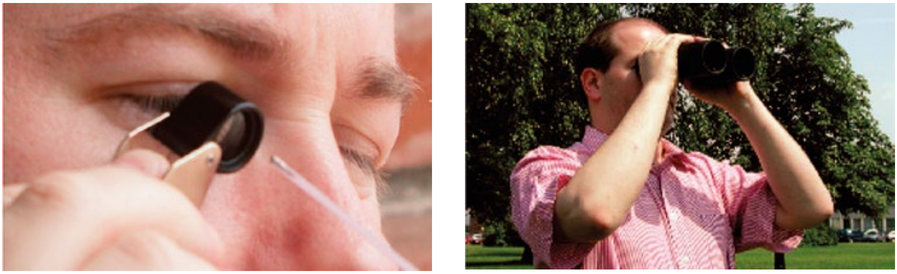


Fig. 18: Using a magnifying glass or binoculars

	Direct long time exposure		Direct short time exposure		Diffuse reflection		Direct radiation
	Optical instrument	Naked eye	opt. Instr.	Naked eye	Eye	Skin	Skin
Klasse 1	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Klasse 1M	⚠	Safe	⚠	Safe	Safe	Safe	Safe
Klasse 2	⚠	⚠	Safe	Safe	Safe	Safe	Safe
Klasse 2M	⚠	⚠	⚠	Safe	Safe	Safe	Safe
Klasse 3R	⚠	⚠	Low risk	Low risk	Safe	Safe	Safe
Klasse 3B	⚠	⚠	⚠	⚠	Low risk	Safe	Low risk
Klasse 4	⚠	⚠	⚠	⚠	⚠	⚠	⚠

Table 4: Risk summary for individual laser classes

9 Non-beam hazards

Various so-called non-beam hazards may arise when using lasers. Such risks result from using lasers but not from the laser beam itself.

9.1 Mechanical hazards

Fast-moving parts in particular are an example of a mechanical hazard. This may include; robots, automatic door locks, and movable positioning tables or work surfaces.

Special risks are associated with gas pressure. Gas pumping systems, e.g. for CO_2 laser gases or for process gases, are overly pressurised. Particular attention should be paid to using a suitable high-pressure gas hose or fixed tubing in such cases. In contrast, the majority of gas lasers are operated with low pressure in the resonator. The output coupler or glass tube must be carefully clamped or affixed to prevent stress (and the risk of implosion).

After all, mechanical impact or vibrations can lead to beam-axis misalignment and resultant hazards (e.g. reflection).

9.2 Electrical hazards

Every powerful laser device requires an adequate power supply. Inside the device, many contacts rest upon voltages in the kV range. Capacitors may be located inside pulsed lasers, which may remain charged for some time after switch-off. An appropriate anti-static rod should be included. The control electronics (ground) in some laser systems maintain an increased level of potential.

9.3 Chemical hazards

Chemical hazards primarily arise from materials used in laser construction.

- Poisonous fluoride and chlorine are used in excimer lasers. As a result, gas canisters for excimer lasers must be stored safely. When it comes to modern excimer lasers, the gas reservoir is already built into the laser itself.
- The majority of dyes for dye-lasers, such as rhodamine and coumarine, have a neurotoxic effect. Therefore, contact with the skin and inhaling the fumes should be avoided.

- The laser tubes from Ar and Kr lasers contain highly toxic beryllium. These tubes should therefore be handled with the greatest of care!
- Dust particles of broken ZnSe lenses (optics material for CO_2 lasers) are highly poisonous. ZnSe dust should be collected with protective eyewear, gloves, a mask, and a protective suit.

9.4 Fumes and dusts

Fumes and dusts occur when materials are vaporised. Laser-generated fumes and dusts contain suspended particulate matter that may be inhaled.

Depending upon the material, these suspended particles may be toxic, causing

- cancer
- inflammation
- impaired respiration (through deposits, dysfunction)

In addition, it is often unclear which new particles actually form as result of processing. For this reason, sufficient ventilation and/or suitable respiratory protection (a mask) should be used.

Special attention should be paid to the threshold limit values MAK and TRK that must be observed in the work place.

Risks may result from:

- Inhaling released particles or nano-particles. This includes, e.g., nickel and Cr(VI) connections (e.g. in welding fumes) and other metals, and also includes synthetic materials, allergens, and toxic materials from microorganisms during restorations.
- CAUTION: Suspended particulate matter may persist in the air for a long time.
- Nanoparticle risks for the skin: Nanoparticles may enter the blood stream through open wounds. Possible effects have been poorly researched to date. Wiping the eyes with the hand can spread these particles to the eyes, causing inflammation.
- Systemic effects: The effects on the body’s biological membranes (air sacs, vascular walls) from even the smallest particles can result in deleterious effects throughout the body, even far from where they entered the system.

- Particles may enter the body through the skin (including mucous membranes), via respiration, ingestion or a combination of any of these three.

9.5 Collateral radiation

X-rays:

X-rays are produced whenever electrons of high energy strike a heavy metal target.

UV radiation:

UV radiation is produced in the discharge tubes of gas lasers, as well as in a laser-induced plasma. UV radiation as well as blue-light resulting from laser welding in welding plasma are considered to be secondary radiation. This radiation can be intense enough to cause photochemical damage such as e.g. corneal inflammation (ophthalmia).

