Review Article

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Selecting laser eye protectors – a helping hand

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Abstract: The European laser safety standards EN 207, EN 208, and EN 12254 each contain an annex B, which serves as a guidance for the selection of products. These annexes are informative only and are therefore not binding. As there are a variety of hazard scenarios, it is not recommended to change these annexes to a normative status, through which they would become mandatory. Instead, it is recommended to allow users to apply their own skills and know-how in selecting appropriate products, justifying where and why they deviate from the guidance in the standards. This paper explains the background on which the guidance for selection in the annexes of the standards is based and shows physically meaningful leeway.

Keywords: European standard; laser safety; personal protective equipment.

1 Introduction

Individuals who may be exposed to laser radiation should take special care to protect their eyes because the retina belongs to the most sensitive tissues of the human body. The cornea of the eye, which is only ca. 0.5 mm thick, may be endangered by laser radiation. Various measures can be employed to protect the eyes. Technical and design measures shall be the first choice, in order to decrease the hazard as much as possible. These measures may include, for example, passive guards or screens in accordance with standard EN 12254 [1] and interlock devices. Second, administrative control measures should be defined and implemented. These may consist of operation manuals, restricting access to the hazard area, and training, for example. Details are given in the standard EN 60825-1 [2] and in national regulations. Finally, after these measures have been taken into account, laser eye protectors as per standards EN 207 [3] or as per EN 208 [4] for alignment shall be considered. Both types of protectors are Personal Protective Equipment (PPE) as per the European Directive 89/686/EEC [5]. Approval by a Notified Body is required for such products in Europe. Another important component of European regulations governing safety at work is Directive 2006/25/EC Artificial Optical Radiation [6], which lays down the minimum health and safety requirements regarding the exposure of workers to such sources.

Generally speaking, laser radiation may be released in various ways. Strong focusing of the beam or beam expansion is just as feasible as short pulses or continuous emission. This flexibility is ideal for the range of laser applications, but unfortunately, it makes the selection of PPE rather complex.

At the beginning of any selection process a risk assessment shall be performed, which takes into account all possible scenarios of exposure. All hazards shall first be reduced by technical and administrative measures. The worst case which remains thereafter shall provide the basis for selecting suitable PPE.

2 Hazard analysis

The hazard presented by laser systems depends on the laser source, the beam delivery system, and conditions at the point of interaction. The core question is: From which parts of the laser system can a hazard arise and in which form? To answer this, one can proceed component by component:

– **Source:** In most cases, the laser source is an enclosed unit with an aperture as the first point where laser radiation can be accessible. With diode pumped solid

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state lasers, the radiation of the pump laser might also be accessible. In rare cases, the radiation inside the laser resonator can be accessible. In the case of devices designed for frequency conversion, the accessibility of the basic wavelength should be checked for: either prior to the frequency conversion or at the aperture in the form of radiation, which has not been converted entirely.

– **Beam delivery system:** The beam delivery system usually consists of optical components, between which the laser beam is freely guided or of a laser beam coupled into an optical fiber. One should check whether laser radiation could be released along this path. With fiber-based delivery systems, take into account that the fiber might break. In this case, one can assume that the beam characteristics will be approximately the same as if the radiation was released from the regular fiber head. The beam divergence is then governed by the numerical aperture of the fiber. At the end of the beam delivery system, there may be an objective, which focuses the laser radiation onto the target. Direct exposure to the focus is usually unlikely, with the exception of devices for medical or beauty applications used to treat facial areas of patients.
– **Target:** The target can be exposed to a focused or collimated laser beam. Many materials show strong reflection so long as plasma has not been generated. Usually, one may assume that such reflections show the same divergence as the incident beam. Thus, a laser beam focused onto the target by an objective with focal length *f* would achieve the same diameter as at the objective at a distance of *f* after reflection. If plasma is formed at the target by sufficiently high irradiation, the laser power will usually be absorbed by the plasma. However, if a target is exposed to ultrashort laser pulses and forms plasma, then, the plasma can reflect the laser radiation.

