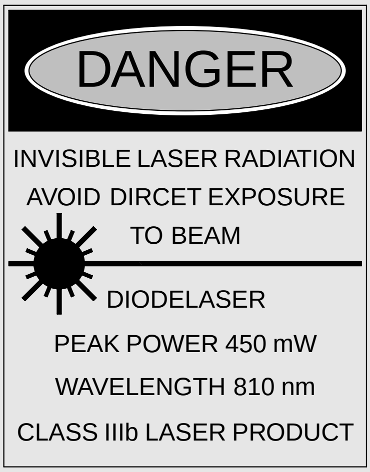
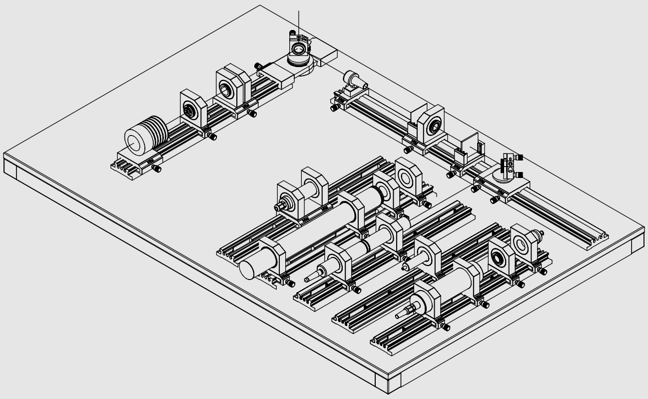
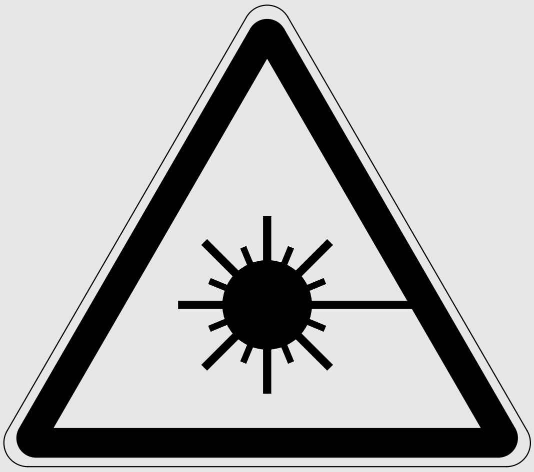
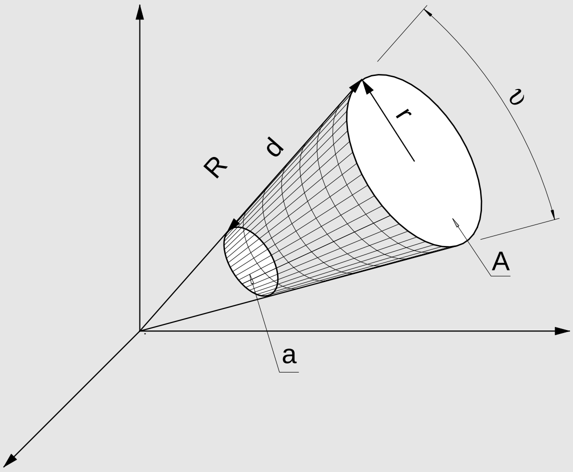






EXP20 LASER SAFETY



MEOS

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1 Introduction

In this experiment you are requested to convert the essential theoretical contents regarding "Laser Safety" into practice. The application and use of the basics in calculation defined within the standards is submitted and trained by means of practical examples. The experiment is composed of seven segments. Aspects such as the following ones have been respected: determination of the maximum permissible radiation for skin and eyes, minimum safety distance from a radiation source for direct and indirect irradiation of the skin and the eyes, demonstration of the damaging effect of laser radiation and the characterisation of pulsed laser systems. In addition the experiment is supposed to generate a sensitivity for the dangers of laser use.

2 Fundamentals

Within this section some selected topics (especially tables needed for calculations) with regard to laser safety are presented in a short version. This is to be understood as a survey and aid and is not sufficient for the understanding of the complete experimental content. The fundamentals of VBG[1], EN 60825-1[2] or corresponding literature [3] must be known. The dangers of lasers are understood by the characteristic properties of the laser radiation. In comparison with other optical radiation sources a high energy and power density is attained. Because of the generally small beam divergence the radiation density can be very appreciable even at large distances from the laser (potential danger of lasers used in metrology). Besides of the direct radiation also reflected and scattered radiation can cause damage at a large distance from the radiation source. A comparison of radiation densities is shown in Table 1 for different radiation sources. The small radiation density of conventional radiation sources can partially be explained by their emission characteristics. The emission is performed into a large solid angle with priority (frequently in approximation into the total space). Besides to directly looking into the beam the main sources of danger when using lasers are reflection and scattering (for example in material processing), non-shielded beams (special danger with UV- and IR- radiation) and radiation sources which are not stationary like scanners and movable mirrors.