Microwave radiation and radio waves:

Lasers stimulated by high frequency produce microwave radiation and radio waves. They may be emitted if the equipment facilities are not properly shielded.

9.6 Risk of fire and explosion

Flammable material used in combination with high-power lasers poses a fire hazard. Flammable materials in the **beam-guidance system**, at the **processing location** and in the **environment** are a fire hazard. The risk of fire is increased in oxygen-enriched atmospheres (oxygen is used in some laser applications).

Exercise caution in atmospheres where explosions are possible. An output power of only 35 mW at a suitable power density (for example with optical single-mode fibres) is enough to ignite a fire. When it comes to high-power lasers, a laser beam can ignite a fire in solvent vapours, smoke or flammable gases. This may lead to an explosion.

Electrical capacitors (like those used in pulsed systems) may explode if overloaded.

10 Protective measures on the part of the manufacturer

Laser manufacturers must classify their laser products. Depending upon the classification, appropriate safety measures must be put into place. These measures are naturally limited to technical protective measures, as well as the provision of information (including, among other things, warning signs/notifications).

10.1 Technical safeguards (design requirements)

Access covers, protective housings

Every laser device must have a protective housing capable of preventing radiation from discharging. This housing should be independent of device function. Service covers must be protected by a safety switch (interlock) or must be constructed so that removal requires tools. Cover plates must be secured, especially if the intended operation and maintenance requires opening.

Remote safety interlocking (interlock)

Lasers of classes 3B and 4 must feature a connection port for remote safety interlocking.

Resetting by hand

Following a power interruption of at least 5 seconds or after the interlock has been opened, operation of the laser may not be resumed automatically.

Key switch

Lasers of classes 3B and 4 must feature a key switch. The term "key" may include magnet cards, digit combinations, passwords, etc.

Emission warning systems

Class 3R lasers with invisible radiation and class 3B and class 4 lasers must emit an acoustic or optical signal if the device is powered on or if the capacitors of pulsed lasers are charged. This emissions warning system must be redundant or fail-safe.

Beam stop (shutter), beam attenuator

According to the EN 60825-1 standard, class 3B and class 4 lasers must feature equipment that allows the user to prevent the device from emitting radiation independent of an on-off switch. A beam shutter/attenuator or direct triggering of the beam generator may be employed for this purpose.

Control and operation facilities

The device's controls or operation facilities must be situated such that the adjustment and operation of the laser device is possible without being exposed to class 3R, 3B and 4 laser radiation.

Observation optics

For lasers equipped with observation equipment, radiation made available by the optics may not exceed the allowed values for class 1M.

Directionally variable radiation (scan laser)

Should a deflection failure or scanning speed or amplitude change occur, scan lasers are not allowed to permit radiation above the limits of their particular class.

Access via walk-in entry

Should individuals stay inside the laser cabin, class 3B or class 4 emissions of laser radiation must be constructively prevented.

10.2 Warning and notification signs

In accordance with EN 60825-1, all warning signs must be consistently signposted, legible, and clearly visible during operations. Text, bordering and symbols must be black on a yellow background (with the exception of class 1).

Laser warning sign

Meaning: Caution laser beam.
Must be present for class 2 lasers and above

Fig. 19: Warning sign for laser beams

Classification and warning text

Laser radiation Do not stare into beam **Class 2 Laser product** EN 60825-1 (2007)	or	**Laser radiation** Avoid eye and skin exposure to direct or scattered radiation **Class 4 Laser product** EN 60825-1 (2007)

All laser equipment must feature an applied or attached warning text. For laser classes 1 or 1M, reference can be made in the user manual. The sign must include information about the laser class, corresponding warning text, as well as the standards and their publication dates.

Beam parameters

Every laser facility with the exception of class 1 must exhibit a warning sign featuring statements about the maximum beam power or energy, impulse duration and wavelength.

Cover

If laser radiation could be emitted in excess of the MZB values for class 1 (with an appropriate class warning) by opening a cover, the following wording should be used:

Caution – class XX laser radiation
If the cover is open + warning text

If there are safety interlocks bridged:

Caution – class XX laser radiation
If the cover is open and the safety interlock is bypassed + warning text

Beam exit aperture

Exit aperture for laser radiation

Additional provisions

a) If the laser product emits visible laser radiation, then the term "laser radiation" can be substituted for the term "laser light".

b) If the laser product emits an invisible laser beam, then the word "invisible" must appear before the term "laser beam" in the warning text.

10.3 Information for the user

The following information must be an integral part of the usage instructions for laser products:

a) Instructions for the correct mounting, maintenance, and operation.

b) Additional warning signs regarding possible hazards are necessary for laser products in classes 1M and 2M (regarding which optical instruments may increase the risk).

c) Beam parameters statement (divergence, pulse energy, pulse duration, etc.) including uncertainty of measurement.

d) For encapsulated (built-in) laser products, all necessary signs must be present to prevent a hazardous exposure.

e) If relevant, the nominal hazard zone for class 3B and 4 laser products should be stated (or the expanded hazard zone for 1M or 2M).

f) Information about suitable protective eyewear.

g) Legible reproductions of all signs and descriptions of where the warning signs are affixed.

h) In the event that the manufacturer does not affix the warning signs, the manufacturer is required to make this fact known and to state the form and manner in which the signs have been delivered.

i) Information about the location of the laser beam exit apertures.

j) List of operating options (including adjustment device) and modus operandi, in addition to a warning about operating errors and their consequences.

k) Should the laser product not feature its own energy supply, the type of energy supply must be specified.