Normally, different hazards will be calculated when servicing laser systems compared to during regular operation. The hazard may often be reduced while servicing laser systems by running the system at lower power.

Laser eye protectors are intended to cover a residual hazard and must not be used to stare directly into the beam. All other possible technical and administrative measures, which may include enclosures, interlocks, and a limitation of the possible angle of emission, shall be implemented prior to laser eye protectors being selected.

Laser eye protectors do not necessarily survive an exposure to laser radiation without any damage. Even if selected properly and having protected the eyes sufficiently when an incident occurs, the eye protector may not be suitable for further use. The major requirement is to protect the user for at least 5 s so they can react, i.e. leave the area of hazard and switch off the laser.

3 Evaluation of the exposure

The standards EN 207 and EN 12254 distinguish between the modes of operation, which are defined in Table 1. The exposure must be evaluated for all modes of operation, which are possible with the laser system concerned. The evaluation process is described in Annex B of each standard.

The standard EN 208 considers only one mode of pulsed operation.

The following factors play an important role:

– **Laser wavelength:** Some lasers can be run at different wavelengths or emit a wavelength range. In operation mode M with pulse durations shorter than picoseconds (ultra-short pulse lasers), you must take into account a broadening of the emitted wavelength range, whereby the pulse energy might be unevenly distributed over the spectral range.
– **Continuous wave:** In cw operation, a constant laser power is emitted against which the eye protector must not fail over a certain time. An increased resistance time of 100 s is required for the reaction time to an exposure for screens for laser working places (EN 12254). For PPE (EN207 und EN 208), 5 s are considered to be sufficient because the user is able to react much faster. Many laser manufacturers give an average laser power, which indicates that it is not really cw, but a pulsed laser system with pulse repetition. It is possible

Table 1: Modes of operation as per EN 207 and EN 12254 for selecting an eye protector.

Character	Meaning	Definition
D	Continuous wave (cw)	Constant power over a duration, which depends on the wavelength (see Table 2)
I	Impulse	Emission of short duration (also periodic) of at least 1 μs up to the duration for mode D (see Table 2)
R	Giant impulse	Emission of very short duration (also periodic) of at least 1 ns up to 1 μs
M	Mode coupled	Emission of extremely short duration (almost always periodic), but <1 ns

to adjust the power within certain limits for many laser systems. In this case, the decisive factor when determining the hazard is the maximum power emitted.

- **Pulsed operation:** The energy of a single pulse, the pulse duration, and repetition frequency are often adjustable within certain limits. These parameters may also depend on one another. Therefore, different sets of parameters should be considered. This should include at least the situations with the minimum and maximum pulse energy, with the maximum repetition frequency in each case. The average laser power is the pulse energy times the repetition frequency. Therefore, if two parameters are known, then, the missing parameter can be calculated. In the case of ultrashort pulsed lasers, the peak power of a single pulse is often required. This can be approximately evaluated by dividing the pulse energy by the pulse duration, if we assume a rectangular pulse shape. However, there is no definition of the peak power given in the standard. So other approximations may also be useful.
- **Beam diameter:** In laser safety, the beam diameter is defined by the circle diameter, which contains 63% of the total power or energy. Rectangular beam profiles may be converted to circles of the same area. However, the current version of the standard does not define this in detail. There are two different methods of evaluating the beam diameter at the location of a possible exposure, depending on the beam delivery system. For divergent beams, the diameter at a distance of 100 mm from the focus, fiber head, or aperture may be used. Figure 1 shows the beam diameter in a distance of 100 mm from the fiber head over the numerical aperture of the fiber (Figure 1).