Radiation source	**Intensity W/cm^2**
Solar constant	0.14
Sun with magnifying lens	10^2 - 10^3
Gas flame	10^3
Arc lamp	10^4
Electron beam	10^7 - 10^8
Continuos Laser	10^7
Pulse Laser	10^8
Giant pulse Laser	10^{10} - 10^{14}

Table 1: Comparison of typical radiation intensities for various light sources

Laser radiation can be generated within a broad spectral range. It extends from a few nanometer up to some hundred micrometers and is, in many cases, outside of the visible spectrum. Some examples are shown in Tab. 2. The damage of the biological tissue (skin, eye) depends strongly on the wavelength and on the duration of the radiation. This is of great importance under safety aspects when classifying the lasers and fixing radiation limits. In this regard the maximum permissible radiation values are very different for the lasers listed in Table 2. the spectral range between 180 nm and 10^6 nm has been subdivided into 11 sub-ranges with partially very fine graduation due to actual standards.

Laser	Wavelength nm	cw power/ pulsed peak power
Hydrogen (H_2)	116, 123, 160	-/ 1 MW
Nitrogen (N_2)	337	-/ 5 MW
Excimer	193, 248, 308, 351	-/ 1000 MW
Argon (Ar^+)	488, 514	10W /-
HeNe	543, 594, 632.8	<1W /-
Nd:YAG	473, 532, 1064	2 kW / 1TW
GaAlAs, In-GaAsP	650 - 1500	some Watt /-
CO_2	10600	20kW / 100TW
1 kW =1000 Watts, 1 TW = 10^9 kW		

Table 2: Survey of the attainable powers and emission wavelengths of some lasers. Excimer, Nd:YAG and CO_2 - lasers are particularly used in material processing

2.1 Laser safety classification according to IEC 825

The classification of lasers into classes signifies an increase in danger with increasing class number. In this way a laser system can directly be judged upon even by non-experts with regard to its potential of danger.

Class 1:
A laser of class 1 is considered as safe over an exposition time not exceeding 8 hours (30000 s). Systems with built-in lasers of higher class number can also be considered in this category (example: CD-player containing a class 3A Diode Laser) if they have been secured with a protective housing with safety interlocks in such a way that under no circumstances Laser light can leave the system.

Class 2:
Lasers of lower power in the visible spectral range (400 – 700 nm). The maximum laser power is permitted in maximum up to 1 mW. These lasers are not really safe. Nevertheless the eye protection is guaranteed by the eye lid reflex (t = 0.25 s). That means if the eye will hit by such a laser beam the natural reflex of shutting the eye is sufficient to prevent any damage of it.

Class 3A:
Generally these lasers are safe when looking to it with the naked eye and without optical device like glasses or binoculars. The rule of thumb is: the maximum power P_L is allowed to be 5 mW if the power density E does not

exceed a value of 25 W/m^2. In this case a maximum power of 1 mW is allowed to enter the eye without serious danger presuming a pupil diameter of 7 mm. In the non-visible spectral range (UV, IR) the danger for the eye is comparable with the one for lasers of class 1. A direct view into the beam with optical devices is always dangerous and should be avoided.

Class 3B:
Continuous working (cw) Lasers with a maximum power of 500 mW. The radiation is always dangerous for the eye as well as for the skin.

Class 4:
Lasers of class 4 are always dangerous for eyes and skin even due to diffuse reflection. There is danger of fire and explosion.

Although it seems to be simple to classify a certain Laser into one of the 5 safety classes so far, but the knowledge of the output power alone is not sufficient. Responsible for a damage of the human eye or skin is at least the intensity of the laser beam. Since the intensity is defined as power per square centimetre (W/cm^2) one has to know the actual laser power and the dimension of the laser beam for the location or distance L from the laser for which the safety considerations have to be performed.

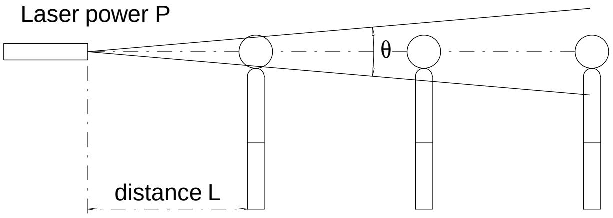


Fig. 1: The larger the divergence θ of the Laser will be the lower the intensity and potential danger will be at more distanced points for an observer

In the next chapter the limits for this intensity or in other words the maximum permissible exposure also termed as MPE value will be discussed in detail.

2.2 The accessible emission limit (AEL)

Limiting values of the AEL are defined for the individual laser classes. Here the wavelength as well as the duration of emission or radiation are the decisive parameters.

Whereas the limiting values for the maximum permissible radiation (MPR) are defined by the wavelength or by a mixture of wavelengths, by the duration of emission (of special importance for pulsed systems) and by the irradiated part of the body (eyes, skin).

