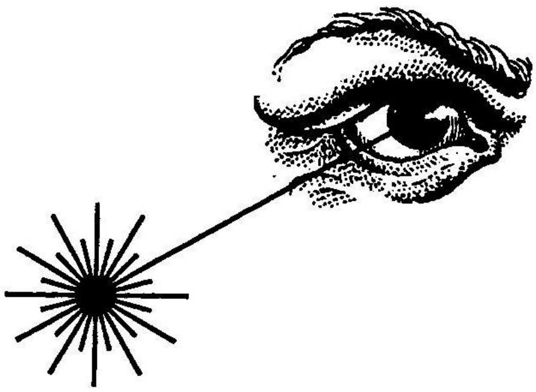
Course literature in Laser Engineering

Laser Safety



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Safety considerations

Risks associated with laser use

Optical radiation can produce different types of biological damage at high incident power densities. Ultraviolet (UV) radiation from the sun can give skin damage after long exposure. Focusing the sun's rays onto the retina can give burns in that tissue. It is well known that such injuries often turn up after a solar eclipse, when people are incautious and observe the sun directly without the use of an attenuating glass filter. Even Infrared (IR) radiation (heat radiation) can at high intensities give injuries to the eye, such as the lens, or give burn damage to the skin.

Damaging effects of optical radiation have been known for ages, but not much attention has been paid to artificial light sources, such as lamps, discharge arcs and flames. One exception is the case of sources of blue/violet and ultraviolet radiation, such as welding flames, where the risks have long been realized, and protective measures and regulations have been used. The situation was radically changed upon the advent of lasers. They have properties which are vastly different from those of conventional light sources. Laser beams are generally well collimated, that is we have a parallel ray bundle which for visible radiation is focused to a single point on the retina. Radiation pulses from a laser can have high power and short duration. Often the pulses are repeated at a high frequency. Specially if the laser radiation is in the UV or IR spectral range, humans have no sensing mechanism to warn against dangerous radiation.

Laser radiation (coherent radiation) is not known to have special properties regarding damage mechanisms in biological material. That is, the damage mechanism is assumed to have the same dependence on power, wavelength and exposure time as any other (incoherent) radiation.

There are a number of indirect and secondary risks involved with the use of lasers. The direct effect of the laser radiation can for instance be that it causes a fire in the material on which it is incident. A material which is heated by the laser beam can also give off dangerous gases. High electrical currents and voltages are often present in laser power supplies. In a few lasers, cooling of liquids to cryogenic temperatures is necessary, and the risk of explosion must then be taken into account (one liter of liquid nitrogen at 77K is equivalent to about 750 liters of gas at room temperature).

Biological damage mechanisms

An overview of the different types of damage mechanisms which a person can be subject to upon exposure to optical radiation is given in table A. Short wavelengths can give photochemical reactions while radiation at long wavelengths mainly gives burn injuries. The eye is the human body's most radiation-sensitive organ. However, it is only in the region 0.4 – 1.4 μm that the radiation can penetrate the eye and reach the retina ("näthinna"), (see figure 1). This radiation is focused on the retina and can give retinal damage. Short wavelength UV radiation and long wavelength IR radiation are absorbed in the cornea ("hornhinna").

Table A: Biological damage mechanisms for optical radiation in the spectral region 200 nm – 1 mm

Biological classification of spectral range	Eye damage	Skin damage
UV C 200-280 nm		Erythema (reddening) Skin cancer
UV B 280-315 nm	Corneal inflammation (keratitis)	Aging of skin Increased pigmentation
UV A 315-400 nm	Photochemical cataract (lens clouding)	Darkened pigmentation
Visible light 400-780 nm	Photochemical damage Retinal burn	Photochemical reactions
IR A 780-1400 nm	Thermal cataract Retinal burn	Skin burn injury
IR B 1.4 - 3.0 µm	Corneal burn Vitreous humour damage Cataract	
IR C 3.0 µm – 1 mm	Corneal burn	