11 Protective measures on the part of the user

While part 1 of the EN 60825 standard is directed towards the manufacturer, recommended protective measures for the user are outlined in part 14 (DIN EN 60825 supplement 14). Specifications from VOPST are mandatory. These demand a hazard assessment, as well as the implementation of various protective measures, especially the prevention of exposure to the eyes or skin beyond the exposure limits. The following quoted protective measures have been established over the last 30 years in the area of laser safety (i.e. before the VOPST came into force). They generally cover the demands presented in VOPST. Specific measures can or should be established depending on usage and based on a hazard assessment.

11.1 Technical and structural protective measures

11.1.1 Laser control area

A laser controlled area should be established anywhere where a risk of injury as a result of laser radiation or a laser facility may be expected in the future, e.g. if individuals must work in a nominal hazard zone. This applies to all class 3B and 4[8] laser products. Laser control areas[9] should be clearly differentiated, labelled, and safeguarded if necessary. Admittance should be restricted to individuals with appropriate safety training.

For industrial applications in the broadest sense, one should aspire to keep the nominal hazard zone as small as possible with the help of shielding barriers. By minimising the nominal hazard zone, less effort can be expended in shielding and ensuring safety in the laser controlled area.

[8] If the future use of a telescope is planned in conjunction with a well-collimated class 1M or 2M laser beam, then a laser-controlled area should be created for this purpose. Close attention should be paid to the expanded nominal hazard zone (ENOHD).

[9] In most cases, the laser-controlled area is the same space as the application environment or the borders of the laser facility (not applicable for exterior applications).

Labelling	■ Ground marking ■ Barrier chains ■ Warning signs, warning lamps, etc.
Shielding	■ Laser-protection curtains ■ Mobile/fixed laser shielding walls ■ Immediate coverage of the process zone ■ Limiting beam path to the necessary distance, etc.
Safeguarding	■ Safety switch (interlock) ■ Light curtain ■ Safety mats, etc.
Constructive measures	■ Beam guidance (e.g. place overhead, elevate laser position). ■ Prevent the beam axis from migrating. ■ Shield beam paths for class 4 lasers. ■ Do not direct the beam path toward doors, windows, etc.

Table 5: Example of possible protective measures

Fig. 20 and fig. 21 exemplify two possible laser controlled area arrangements. Either the entire room is defined as a laser controlled area (if so, warning lights and warning signs must be installed outside of the room as well as the entrance door has to be guarded by a safety switch) or the process field will be correspondingly enclosed in the inner room.

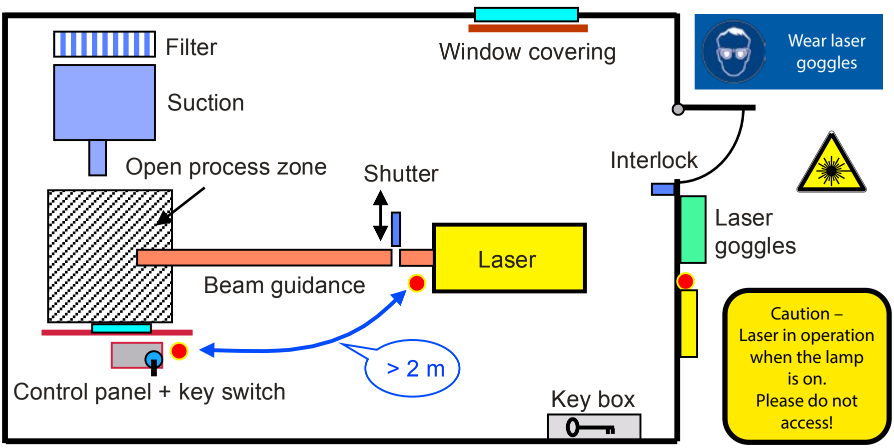


Fig. 20: The entire room is labelled and safeguarded as a laser control zone for technical/ industrial applications. For medical purposes, the interlock on the door can be omitted.

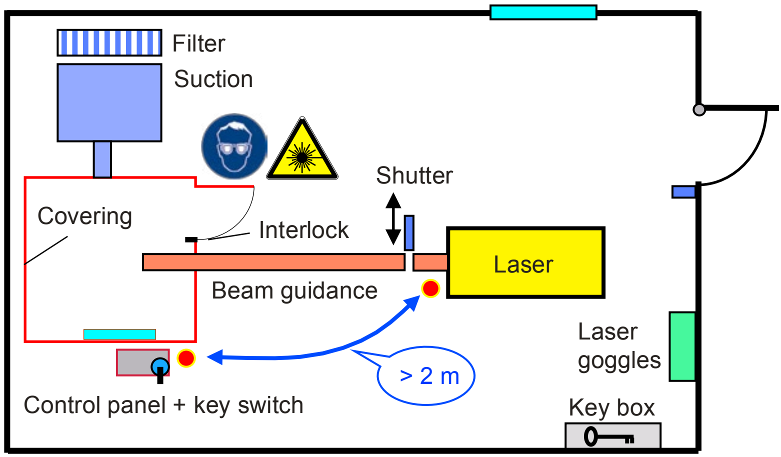


Fig. 21: Labelling and safeguarding of the walk-in process zone as a laser control zone for technical/industrial applications.