The smallest accessible beam diameter can be evaluated as follows, which can be useful if an exposure at the standard distance 100 mm is not possible. In this case, the beam diameter can be calculated approximately by

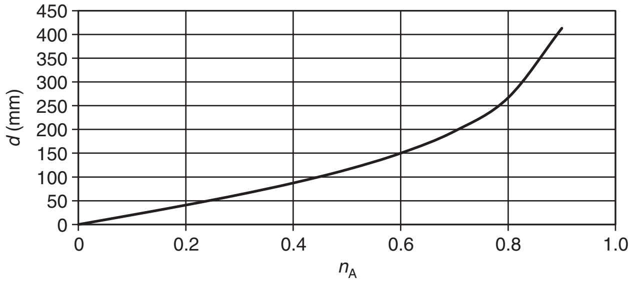

Figure 1: Beam diameter d over the numerical aperture n_A of a fiber at a distance of 100 mm from the fiber head.

$$d = d_0 \cdot \frac{x}{f}$$

where d_0 is the beam diameter at the objective, x is the distance from the focus, and f is the focal length of the objective. The direct exposure to the focus can be excluded in most cases. If this case does need to be considered, then very high required scale numbers may result, which are not always feasible from a product standpoint or sensible from a safety standpoint considering the potential hazard to the skin. The European standards EN 207 and EN 12254 do not define scale numbers larger than 10 and the standard EN 208 no larger than 5. Beyond these scale numbers, the irradiation is much too large to be able to achieve sufficient protection. In such cases, sufficient protection can only be achieved if additional protective measures of a technical or administrative nature are implemented.

The required scale numbers as per the European laser safety standards may be evaluated using these parameters. Software can be used to do this. But the evaluation can also be done manually as explained in the following sections.

Many laser devices work in the cw as well as in the pulsed mode. A combination of both modes of operation is also possible. For example, many solid state and CO_2 lasers show strong spiking to start with in cw emission. This is a short power peak like a pulse at the start of emission. After peaking, the power decreases to a constant value. Even if a laser can only be run in the pulsed mode, a cw load may occur. This is possible if during the critical time of 5 s (EN 207) or 100 s (EN 12254) a higher number of pulses are released. This is called quasi-cw operation. The impact of such subsequent pulses may cumulate and produce the same impact as in real cw operation. Furthermore, it is possible that long pulses may have the same impact as cw operation. This effect depends also on the wavelength.

4 Evaluation of the required scale numbers as per EN 207

To start with, obtain an overview of the operation mode(s) of the laser system as per Table 2. The wavelength λ and duration of the emission Δt are factors to consider. It is possible that these parameters mean that a pulsed laser must be handled like a cw laser. For lasers with a pulse repetition, a scale number for the D mode must also be calculated due to the average power.

Table 2: Scale numbers as per standard EN 207.

Scale number	Spectral transmittance $\tau(\lambda)$	Maximum energy and/or radiant exposure in the wavelength range								
		λ=180–315 nm			λ=>315–1400 nm			λ=>1400 nm–1000 µm		
		Mode of operation and pulse duration Δt (s)								
		D ≥3×10^4	I, R 10^{-9} to 3×10^4	M <10^{-9}	D >5×10^{-4}	I, R 10^{-9} to 5×10^{-4}	M <10^{-9}	D >0.1	I, R 10^{-9} to 0.1	M <10^{-9}
		E (W/m²)	*H* (J/m²)	*E* (W/m²)	*E* (W/m²)	*H* (J/m²)	*E* (J/m²)	*E* (W/m²)	*H* (J/m²)	*E* (W/m²)
LB1	10^{-1}	0.01	3×10^2	3×10^{11}	10^2	0.05	1.5×10^{-3}	10^4	10^4	10^{12}
LB2	10^{-2}	0.1	3×10^3	3×10^{12}	10^3	0.5	1.5×10^{-2}	10^5	10^5	10^{13}
LB3	10^{-3}	1	3×10^4	3×10^{13}	10^4	5	0.15	10^6	10^6	10^{14}
LB4	10^{-4}	10	3×10^5	3×10^{14}	10^5	50	1.5	10^7	10^7	10^{15}
LB5	10^{-5}	10^2	3×10^6	3×10^{15}	10^6	5×10^2	15	10^8	10^8	10^{16}
LB6	10^{-6}	10^3	3×10^7	3×10^{16}	10^7	5×10^3	1.5×10^2	10^9	10^9	10^{17}
LB7	10^{-7}	10^4	3×10^8	3×10^{17}	10^8	5×10^4	1.5×10^3	10^{10}	10^{10}	10^{18}
LB8	10^{-8}	10^5	3×10^9	3×10^{18}	10^9	5×10^5	1.5×10^4	10^{11}	10^{11}	10^{19}
LB9	10^{-9}	10^6	3×10^{10}	3×10^{19}	10^{10}	5×10^6	1.5×10^5	10^{12}	10^{12}	10^{20}
LB10	10^{-10}	10^7	3×10^{11}	3×10^{20}	10^{11}	5×10^7	1.5×10^6	10^{13}	10^{13}	10^{21}