For the irradiation of the eye this value is mainly given by the size of the image of the light beam produced on the retina and therefor the subsequent consideration are based on the limits for permitted exposure of the retina. In this context we will briefly discuss the interaction and possible damage of light with biological tissues
The damage of biological tissue through optical radiation is caused by various wavelength dependent mechanisms. Light which is absorbed in tissue is generally converted into heat and causes so-called thermal damages. Furthermore, thermo acoustical and photochemical reactions can occur. Keywords in this context are de-naturation of proteins and enzymes, coagulation, explosive evaporation of tissue (cavitation) and photo ablation. Examples of the damaging effect of laser radiation on skin and eyes are represented in Table 3 as a function of the wavelength.

The limiting values, fixed due to standards, differ with regard to the effect of laser radiation on:

1) The cornea of the eyes (direct view into the beam)
2) The cornea of the eyes at a view of extended sources or after diffuse reflection
3) The skin

Wavelength	Spectral class	Eyes	Skin
100 - 280 nm	UV-C Far UV	Photo ceratitis	Red colouring, burning danger of cancer
280 - 315 nm	UV-B Medium UV	Photo ceratitis	Progressive skin ageing danger of cancer
315 - 400 nm	UV-A Near UV	Photochemical cataract	Browning, burning photosensitive reactions
400 - 780 nm	Visible	Photochemical and thermal damage of the retina	Browning, burning photosensitive reactions
780 - 1400 nm	IR-A Near IR	Burning of the retina cataract	Burning, photosensitive reactions
1400 - 3000 nm	IR-B Middle IR	Burning of the cornea, cloudiness of lens, streaks in the eye chamber liquid	Burning, photosensitive reactions
3000 - 10000 nm	IR-C Far IR	Burning of the cornea	Burning, photosensitive reactions

Table 3 : Examples of the damaging effect of optical radiation on biological tissue. The resulting biological effects are partially used for therapeutically treatment in laser medicine

1) **Eyes**

Here the limiting values within the visible and near IR-range ($400 < \lambda/\text{nm} < 1400$) are particularly low due to the spectral properties of the human eye. In this wavelength range radiation enters the eye and is focused onto the retina. For a presumed pupil diameter of 7 mm the image on the retina can reach a size of about 10 µm. This corresponds to an increase of the power density by a factor of 500 000.The limiting values, currently fixed for irradiation of the eyes at direct view into the beam (irradiation of the cornea) are shown in Table 5 due to standard EN 60825-1. When calculating the MPR-values the correction factors C_i , T_i have to be applied. For exposures under 10^{-9} s there are no or only limited information with regard to the effect of ultra short laser pulses for the time being. For this time range the MPR-values have been derived from the values of an exposure or pulse duration of 10^{-9} s. Generally all the MPR-values are below the recognised and scientifically proved risk levels. Nevertheless, they are not to be treated as precise limiting values in between "safe" and "dangerous".

2) **Skin**

The structure of the limiting values within the spectral range $400 < \lambda/\text{nm} < 1400$ is relatively simple for the irradiation of the skin, since - compared with the eye - there is no focussing effect. The relevant part of the actual DIN EN 60825-1 is shown in Tab. 6.

MPR-values irradiation of human skin (DIN EN 60825-1)			
λ/nm	Duration of Exposition t_E in sec		
	10^{-7}-10	10-10^3	10^3-$3*10^4$
400-700	$1.1*10^4\ t_E^{0.25}$ Jm^{-2}	2000 Wm^{-2}	2000 Wm^{-2}
700-1400	$1.1*10^4\ t_E^{0.25}$ Jm^{-2}	2000 C_4 Wm^{-2}	2000 C_4 Wm^{-2}
C_4=1 for λ<700nm $C_4=10^{0.002(\lambda-700)}$ for 700< λ/nm <1050 C_4=5 for λ>1050nm			