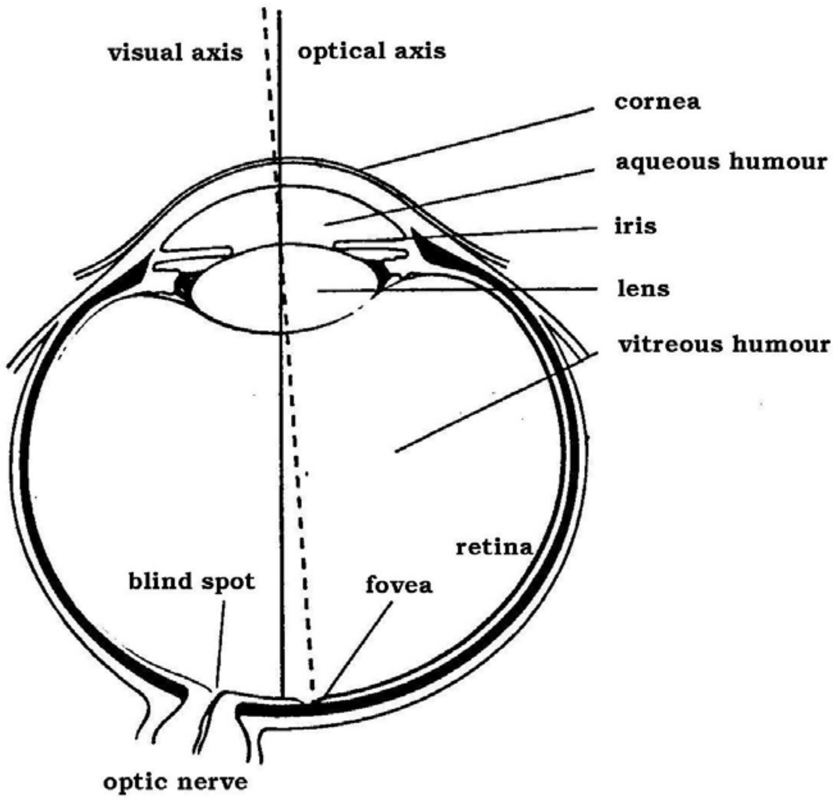

Fig. 1: Human eye

It is not only the wavelength of the radiation that determines the nature of the damage. The exposure time can also be an important factor. For the most serious injuries, retinal injuries, one finds the following approximate dependence on exposure time: For long exposure times (minutes, hours), damaging photochemical reactions can take place. This happens, in comparison to other damage mechanisms, at relatively low radiation levels. I the time domain of seconds to milliseconds, the damage mechanism is thermal, that is the functions of the biological tissue are damaged due to heating. For short pulses, microseconds and shorter, there is a strong element of mechanical damage, as a result of a micro-explosion.

While the photochemical effects at long exposure times and the mechanical effects at short exposure times are not completely understood, one has a fairly good appreciation of the dominating thermal damage mechanism.

Optical radiation that is incident on a solid or liquid medium is usually absorbed after a very short distance in the medium. There are of course exceptions, transparent media, which allow the radiation to pass. Light can for example propagate in glass and water. Optical radiation is absorbed in a person's outer "shell", skin and clothing, with the exception of light which passes the eye's imaging system and is absorbed in the pigment of the retina. The vitreous humour ("glaskroppen") can be seen as a sphere filled with water, of refractive index $n \approx 1.33$ and with a diameter of about 4 cm.

When absorbed, the optical radiation is converted into heat in the absorbing material layer. Depending on a number of radiation parameters and characteristics of the biological material, either the temperature builds up to a dangerous level, or the heat is conducted away fast enough that the material is not damaged. The biological material that absorbs optical radiation has very similar resistance to thermal damage, be it situated either in the retina of the eye, or in the skin. What makes the risk of eye injury so high is the fact that the eye focuses the radiation on the retina. The power density on the retina is, for a laser beam, more than 10^5 times higher than in the plane of the cornea. Skin is thus exposed in a comparable illumination situation to a power density which is extremely small in comparison with what the retina is exposed to.

For infrared radiation and visible light, the thermal damage mechanism dominates. For very short pulses, however, micro-explosions will occur. This is a result of the excess energy which occurs during exposure but which can not be quickly dissipated through the slow process of heat diffusion. Instead, a mechanical shock wave is developed. This can easily be observed through concurrent sound and light phenomena.

With ultraviolet radiation, photochemical processes are generated and other types of injuries occur – at low levels irritation of skin and the cornea of the eye. Photochemical processes can also be of importance in the visual part of the spectrum, especially in the blue and green regions. It appears that laser radiation is in no way unique in its ability to cause damage of photochemical nature, and one observes the same threshold levels for damage as with conventional UV or visible light sources.

The effects of laser radiation which have been discussed above involve threshold damage to biological material. By using radiation of an intensity considerably above the threshold value, new types of physical effects appear.