Comment on class 3R

For class 3R or target lasers (pilot lasers) starting at up to 5 mW output power, the MPE (which can be displayed as a maximum 1 mW output through the 7 mm aperture) is exceeded in the hazard zone. The hazard zone can be up to about 30 metres for a well-collimated beam and 5 mW power. Should the possibility of radiation exposure to the eyes exist within the hazard zone, protective eyewear must be worn when working with a class 3R laser. It is, however, not necessary to wear protective eyewear when working with a laser beam whereby exposure to the eyes is avoided, or if the principal activities of employees are not oriented towards viewing the laser source. Due to the minimal risk of eye injury when using class 3R lasers, possible exposure to light, e.g. inadvertent reflection, are evaluated less strictly than with class 3B or 4 lasers, which require wearing protective eyewear within the hazard zone (including possible reflections).

Note regarding class 3B and 4:

Potential hazards (possible injuries) associated with class 3B or 4 lasers are primarily determined by the nominal hazard zone. These can be reduced to a minimum by the introduction of adequate measures. The goal of these protective measures is not to turn a class 3B or 4 laser into a class 1 laser (this is normally only possible with a high degree of technical effort), but to ensure safe practices and operation so that the protective eyewear must not be worn outside of the shielded barrier area.

Additional practical protective measures

The following points should be observed if possible:

- Provide for good room lighting
- Avoid reflective surfaces
- Avoid trip hazards
- Affix all optical elements
- Mechanical parts should not fall over or become loose
- Do not store flammable material in a work place with class 3B and class 4 lasers
- All safety measures must be regularly reviewed
- Work instructions should be prepared where appropriate (e.g. for cleaning of the focus unit)

Working with exposed beams

Such activities have the highest potential hazard. The following measures should be embraced dependent of the class:

Class 2 and up	■ Run the beam path above or below eye level. ■ Do not focus the laser beam at people (risk of glare! Especially critical for those driving or operating machines) ■ Walkways should not cross the beam ■ Do not direct the beam path toward doors, windows, etc. ■ Limiting beam path to the necessary distances
Class 1M, 2M[10] and above (additional)	■ Use minimal necessary power ■ Avoid mirroring reflections
Class 3R and above (additional)	■ Ensure that no one looks at the beam
Class 3B and 4 (additional)	■ Use protective equipment within the nominal hazard zone ■ Application approval though the LPO ■ Label and cordon off the nominal hazard zone

11.2 Organisational protective measures

There are two different types of organisational protective measures. The first consists of recommended actions, such as appointing a Laser Protection Officer (LPO), etc. The second protective measure includes assuring all indicating safety measures, e.g. warning signs, notifications, and access restrictions. Organisational protective measures take the place of or complement technical protective measures in cases where these may be excessively complicated (e.g. automatic person detection for walk-in cabins) or not appropriate (e.g. safety switch on the door for medical uses).

Training employees

In accordance with VOPST, employees must be trained when the MPE for the eyes or skin may be exceeded. These measures are necessary for all individuals who spend time in the hazard zone of the laser or in the controlled access area.

[10] For class 1M and 2M lasers, additional measures should be put into place to ensure that no one looks into the beam with optical instruments.

11.3 Laser Protection Officer (LPO)

According to VOPST, the evaluation of a given laser beam must be completed by competent persons. The appointment of a laser protection officer (LPO) is currently not expressly prescribed; however, in training to be an LPO, the qualifications demanded by VOPST can be achieved. Naming an LPO complies with both the international and national state of the art and standards (ÖNORM 1960825-8, ÖNORM S1100-1, IEC TR 60825-14)

11.3.1 Tasks and duties of an LPO

The job of an LPO is to support and advise the responsible operator (employer) with respect to protective measures and the safe use of laser products. Specifically, the tasks of an LPO may include:

a) Supporting professional occupational safety staff in completing hazard analyses (evaluation – see below).

b) Consulting with the responsible operator when it comes to questions of safety and operational and occupational health protection measures.

c) Selection of personal protective equipment.

d) Training employees who work with lasers or in the laser controlled area.

e) Functional checks and safety equipment

f) Regular checks to ensure that the prescribed protective measures are being implemented or complied with.→ **Use a checklist.**

g) Creation of work instructions for standardised working methods and processes.

h) Informing responsible persons about laser device defects or failures.

i) Investigating accidents or incidents involving lasers and making information about preventive measures available to all individuals concerned.

11.3.2 Evaluation

The Austrian Workers Protection Act (Arbeitnehmerinnenschutzgesetz) and VOPST require that the workplace be evaluated with regard to potential hazards. Further information is available, e.g. at the website: www.eval.at.
A scheme might include the following points:

- Definition of the area to be evaluated (organisational area, spaces)
- Description of the activities in the laser controlled area
- Description of the laser
- Description of the laser application
- Identification of hazards and risks (NOHD, ...)
- Determination of protective measures

The evaluation documents must be continuously updated!