Table 4: MPR values for irradiated human skin

MPR-values for the irradiation of the cornea of the eye (direct view into the beam) ↘			**Time Duration t of Emission or Exposition in sec.**								
			$<10^{-9}$	$10^{-9}-10^{-7}$	$10^{-7}-1.8\cdot10^{-5}$	$1.8\cdot10^{-5}-5.0\cdot10^{-5}$	$5.0\cdot10^{-5}-10^{-3}$	$10^{-3}-10$	$10-10^{3}$	$10^{3}-10^{4}$	$10^{4}-3\cdot10^{4}$
Wavelength λ	UV	180-302.5 nm	$3\cdot10^{10}\ \mathrm{W/cm^2}$	30 J/m²							
		302.5-315 nm		C_1 J/m² (t<T1) C_2 J/m² (t<T1)					C^2 J/m²		
		315-400 nm		C_1 J/m²					10^4 J/m²	10 W/m²	
	VIS	400-550 nm	$5\cdot10^{10}\cdot C_6\ \mathrm{W/cm^2}$	$5\cdot10^{-3}\cdot C_4\cdot C_6\ \mathrm{J/m^2}$		$18\cdot t^{0.75}\cdot C_6\ \mathrm{J/m^2}$			$10^2\cdot C_6$ J/m²		$10^{-2}\cdot C_6$ W/m²
		500-700 nm							$10^2\cdot C_3\cdot C_6$ J/m² ($t>T_2$) $18\cdot t^{0.75}\cdot C_6$ J/m² ($t<T_2$)		$10^{-2}\cdot C_3\cdot C_6$ W/m²
	IR	700-1050 nm	$5\cdot10^{6}\cdot C_6\cdot C_4\ \mathrm{W/cm^2}$	$5\cdot10^{-3}\cdot C_4\cdot C_6\ \mathrm{J/m^2}$		$18\cdot t^{0.75}\cdot C_4\cdot C_6\ \mathrm{J/m^2}$				$3.2\cdot C_4\cdot C_6\ \mathrm{W/m^2}$	
		1050-1400 nm	$5\cdot10^{7}\cdot C_6\cdot C_7\ \mathrm{W/cm^2}$	$5\cdot10^{-2}\cdot C_6\cdot C_7\ \mathrm{J/m^2}$			$90\cdot t^{0.75}\cdot C_6\cdot C_7\ \mathrm{J/m^2}$			$16\cdot C_6\cdot C_7\ \mathrm{W/m^2}$	
		1400-1500 nm	$10^{12}\ \mathrm{W/cm^2}$	10^3 J/m²			$5620\cdot t^{0.25}\ \mathrm{J/m^2}$		10^3 W/m²		
		1500-1800 nm	$10^{13}\ \mathrm{W/cm^2}$	10^4 J/m²							
		1800-2600 nm	$10^{12}\ \mathrm{W/cm^2}$	10^3 J/m²				$5600\cdot t^{0.25}$ J/m²			
		2600 – 10^6 nm	$10^{11}\ \mathrm{W/cm^2}$	100 J/m²	$5620\cdot t^{0.25}\ \mathrm{J/m^2}$						

Table 5: Representation of the maximum permissible radiation values, MPR, as a function of the wavelength λ and the duration of exposure t. For calculation the correction factors C_i, T_i as well as suitable aperture diameters have to be taken under consideration. (DIN EN 60825-1, 1994)

$C_1 = 5.6\cdot10^3\cdot t^{0.25}$	$C_2 = 10^{0.2\cdot(\lambda-295)}$
$C_3 = 10^{0.015\cdot(\lambda-550)}$	$C_4 = 10^{0.002\cdot(\lambda-700)}$ 700 nm < λ < 1050 nm
C_4 = 5 for λ > 1050 nm	$C_5 = N^{-0.25}$
C_6=1 for point light sources	C7=1 1050 nm < λ < 1150 nm
$C_7 = 10^{0.018\cdot(\lambda-1150)}$ 1150 nm < λ < 1200 nm	C7=8 λ > 1200 nm
$T_1 = 10^{0.8\cdot(\lambda-295)}\cdot10^{-15}$ s	$T_2 = 10\cdot10^{0.02\cdot(\lambda-550)}$ s

Table 6: Used Constants of Table 5

A graphical representation of the maximum permissible energy density as a function of the wavelength and exposure is shown in Fig. 2. Actually it is an illustration of Table 5. Particular attention has to be paid to the logarithmic scaling of the z-axis (MPR values). It is evident that the MPR-values are very low in the visible spectral range between 400 and 700 nm.