Table 2 does not distinguish explicitly between modes I and R. If both modes need to be considered separately, the pulse durations can be concluded from Table 3 in the main body of standard EN 207, which is originally intended to select lasers for testing. The result is shown in Table 4.

In cw operation, the exposure is calculated by using the formula:

$$E=\frac{P}{A}\cdot F(d)$$

where A is the area of the laser beam, and P is the power or average power. Factor $F(d)$ takes the heat dissipation from the impact area to the surrounding material of the exposed component for laser beam diameter d, compared to the standard diameter d=1 mm, into consideration. Experiments have shown that the following values apply: For components made of glass $F(d)=d^{1.1693}$, and for components mainly from plastic

$$F(d)=d^{1.2233}.$$

At values d<1 mm, the heat dissipation is large compared to the laser energy absorbed by the impact volume, and $F(d)<1$ becomes valid. If such diameters are achieved by strong focusing, one should consider that the focus cell may be quite short. So in some of these cases, it is better to use $F(d)=1$. For beam diameters, d>15 mm, $F(d)=F(15\text{ mm})$ is true. For filters whose protection is based entirely on reflection, $F(d)=1$ is always true.

The scale number for mode D depending on the wavelength and the evaluated power density can now be selected from Table 2.

In the case of pulsed operation, the exposure is calculated using the formula

$$H=\frac{Q}{A}\cdot F(d)\cdot k\cdot k_{Ti}$$

where Q is the energy of a single pulse. In the case of repetitive pulsed operation, the scale number also depends on the repetition frequency, which is taken into account by factors k and k_{Ti}.

Factor k_{Ti} considers the phototoxic impact, which depends on the wavelength and repetition frequency.

Table 3: Cumulation of repeated pulses.

λ (nm)	T_i (s)	ν_{max} (Hz)
400 to <1050	18×10^{-6}	55.56×10^3
1050 to <1400	50×10^{-6}	20×10^3
1400 to <1500	10^{-3}	10^3
1500 to <1800	10	0.1
1800 to <2600	10^{-3}	10^3
2600 to <10^6	10^{-7}	10^7

Table 4: Separation of modes I and R.

λ (nm)	Mode R	Mode I
180–315	10^{-9}–10^{-6} s	>10^{-6} to 3×10^4 s
>315–1400	10^{-9}–10^{-6} s	>10^{-6} to 5×10^{-4} s
>1400–10^6	10^{-9}–10^{-6} s	>10^{-6} to 0.1 s

If the time between two subsequent pulses is greater than the wavelength-dependent time T_i as given in Table 3, $k_{Ti}=1$ is true. Otherwise, the energy of all pulses during time T_i must be cumulated and used instead of the single pulse energy Q. The repetition frequency ν for the evaluation of factor k must then be replaced by ν_{max} from Table 3, and one obtains

$$k_{Ti}=\nu_{max}\cdot 5s.$$

Factor k represents the thermal impact of pulsed laser radiation on tissue. If tissue is exposed to pulsed laser radiation repeatedly, the heat generated by the laser radiation cannot necessarily dissipate into the surrounding tissue fast enough. This will increasingly be the case as the repetition frequency increases. This is considered by factor k, which is

$$k=N^{1/4}.$$

This is only true in the range 400–10^6 nm, whereas outside this range, $k=1$. N is the number of pulses during the standard exposure time $T=5$ s and can be evaluated from the repetition frequency by

$$N=\upsilon\cdot T.$$

After the radiant exposure has been corrected by these factors, the scale number for mode I or R can be read from Table 2.