11.3.3 Behaviour during incidents and accidents

Incidents are events that have not resulted in an injury or caused other damage to equipment, but nevertheless had the potential to do so. Incidents and accidents must be reported to the LPO or to the employer. Based upon an investigation of the accident, recommendations should be made to prevent a reoccurrence of the event. The laser should not be used again until all appropriate measures are put into place to prevent an additional incident or accident from occurring.

11.3.4 Report scheme

Should an incident or accident occur, the LPO should complete a report about the circumstances in cooperation with occupational safety professionals. This report should, at a minimum, include:

a) A summary of the incident circumstances that lead to an injury including:
   1) Date, place and time of incident
   2) Names and functions of all involved persons
   3) Details of injury as described by the injured person
   4) Obvious or supposed type of injuries
   5) Factors that obviously contributed to the incident
   6) Recommendations from the LPO to avoid a repeated event and

b) Written explanations of all involved persons where appropriate

c) Medical reports about all injured persons.

d) Data about the laser product, especially about the condition and settings of the device as well as the accessories, immediately after the incident.

e) A list of devices and accessories used during the incident.

11.4 Laser safety goggles (Laser eye-protectors)

The exact requirements of laser safety goggles are defined in the ÖNORM EN 207. **Laser safety goggles are not intended to allow the viewer to look at the beam for long periods. They are intended to protect the viewer from inadvertent views!**

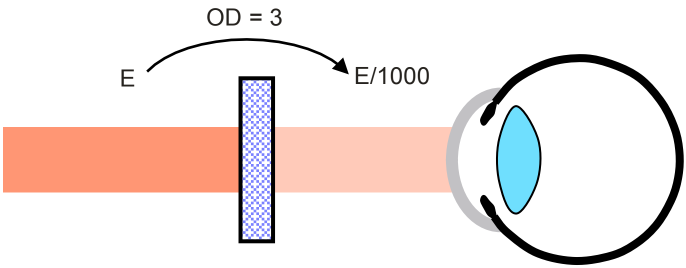


Fig. 22: Optical density

Protective eyewear is used to weaken the effects of incoming laser radiation to the extent that they are less dangerous. For a given laser wavelength λ, the transmittance degree $T(\lambda)$ of eyewear must be small enough that the irradiance E (W/m^2) is below MPE:

$T(\lambda) < EGW(\lambda)/E.$

In comparison to the EN 60825-1 standard, the EN 207 uses a simplified threshold scheme with only three defined wavelength ranges. To describe the filter effect, the optical density (OD) is generally used. This is defined as a negative, decadic logarithm of the transmittance degree:

$OD = -\log T = -\log (EGW/E)$

This definition means that with OD = 2 the filter lets through one one-hundredth of the radiation and with OD = 3 one one-thousandth of the radiation is permitted through, etc. See table 6.

Optical density	Transmission factor T
OD = 1	0,1
OD = 2	0,01
OD = 3	0,001 etc.

Table 6: Optical density and transmission factor

In addition to the filter effect, the eyewear must be resistant to laser radiation. This resistance is certified according to a standardised test (EN 207). If the laser safety goggles pass the test, they are classified according to optical density with the corresponding protection level. If the optical density is 4, then the safety goggles have passed a level 4 test (the resistance refers not only to the glass but also to the frame of the eyewear).

Example:
The (thermal) MPE value in the visible range is 10 W/m² for a radiation period of 10 s. Protective eyewear with a protection level of level 4 would therefore provide suitable protection for up to 10^5 W/m² of light impinging on the front surface of the eyewear. At a supposed beam diameter of 2 mm, the power of the arriving beam may therefore be up to 0.31 W.

11.4.1 Labelling

Laser safety goggles are labelled pursuant to EN 207:2010 according to the following scheme:

D I R M	1064	LB6	XXX	CE
Type of operation	Wavelength	Protection level	(Manufacturer's symbol)	

11.4.2 Type of operation (abbreviations)

D	Continuous wave	above 0.25 seconds
I	Pulsed laser	10^{-6} to 0.25 s pulse duration
R	Giant impulse laser (Q switch)	10^{-9} to 10^{-6} s pulse duration
M	Mode-locked lasers	$< 10^{-9}$ s pulse duration

All modes of operation are stated for which the eyewear is approved. All eyewear must be certified for continuous wave operation. If no operation mode is quoted, then the level of protection is valid for continuous wave. The designation IR for protective eyewear refers to the operating modes "Impuls" and "Riesenimpuls" (impulse and giant impulse) and should not be confused with an abbreviation for infrared.

11.4.3 Wavelengths

Wavelengths are measured in nanometres (nm), although this abbreviation is seldom used. Range specifications, e.g. 600-800, or the specifications of numerous areas, even those with different levels of protection, are possible. The wavelength of the laser used must correspond to the wavelength range of the protective eyewear in order to guarantee effective protection!

11.4.4 Protection level

The level of protection is labelled "LB" and ranges from 1 to 10.