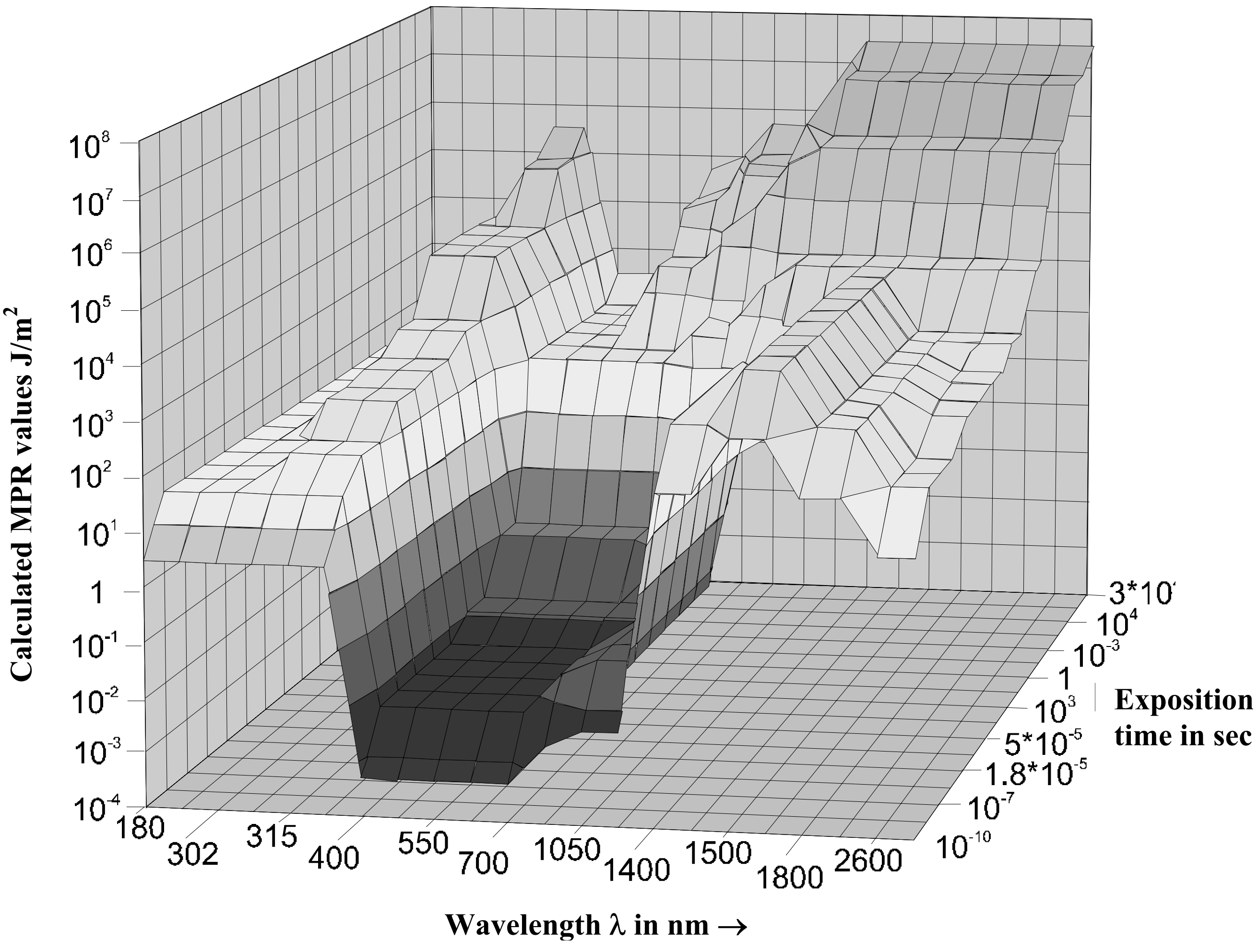


Fig. 2: Logarithmic representation of the MPR values versus the wavelength λ and the exposure time t. Within the visible spectral range (400 < λ/nm < 700) the MPR values are particularly low.

2.3 Laser safety goggles

The standards request suitable laser safety goggles for use of laser systems when no other precautions can be taken to avoid the occurrence of dangerous radiation. Actual standards for laser protective glasses are defined for example in EN207 and for laser safety goggles in EN208. These glasses are comparable to a filter with a transmission $\tau(\lambda)$. A measure for the attenuation of a filter is its optical density D.

$$D = -\log \tau(\lambda)$$

Example: an optical density of 6 represents an attenuation factor of 10^{-6}.
Laser safety goggles for visible Laser adjustment purposes are characterised by a small attenuation within the visible spectral range and transmit in this range a residual radiation for performing the adjustments. The attenuation is much stronger outside the visible range. The total range is subdivided into five protective classes (Table. 6).

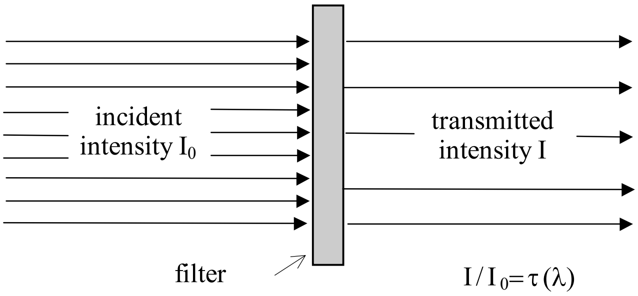


Fig. 3: Illustration of the attenuation of laser radiation by a filter with spectral transmission $\tau(\lambda)$ or optical density D

Protective class	Spectral transmissions $\tau(\lambda)$	Maximum permitted Laser power P/Watt	Maximum permitted peak energy Q/Joule
R1	$10^{-2} < \tau(\lambda) < 10^{-1}$	0.01	$2 \cdot 10^{-6}$
R2	$10^{-3} < \tau(\lambda) < 10^{-2}$	0.1	$2 \cdot 10^{-5}$
R3	$10^{-4} < \tau(\lambda) < 10^{-3}$	1	$2 \cdot 10^{-4}$
R4	$10^{-5} < \tau(\lambda) < 10^{-4}$	10	$2 \cdot 10^{-3}$
R5	$10^{-6} < \tau(\lambda) < 10^{-5}$	100	$2 \cdot 10^{-2}$