Safety regulations and risk assessments

Ever since the first lasers appeared one has been aware that people can be at risk of injury from their radiation. To begin with, the situation was clear that certain irradiation geometries at intensities exceeding certain levels gave rise to serious burn injuries. The risk of eye injuries with impaired vision as a consequence was and still is considered to be the most acute danger. Even skin damage can occur. Even though it was relatively easy to define the situations under which injuries definitely occur in humans, it was much more difficult to summarize the radiation exposure conditions under which no danger was presented to humans.

During the 1960's and 70's, experiments and calculations were performed, mainly in the USA, seeking to determine the upper limit for safe exposure. This research work is the basis for the safety standards that now govern the use of lasers in Sweden (and many other countries), and that are specified in the Swedish Standard SS-EN 60825-1 utg. 3, 2003-09-22. This standard has been established by Svenska Elektriska Kommissionen, SEK, and is identical to the international standard IEC 60825-1, approved by CENELEC (Comité Européen de Normalisation Electrotechnique). Two other Swedish documents summarize the laser standards in effect, one from Statens Strålskyddsinstitut, SSI, and one (based on that of SSI) from Arbetarskyddsstyrelsen. The two latter documents are presently (2004) being up-dated to match the updated Swedish standard from SEK. The appendix of this course material contains excerpts from the SSI document which is presently in the form of a proposed document, soon to be established as the Swedish laser safety regulation.

The changes to the laser safety standard which are being made now (2003-2004) involve a new grouping of laser safety classes, new limits for extremely short pulses, less restrictive limits for 1400 – 2000 nm wavelength, and the inclusion of LED (light emitting diode) sources as well as lasers. Previously, collimated and extended sources were dealt with by different methods, comparing collimated beam exposure to tables of allowed corneal irradiance while extended source exposure was compared to tables of source radiance. This difference is evaluation of the safety situation has, in the new standard, been greatly reduced, with both collimated and extended sources now compared to the same tabulated values of allowed corneal irradiance, now including a simple correction factor for extended sources.

Laser safety standards provide values of maximum permissible exposures (MPE) which are dependent on many different parameters. In order to simplify the safety evaluation when marking lasers with suitable warnings, the standards also provide values of accessible emission limits (AEL) for well-defined laser safety classes.

Lasers can be classified for safety evaluation in four main classes, with sub-classes resulting in seven classifications. Class 1 involves lasers that can be treated as safe. Classes 2, 3 and 4 include lasers with an optical power which can qualitatively be treated as low, medium, and high. Class 2 requires the output to be in the visible range of the spectrum, where our vision can help to avoid accidental prolonged exposure. The laser classes are summarized in table B.

Control and safety measures are necessary for use of lasers of class 2-4, among other things, the lasers must be labeled with a warning text. Safety measures are increased successively from class 2 to 4, for class 3-4 becoming more rigorous, e.g. use only allowed under certain well-controlled conditions.

The most problematic laser safety situations are those involving outdoor use of lasers. In such situations, it can be difficult to assure that people, who may not be informed of the laser use and the degree of danger presented by the radiation, are not present within the radiation region. In some cases, such as in the use of low power He-Ne lasers for alignment during building projects, surveying etc. an accidental eye exposure can be completely safe. However, the glare discomfort as well as the awareness that laser radiation in general can give rise to injuries, even if the risk of injury in reality involves completely different exposure conditions, can give rise to strong worries for those exposed to the low level radiation.