The optical density (OD)[11] is at least as high as the level of protection LB (i.e. the OD may be larger if the material indeed offers good optical filtering but does not pass the 5-sec test at the respective power density). In earlier versions of EN 207, the level of protection was labelled L. Laser safety goggles labelled accordingly can still be used.

Manufacturer and standard marks (symbols) are additional information, but are irrelevant from a safety perspective. Laser eye-protector eyewear for lasers sold in Europe must, of course, feature the CE mark.

[11] Many manufacturers of protective eyewear state the optical density, as well as the protection level.

11.5 Laser adjustment goggles (Adjustment eye-protectors)

When working with visible laser beams (radiation), it may be necessary to view the beam itself sufficiently. This is often not possible with protective eyewear for lasers, as the optical density is often too high. For this purpose, alignment eyewear is offered. The exact requirements of alignment eyewear are defined in the EN 208 standard.

In addition to providing information about the maximum power in watts allowed or the energy per pulse in joules, the label also indicates the level of protection. The protective level of the filter is labelled with "RB", e.g. **0.01 W 2.10-6J 670 RB1 XXX CE**[12]. The permissible power of 10 mW is derived from the MPE of 1 mW for short-term radiant exposure of the eye (0.25 s) and an optical density of OD1 (transmittance 1/10). Additionally, the eyewear must be labelled "Justierbrille" (Adjustment eye-protectors). A statement regarding the energy of 2.10-6J should be interpreted as a factor of 10^{-6} and means 2 µJ.

Laser adjustment goggles are designed for viewing scattered reflections only, not for looking at the laser beam. Inadvertent radiant exposures are considered too risky.

11.6 Windows

Viewing windows or shielding barriers must be able to withstand a radiant exposure lasting for an expected irradiation period. At this point, it is important to mention that glass acts as an absorbent for wavelengths $\lambda > 2.8$ µm. For a correspondingly high beam power, simple glass windows are not appropriate, as the thermally induced tension of the window could lead to burst. For wavelengths smaller than 2.8 µm, e.g. use of an Nd:YAG laser, the NOHD hazard zone may extend into neighbouring rooms due to viewing windows (like those of some doors). For this reason, glass windows must be covered from the inside with opaque materials during the period of laser use (appropriate to the wavelength used).

[12] The indication of energy of 2.10-6J is to be interpreted as exponent 10^{-6} and means 2 µJ.

12 Regulations, laws and standards

EU regulations for products

One of the main goals of the European Community was and still is to achieve a domestic market. It was therefore necessary to compare national laws and regulations concerning products throughout the EU, so that the laws of a single country do not impede the free flow of goods. EU directives were created for this purpose. In German, they are abbreviated to RL (for Richtlinien). The EU member countries are required to adopt the content of these EU guidelines in their national legislation. Examples of this include:

Directive	RL-Number	Law
Low voltage directive	2006/95/EC	Niederspannungsgeräteverordnung
Machinery safety directive	2006/42/EC	Maschinensicherheitsverordnung
Medical devices directive	93/42/EEC	Medizinproduktegesetz
…..		…..

Table 7: EU directives for products/manufacturers and corresponding laws

The directives contain only general and fundamental requirements. Additionally, harmonised standards are therefore created that include technical details for meeting these general requirements. Technical standards are not laws! The use of standards is, in principle, voluntary and should be considered a resource in order to meet the directives/enactments.

In most cases, this does not excuse the manufacturer from completing a risk analysis above and beyond the harmonised standards. This risk analysis serves to determine the possible risks associated with a product and is therefore expected or demanded in the Single Market Directive (Binnenmarkt-RL).

The most important standards concerning laser safety are listed in tables 8 and 9,

Standard	Title
ÖVE/ÖNORM EN 60825-1	Sicherheit von Lasereinrichtungen – Teil 1: Klassifizierung von Anlagen und Anforderungen.
ÖVE/ÖNORM EN 60825-2	Sicherheit von Lasereinrichtungen – Teil 2: Sicherheit von Lichtwellenleiter-Kommunikationssystemen.
ÖNORM EN 60825-4	Sicherheit von Lasereinrichtungen – Teil 4: Laserschutzwände.
ÖNORM EN ISO 1 1553-1	Sicherheit von Maschinen – Laserbearbeitungsmaschinen – Sicherheitsanforderungen.
ÖNORM EN 12254	Abschirmungen an Laserarbeitsplätzen – Sicherheitstechnische Anforderungen und Prüfung.
ÖNORM EN ISO 11252	Laser und Laseranlagen, Lasergerät; Mindestanforderungen an die Dokumentation.
ÖNORM EN 207	Persönlicher Augenschutz – Filter und Augenschutzgeräte gegen Laserstrahlung (Laserschutzbrillen).
ÖNORM EN 208	Persönlicher Augenschutz – Augenschutzgeräte für Justierarbeiten an Lasern und Laseraufbauten (Laser – Justierbrillen).
ÖVE EN 60601-2-22	Medizinische elektrische Geräte, Teil 2: Besondere Festlegungen für die Sicherheit von diagnostischen und therapeutischen Lasergeräten.
ÖNORM EN ISO 10079-1	Medizinische Absauggeräte, Teil 1: elektr. betriebene Absauggeräte – Sicherheitsanforderungen.
ÖNORM EN ISO 11810-1 and -2	Laser und Laseranlagen - Prüfverfahren und Einstufung zur Laserresistenz von Operationstüchern und/oder anderen Abdeckungen zum Schutz des Patienten.
ÖNORM EN ISO 11990	Optik und optische Instrumente – Laser und Laseranlagen – Bestimmung der Laserresistenz des Schaftes von Trachealtuben.
ÖNORM EN ISO 14408	Trachealtuben für die Laserchirurgie - Anforderungen an die Kennzeichnung und die begleitenden Informationen.