Table 8: Representation of the protective classes of the spectral transmission $\tau(\lambda)$ and the maximum permissible casual radiation (no intentional, direct view into the beam) for laser adjustment glasses (complies with DIN EN 208, 12/93)

Protection classes L	maximum spectral Transmission $\tau(\lambda)$	Permissible power or energy density in the range of $315 < \lambda/\text{nm} < 1400$ for cw-Laser (**CW**) given in W/m^2, pulse or giant pulse (**I, R**) given in J/m^2 and mode coupled pulsed lasers (**M**) given in W/m^2		
		CW	I, R	M
L 1	10^{-1}	10^{2}	$5 \cdot 10^{-2}$	$5 \cdot 10^{7}$
L 2	10^{-2}	10^{3}	$5 \cdot 10^{-1}$	$5 \cdot 10^{8}$
L 3	10^{-3}	10^{4}	$5 \cdot 10^{0}$	$5 \cdot 10^{9}$
L 4	10^{-4}	10^{5}	$5 \cdot 10^{1}$	$5 \cdot 10^{10}$
-	-	-	-	-
L 10	10^{-10}	10^{11}	$5 \cdot 10^{7}$	$5 \cdot 10^{16}$

Table 7: Representation of the protective classes, the spectral transmission and the permissible power and energy density for laser safety filters used for either safety goggles or protective shields

Laser safety goggles for pure protection and not for Laser alignment purposes are available and classified for a wavelength range between 0.180 and 1000 µm. The protection is maintained even for a direct view into the laser beam. An extract of the protective zones for the spectral range from 315 nm to 1400 nm is shown in Table 7. The basis was a duration of 10 s or 100 pulses at a small pulse repetition rate. The degree of transmission of the protective glasses is not allowed to change under the influence of the laser radiation. A HeNe-laser beam is, for instance, attenuated by a factor of 10^1 when using a L1 protective class. Depending on the output power of the Laser and the maximum permissible radiation decides which type of protective class should be used.

3 Theory

To take the right measures for Laser safety reasons one has to know the intensity of the considered light source for a given distance. When this intensity is below the MPR value their will be no risk for damaging the eye. The intensity is defined as the flux of radiation passing a cross section of 1 square metre. The flux of radiation is measured in Watts and can be either measured or one trusts the manufacturer of the particular light source or Laser. Another definition of the intensity is quite often used as radiation namely the flux per solid angle $d\Omega$

3.1 NOHD, Nominal Ocular Hazard Distance

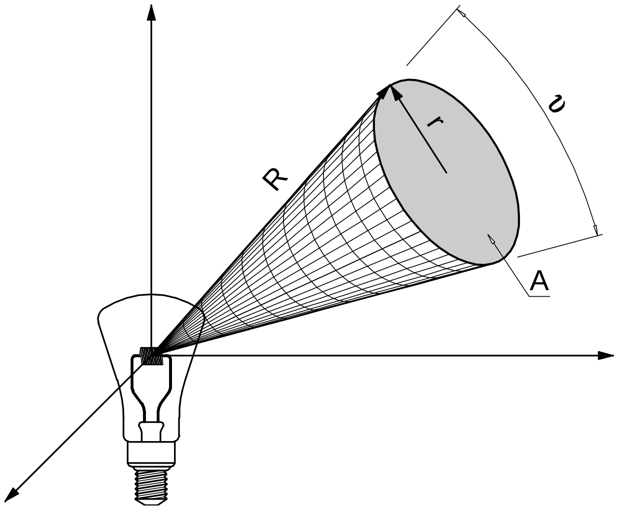


Fig. 4:

The frequently used expression, “solid angle $d\Omega$” will be clarified once again with the help of Fig. 4. The solid angle $d\Omega$ is defined as the ratio of the spherical surface A to the total surface of the sphere of radius R:

$$d\Omega = \frac{A}{4\pi \cdot R^2}$$

For $A = 1\ m^2$ and $R = 1$ m (unit sphere)we get the unit of the solid angle, the steradian sr

$$1 sr \equiv \frac{1}{4\pi}$$

The solid angle 1 sr cuts a cone out of the unit sphere with an angle υ (see Fig.20) If the surface of the corresponding spherical section is approximated by the circular surface πr^2 we get with

$$A = \pi r^2$$

$$\text{for} \qquad A = 1\ m^2$$

$$r = \frac{1}{\sqrt{\pi}}$$

and for υ :

$$\sin(\frac{\upsilon}{2}) = \frac{r}{R} = \frac{1}{\sqrt{\pi}}$$

$$\text{or} \qquad \upsilon \cong 34°$$

The light that passes by the solid angle unit is called radiant intensity I_e and is measured in W/sr. To measure the radiant intensity in Wsr^{-1}, it is necessary to know the solid angle used during the measurement. A diaphragm with a radius r is used for this purpose and a distance R to the radiator is selected. The solid angle $d\Omega$ for this arrangement is therefore

$$d\Omega = \frac{\pi \cdot r^2}{4 \cdot \pi \cdot R^2} = \frac{1}{4} \cdot \frac{r^2}{R^2}$$