Finally, the scale number for quasi-cw mode must be calculated. For this, the average power is calculated by

$$\tilde{E}=H\cdot\upsilon$$

The D scale number for the quasi-cw mode can be selected from Table 2. The final required scale number for the laser eye protector is the larger one of the two values calculated.

From the physical point of view, the eye protector must be selected such that the exposure is reduced to the limits of laser class 1. At the same time, the materials used must exhibit sufficient resistance to laser radiation. Therefore, the evaluated scale numbers represent the values, which would be required to meet both these criteria. For this reason, the actual optical density of an eye protector is often larger than the scale number it can achieve. Factor $F(d)$ actually only applies to the laser resistance, whereas factors k and k_{Ti} serve only to correct the required optical density due to the interaction of repetitively pulsed laser radiation and tissue. As such, when all these factors are applied, exaggerated scale numbers for pulsed operation may result. If this is the case, one may check if there is a possibility to warrant a reduction in the required scale number. This is justified, if both factors $F(d)$ and $k\cdot k_{Ti}$ are large. It may be justifiable to only use the larger of these factors. This procedure would be outside of the guidance for selection in the standards, which is possible because the annexes B of these standards are informative only. Nevertheless, this step should always be explainable by physical considerations. For cw operation, factor $F(d)$ should always be applied.

5 Evaluation of the required scale number as per EN 12254

Although the procedure for the selection of screens as per EN 12254 is comparable to the procedure as per EN 207, there are some fundamental differences:

- Such screens are not PPE and, therefore, are not subject to the European Directive 89/686/EEC.
- The screen must be supervised, and the exposure is limited in the entire spectral range 180–10^6 nm to 100 W average laser power and 30 J single pulse energy. Otherwise, this standard is not applicable.

The values for modes I and R are the same as in EN 207, Table 2. If this is not applicable, the scale numbers may be evaluated using Table 1 of the standard EN 12254, which shows the exposure times for each mode of operation, and the values of Table 5 are achieved.

The evaluation of the scale numbers are performed analog to standard EN 207, except with the longer exposure time $T=100$ s, which influences factor k for the pulsed mode. Furthermore, $k_{Ti}=1$ is always valid.

If for the pulse mode unrealistically high scale numbers are achieved, one can check the factors $F(d)$ and k as recommended earlier for standard EN 207. When both factors $F(d)$ and k are very large, it may be justifiable to use only the larger of both factors. Again, this procedure would be outside of the guidance for selection in the standard, which is possible because the annexes B of these standards are informative only. Nevertheless, this step should always be justifiable by physical considerations. For cw operation, factor $F(d)$ should always be applied.

6 Evaluation of the required scale number as per EN 208

Laser alignment eye protectors as per standard EN 208 shall protect against direct exposure. However, they only decrease the exposure to the limits of laser class 2/2 M. This enables the laser radiation to remain visible while the

Table 5: Scale numbers as per EN 12254.