Table 8: List of harmonised standards for manufacturers

Standard/AUVA-leaflets	Title
ÖNORM S 1100-1	Laserschutzbeauftragter Teil 1: Verantwortlichkeiten und Zuständigkeiten.
ONR 1960825-8	Sicherheit von Lasereinrichtungen Richtlinien für die sichere Anwendung von medizinischen Lasergeräten (IEC/TR 60825-8:2006, modifiziert)
DIN EN 60825 Supplement 14	Sicherheit von Lasereinrichtungen - Teil 14: Ein Leitfaden für Benutzer (deutsche Übersetzung IEC TR 60825-1: 2004); derzeit nicht als ÖNORM veröffentlicht
ÖNORM S1105	Strahlenschutztechnische Anforderungen bei der Erzeugung von Lichteffekten mittels Laserstrahlung vor Publikum oder bei der Vorführung von Laser-Einrichtungen.
ISO/TR 11991	Guidance on airway management during laser surgery of upper airway.
M 081 leaflet	Lasersicherheit bei optischem Richtfunk.
M 082 leaflet	Lasersicherheit bei LWLKS (Lichtwellenleiterkommunikationssystemen).
M 087 leaflet	Sicherheit bei der Lasermaterialbearbeitung
M 088 leaflet	Sicherheit bei handgeführten Laserbearbeitungsgeräten
M 140 leaflet	Lasersicherheit in der Medizin

Table 9: Standards and AUVA leaflets for users

Statutory framework

Generally speaking, technical standards do not have a legal character, but serve instead as minimum standards. Standards may be named in laws and regulations, thereby making the standards mandatory. The legal basis for laser safety in the workplace is the Workers Protection Act (ASchG) along with corresponding regulations. For lasers, the regulation for optical radiation (VOPST) is particularly relevant. It came into force in 2010.

CE Mark

Only products that meet the requirements of all of the respective guidelines may be brought to market. Then, and only then, can the manufacturer make use of the CE Mark and issue a conformity declaration. The CE Mark is a signal to market-surveillance authorities that the product complies with the guidelines in question.

It should be noted that the product safety guidelines do not require a CE Mark, although the mark certainly plays an important role. It is, in a sense, a fallback guideline for consumer products if there are no appropriate guidelines. It covers laser pointers, for example.

Effects on laser products

The ÖVE/ÖNORM EN 60825-1 standard specifies technical protective measures that the manufacturer must integrate (see above). The correct classification of a laser product does not automatically mean that it is “safe”. A class 4 laser remains potentially dangerous. Additional protective measures like suitable shielding, access policy, etc. will make the laser **safe under normal operating conditions**. These additional protective measures are partly the responsibility of the user as well. Remember that the goal is not to achieve class 1 status for all lasers/products/facilities - the goal is safety.

Appendix A

Visible light

Light is a small part of the electromagnetic spectrum that can be perceived by the human eye. Which radiation is actually "visible" depends on the individual person. Therefore, the visible area must be defined. For this purpose, there are two different definitions:

a) Definition according to CIE*: 380 nm – 780 nm.

b) Definition according to IEC**: 400 nm – 700 nm.
(this definition is applicable in terms of laser safety)

Moreover, not every colour is perceived as equally bright. Green light, for example, is perceived as 10 times brighter than red light at the same power. To this end, many attempts with test subjects have been performed in order to achieve a luminous efficiency curve, which was subsequently standardised. This was published under DIN 5031 in Germany – see figure A.

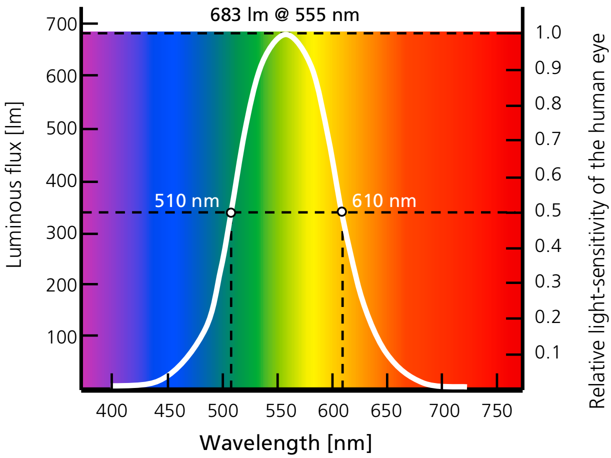


Fig. A: Standard spectral sensitivity curve V(λ) for daytime vision pursuant to DIN 5031. For night vision, the curve must be partially moved about 50 nm towards the blue range.

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* Commission Internationale de l'Éclairage (CIE), the international commission on illumination, does not define strict boundaries.