If, for example, the radius of the diaphragm is 15 mm and the distance to the light source is 80 cm, the solid angle will be

$$d\Omega = \frac{1}{4} \cdot \frac{0{,}015^2}{0{,}8^2} = 8{,}79 \cdot 10^{-5} sr$$

If the total emitted radiation into the full solid angle of 4π is 250 mW, for example, the flux P_e through the diaphragm will be:

$$P_e = P_\Omega \cdot \frac{d\Omega}{\Omega} = P_\Omega \frac{1}{4\pi} \cdot \frac{A_d}{A_R}$$

and the intensity:

$$I_e = \frac{P_e}{A_d} = P_\Omega \cdot \frac{1}{4\pi} \cdot \frac{1}{A_\Omega} = P_\Omega \cdot \left(\frac{1}{\pi \cdot R} \right)^2 \qquad \textbf{Eq. 1}$$

$$I_e = P_\Omega \cdot \left(\frac{1}{\pi \cdot R} \right)^2 = 0.25 \cdot \left(\frac{1}{\pi \cdot 0.8} \right)^2 = 0.04 \frac{W}{m^2}$$

From Eq. 1we can deduce, that for a fixed aperture the intensity will decrease inverse quadratically with increasing distance R from the light source.

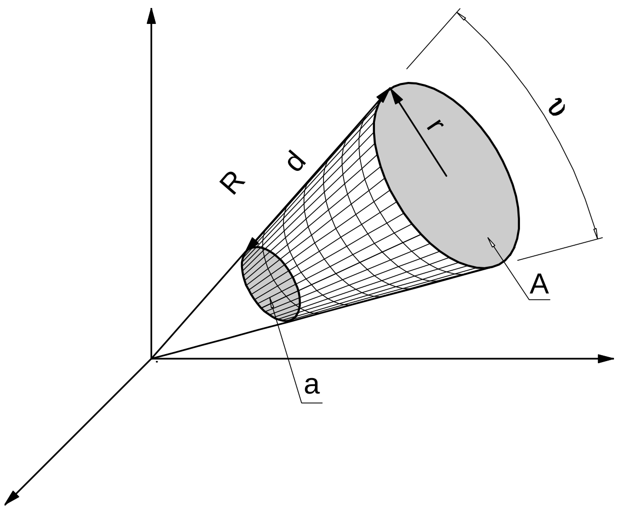


Fig. 5: Surface emitter

From the surface a the light source emits the power P_0. In point of view of laser safety we have to know the intensity at a distance d where for instance the eye of the observer is located. The intensity at the surface is simply

$$I_s = \frac{P_0}{a}$$

and the intensity at the distance d will be:

$$I_d = \frac{P_0}{A}$$

Commonly the cross section a as well as the beam radius r_a is known and we have to derive an expression for A. Since

$$r_A = r_a + l \cdot \tan\left(\frac{\vartheta}{2}\right)$$

we find for the intensity I_d :

$$I_d = \frac{P_0}{\pi \cdot \left(r_a + l \cdot \tan\left(\frac{\upsilon}{2}\right)\right)^2}$$

If we consider the case of Laser beam, we know that the divergence or the angle υ is fairly smaller than 15 °. In this case we can use the approximation:

$$\tan(\vartheta) \cong \vartheta$$

To be in accordance with the IEC 825 nomenclature we now will assign the beam diameter of the laser beam to d_0, the distance from the Laser exit as z, the intensity at location z as E and finally the divergence angle as θ.

$$E = \frac{4 \cdot P_0}{\pi \cdot (d_0 + z \cdot \theta)^2} \qquad \textbf{Eq. 2}$$

A Laser can be considered as save when for each distance z

$$\text{MPR} \le \text{E} \ \textbf{is.} \qquad \textbf{Eq. 3}$$

For a particular Laser the MPR is taken from Table 5. With the specification given by the supplier the value for E is calculated using the power, the beam diameter at the beam exit, the divergence and the location for which the Eq. 3 must be fulfilled. It may happen, that Eq. 3 is only true for a certain distance z. The minimum of the distance where the Laser can be considered as save is termed as nominal ocular hazard distance or as NOHD. This value can be derived from Eq. 2 and Eq. 3 as:

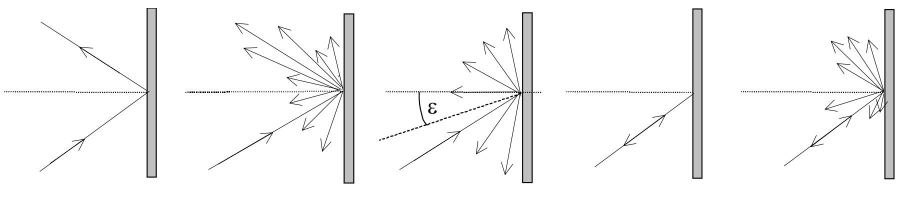
$$z_{\text{NOHD}} = \frac{1}{\theta} \cdot \left(\sqrt{\frac{4P}{\pi \cdot \text{MPR}}} - d_0\right) \qquad \textbf{Eq. 4}$$

If a negative value for z_{NOHD} is obtained, the laser is save and means total safety for each distance.

3.1.1 NOHD for diffuse radiator

By scattering and diffuse reflection the light energy is distributed in a more or less extended space depending on the type of scattering surface. (see Fig. 6) The scattering surface can be considered as a "secondary light source" with modified radiation properties. For the diffuse scattering of a laser beam a hemispherical surface A is anticipated as irradiated area for the approximate calculation of the power density E. It is presumed that the radiating surface emits isotropically into the halve solid angle 2π and onto a considered surface of area $A = 2\pi\ r^2$. The distance to the scattering surface shall be large compared to its diameter. In this case we consider the scattering surface as point source as discussed earlier (Eq. 1). But know we have to modify the equation due to the fact that the emission fills only the half solid angle, therefor:

$$E = 2 \cdot P \cdot \left(\frac{1}{\pi \cdot z}\right)^2 \qquad \textbf{Eq. 5}$$



ideal reflexion (mirror)

diffuse and partially bundled

diffuse reflexion (Lambert emitter)

retro reflector

retro reflexion partially diffuse and bundled

Fig. 6: Different types of reflection and corresponding light intensity distributions

Setting E to MPR to derive the NOHD for diffuse scattered Laser light we obtain the expression for z_{NOHD} :

$$z_{\text{NOHD}} = \frac{1}{\pi} \cdot \sqrt{\frac{2 \cdot P}{\text{MPR}}}$$

3.2 *MPR values for pulsed radiation*

Criteria:

- the irradiation by each single pulse within a pulse sequence is not permitted to pass the permissible value of a single laser pulse MPR_{single}
- the MPR-value for the average irradiation of a pulse sequence of duration T ($MPR_{average}$) is not allowed to pass the MPR-value of the irradiation by a single laser pulse of equal duration T. (equivalent pulse, no passing of $MPR_{equiv.}$)
- the irradiation by each single laser pulse within the pulse sequence is not allowed to pass the MPR-value of a single pulse multiplied by the correction factor C_5 (see Table 5)

Conclusion:

From all determined MPR-values

$$(MPR_{single}, MPR_{average}, MPR_{corr.})$$

the most limiting value is decisive. That means this MPR-value has to be applied to each individual laser pulse. Summarising the steps for the determination of the MPR-value for a pulsed laser system.

1. fixing the exposure T of the pulse sequence (for example 0.25 s in the visible spectral range)
2. determination of the duration τ_P of a single laser pulse
3. determination of the number of pulses N_T during the exposure T
4. determination of the MPR-value for a single laser pulse from Tab. 4 ($H_{MPR, single}$)
5. determination of the MPR-value for an average radiation; here the MPR-value for an equivalent pulse of exposure T is determined from Table 5.
6. The average MPR-value is then calculated by

$$H_{MPR, average} = H_{MPR, equiv.} / N_T$$

7. determination of the MPR-value for a single pulse in connection with a correction factor
8. for the number of pulses during the exposure

$$H_{MPR, corr} = H_{MPR, single}\ C_5$$

9. selection of the most limiting MPR-value (smallest value from $H_{MPR, single}$, $H_{MPR, average}$, $H_{MPR, corr.}$)

Supplement: For irregular pulse sequences (example: modulated laser diodes) the highest instantaneous frequency (reciprocal value of the shortest pulse distance) has to be considered.

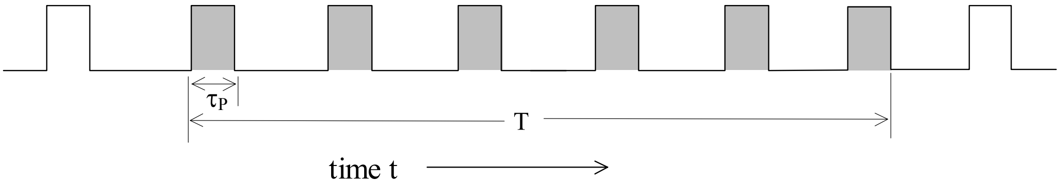


Fig. 7: Regular pulse sequence. The time T has been chosen for exposure. Six individual laser pulses are observed within the interval T. The temporal duration of a single laser pulse is τ_P.