Scale number	Spectral transmittance τ (λ)	Maximum energy and/or radiant exposure in wavelength range									
		λ=180–315 nm			λ=>315–1050 nm	λ=>1050–1400 nm	λ=>315–1400 nm		λ=>1400 nm–1000 µm		
		Laser operation mode and exposure time Δt [s]									
		D ≥0.25	I, R >10^{-9} to 0.25	M ≤10^{-9}	D >5×10^{-3}	D >2×10^{-3}	I, R >10^{-9} to 0.01	M ≤10^{-9}	D >0.1	I, R >10^{-9} to 0.1	M ≤10^{-9}
		E (W/m²)	*H* (J/m²)	*E* (W/m²)	*E* (W/m²)	*E* (W/m²)	*H* (J/m²)	*H* (J/m²)	*E* (W/m²)	*H* (J/m²)	*E* (W/m²)
AB1	10^{-1}	0.01	3×10^{2}	3×10^{11}	10	2.5×10^{2}	0.05	0.0015	10^{4}	10^{3}	10^{12}
AB2	10^{-2}	0.1	3×10^{3}	3×10^{12}	10^{2}	2.5×10^{3}	0.5	0.015	10^{5}	10^{4}	10^{13}
AB3	10^{-3}	1	3×10^{4}	3×10^{13}	10^{3}	2.5×10^{4}	5	0.15	10^{6}	10^{5}	10^{14}
AB4	10^{-4}	10	3×10^{5}	3×10^{14}	10^{4}	2.5×10^{5}	50	1.5	10^{7}	10^{6}	10^{15}
AB5	10^{-5}	10^{2}	3×10^{6}	3×10^{15}	10^{4}	2.5×10^{6}	5×10^{2}	15	10^{8}	10^{7}	10^{16}
AB6	10^{-6}	10^{3}	3×10^{7}	3×10^{16}	10^{6}	2.5×10^{7}	5×10^{3}	1.5×10^{2}	10^{9}	10^{8}	10^{17}
AB7	10^{-7}	10^{4}	3×10^{8}	3×10^{17}	10^{7}	2.5×10^{8}	5×10^{4}	1.5×10^{3}	10^{10}	10^{9}	10^{18}
AB8	10^{-8}	10^{5}	3×10^{9}	3×10^{18}	10^{8}	2.5×10^{9}	5×10^{5}	1.5×10^{4}	10^{11}	10^{10}	10^{19}
AB9	10^{-9}	10^{6}	3×10^{10}	3×10^{19}	10^{9}	2.5×10^{10}	5×10^{6}	1.5×10^{5}	10^{12}	10^{11}	10^{20}
AB10	10^{-10}	10^{7}	3×10^{11}	3×10^{20}	10^{10}	2.5×10^{11}	5×10^{7}	1.5×10^{6}	10^{13}	10^{12}	10^{21}

observer is protected sufficiently. However, the following requirements must be met:
- The user's blink reflex must work sufficiently. This means the eye lid should close within 0.25 s when exposed to radiation.
- The wavelength range is limited to 400–700 nm. Outside this range, the blink reflex is insufficient for physiological reasons.

Table 6 shows the scale numbers and their exposure limits.

Bursts with a repetition frequency ≤0.1 Hz and a single pulse duration $\geq 2\cdot10^{-4}$ *s* show the same impact as cw operation, and so the scale number shall be selected as per the maximum cw power limits in Table 6.

At repetition frequencies >0.1 Hz, the single pulse energy shall be multiplied by factor *k* (see corresponding section for EN 207), and the scale number shall be selected according to the maximum pulse energy in Table 6.

If the blink reflex is delayed, it is recommended to use one scale number higher. However, one should take into account that this might affect the visibility of the laser beam. In most cases, the beam is only satisfactorily visible if the image of the laser beam is observed on a reflective target. Laser beams in the air cannot usually be well recognized from the side, if an eye protector with a sufficient scale number has been selected. This is because only weak radiation is scattered to the sides due to small dust particles and can scarcely be seen with the reduction by the eye protector. For example, the human eye is able to identify a laser power of 0.1 µW at 650 nm. Under lab conditions, the scattered radiation is, however, usually less. This illustrates a frequent dilemma when selecting such eye protectors: Good visibility of the beam and sufficient protection are not always compatible.

Table 6: Laser alignment eye protectors as per EN 208.

Scale number	Maximum cw power	Maximum pulse energy
RB1	0.01 W	2×10^{-6} J
RB2	0.1 W	2×10^{-5} J
RB3	1 W	2×10^{-4} J
RB4	10 W	2×10^{-3} J
RB5	100 W	2×10^{-2} J

7 Conclusion

Knowledge of optics, in addition to the calculation methods in the standards, is required in order to correctly select suitable eye protectors in accordance with the European Standards. This is because the hazard always depends on the actual circumstances. It is not always possible to reduce user-specific conditions to simple and generally applicable interrelationships.

References

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