** International Electro-technical Commission

The photometric unit for luminous flux is the lumen (lm). Luminous flux is a measure of the perceived, total visible radiation emitted, i.e. the measure takes into account the wavelength-dependent sensitivity of the human eye. The luminous flux corresponds to the beam power or the radiant power in radiometry. The relationship between the physiological size of luminous flux and the physical (radiometric) radiant flux is referred to as the photometric equivalent of radiance $K(\lambda)$. The wavelength $\lambda = 555$ nm is the maximal value and is designated with K_m and has a value of 683 lumen/watt (1725 lm/W for night vision). This means that a monochromatic light source, which radiates a physical radiation power of 1 watt at $\lambda = 555$ nm, produces a luminous flux of 683 lumen.

Mathematically speaking, the entire radiant flux ϕ results from the spectral radiant flux of $d\phi(\lambda)/d\lambda$ weighted with the $V(\lambda)$ curve:

$$\phi = K_m \cdot \int_0^\infty \frac{d\phi(\lambda)}{d\lambda} \cdot V(\lambda) \cdot d\lambda$$

Appendix B

TEM-modes

The abbreviation "TEM" stands for "transversal electromagnetic". This term alludes to the fact that the observed wave is electromagnetic in nature. The field vector of electric-field strength oscillates transversely to the direction of propagation (the electric field vector is used as a reference value).

Three indices are used for lasers with cylindrical symmetry to describe the TEM modes: TEM_{plq}, whereby p stands for the number of zeros in the radial direction, and l represents the number of zeroes along the circumference. Therefore, q describes the longitudinal field. However, the index q is not written because only beam cross-sections are observed. Figure B shows a few mode examples.

Lasers with rectangular symmetry form rectangular modes with rectangular forms. The modes are described with TEM_{mn}. m describes the number of zeros in the horizontal direction (x) and n describes the number of zeros in a vertical direction (y).

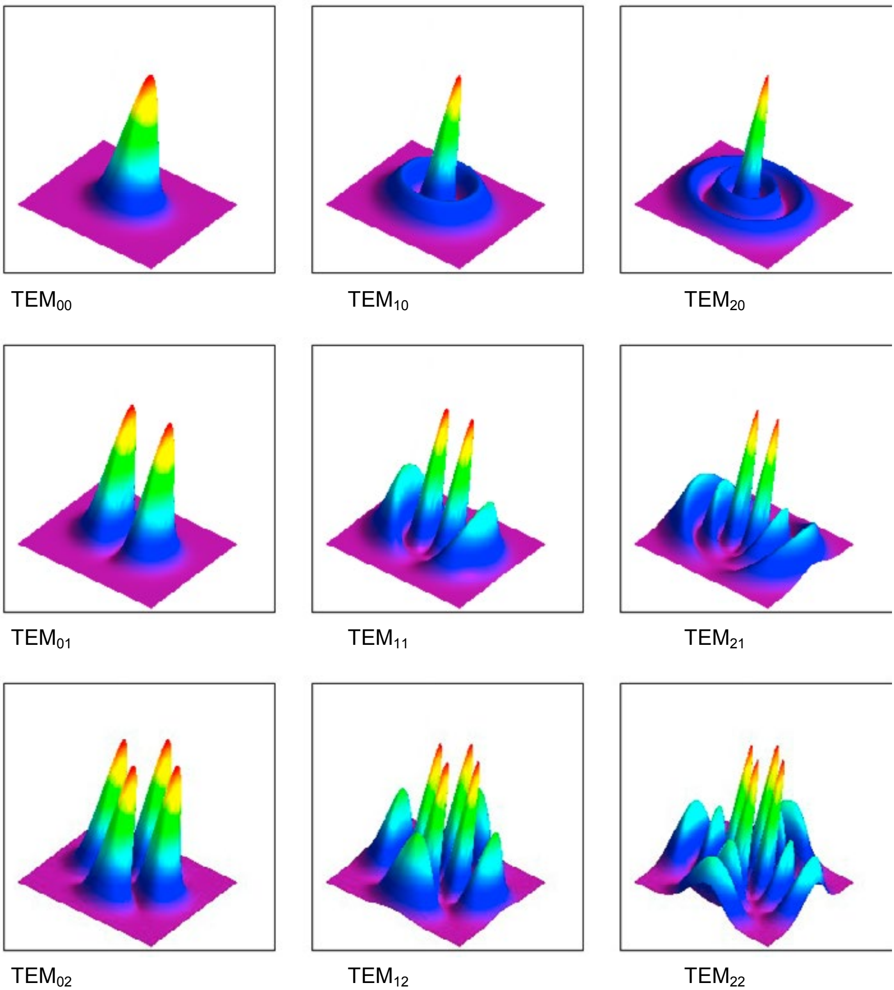

Fig. B: Examples for different modes

This brochure is the result of cooperation between

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HSP – M 080.1 – 02/2017 rer
Layout: Grafikstudio Hutter

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An accessible PDF of this publication conforming to PDF/UA is available on www.auva.at/publikationen.

Media owner:
Allgemeine Unfallversicherungsanstalt (AUVA), Adalbert-Stifter-Strasse 65, 1200 Vienna, Austria
Printed in Austria