Table B: Description of laser classes

Laser Safety Classes, International Laser Safety Standard IEC 60825-1

	Type of Lasers	Potential Eye or Skin Hazard	Allowed CW Laser Power*
Class 1 (embedded)	Laser completely enclosed. Radiation not accessible during use.	Generally safe during use. Hazards according to power of enclosed laser when interlocks overridden or during service.	Power of enclosed laser theoretically not limited.
Class 1	Very low power level	Emitted power generally safe for long-term intrabeam viewing, even with optical instruments such as magnifying glasses or telescopes.	40 µW for blue and 400 µW for red (through measurement apertures for optical instruments).
Class 1M	Low power level. Collimated large beam diameter or divergent.	Safe for long-term intrabeam viewing but potentially hazardous with magnifiers (divergent beams) or binoculars (large-diameter collimated beams).	Same as for Class 1, but measurement aperture for unaided eye.
Class 2	Low power level. Visible wavelengths only.	Safe for brief (accidental) direct exposure with naked eye and optical instruments. Brief exposure can be assumed for bright light. Prolonged staring might injure eye, especially for blue wavelengths.	1 mW
Class 2M	Low-power visible. Collimated large beam diameter or divergent.	Safe for brief direct exposure with the naked eye, but potentially hazardous when exposure occurs with magnifiers (divergent beams) or binoculars (large-diameter collimated beams).	Same as for Class 2, but measurement aperture for unaided eye.
Class 3R visible	Low power. Typically alignment lasers.	Accidental exposure usually not hazardous, but eye injury possible for intentional intra-beam viewing.	5 mW
Class 3R nonvisible	Low power	Accidental exposure usually not hazardous, but eye injury possible for intentional long-term intrabeam viewing.	Five times Class 1 (variable with wavelength).
Class 3B	Medium power	Exposure (including brief accidental exposure) of the eye to the direct beam may cause serious eye injuries. No or very limited skin hazard, and viewing of diffuse reflections is normally safe.	500 mW
Class 4	High power	Exposure (including brief accidental exposure) of the eye to the direct beam and close viewing of diffuse reflections may lead to serious eye injuries. May also cause serious skin injury. Presents a fire hazard.	Not limited

* Power or energy measured with specified apertures must be below emission limit. Values given for small (point) sources (α <1.5 mrad).

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Definitions of important concepts

The following definitions have partly been taken from the international standard IEC 60825-1. References to figure and section numbers of the standard can be disregarded here.

accessible emission limit (AEL)
the maximum accessible emission level permitted within a particular class

angle of acceptance
plane angle within which a detector will respond to optical radiation, usually measured in radians. This angle of acceptance may be controlled by apertures or optical elements in front of the detector (see figure 16). The angle of acceptance is also sometimes referred to as the field of view

Symbol: γ

angular subtense (α)
angle subtended by an apparent source as viewed at a point in space. In this standard, for classification, the angular subtense is determined at a point not less than 100 mm from the apparent source (or at the exit window or lens of the product if the apparent source is located at a distance greater than 100 mm within the window or lens). (See also 3.53 and 3.57.) For an analysis of the maximum permissible exposure levels, the angular subtense shall be determined at the viewing distance from the apparent source but not less than 100 mm. This concept is also discussed in clause A.3 of annex A

beam diameter (beam width)
the beam diameter d_u at a point in space is the diameter of the smallest circle which contains u % of the total laser power (or energy). For the purpose of this standard d_{63} is used

beam divergence
the beam divergence is the far field plane angle of the cone defined by the beam diameter. If the beam diameters (see 3.10) at two points separated by a distance r are d_{63} and d'_{63} the divergence is given by:

$$\varphi = 2 \arctan\left(\frac{d_{63} - d'_{63}}{2r}\right)$$

SI unit: radian

diffuse reflection
change of the spatial distribution of a beam of radiation by scattering in many directions by a surface or medium. A perfect diffuser destroys all correlation between the directions of the incident and emergent radiation

extended source viewing
the viewing conditions whereby the apparent source at a distance of 100 mm or more subtends an angle at the eye greater than the limiting angular subtense (α_{min})

Two extended source conditions are considered in this standard when considering retinal thermal injury hazards: intermediate source and large source, which are used to distinguish sources with angular subtenses, α, between α_{min} and α_{max} (intermediate sources), and greater than α_{max} (large sources). (See also 3.79.)

Examples are viewing of some diffuse reflections and of some laser diode arrays

integrated radiance
the integral of the radiance over a given exposure time expressed as radiant energy per unit area of a radiating surface per unit solid angle of emission (usually expressed in $J \cdot m^{-2} \cdot sr^{-1}$)

intrabeam viewing
all viewing conditions whereby the eye is exposed to the direct or specularly reflected laser beam in contrast to viewing of, for example, diffuse reflections

irradiance
quotient of the radiant flux $d\Phi$ incident on an element of a surface by the area dA of that element

Symbol: E $\quad E = \dfrac{d\Phi}{dA}$

SI unit: watt per square metre ($W \cdot m^{-2}$)

limiting aperture
the circular area over which irradiance and radiant exposure are averaged

maximum angular subtense (α_{max})
the value of angular subtense of the apparent source above which the MPEs and AELs are independent of the source size

maximum permissible exposure (MPE)
that level of laser radiation to which, under normal circumstances, persons may be exposed without suffering adverse effects. The MPE levels represent the maximum level to which the eye or skin can be exposed without consequential injury immediately or after a long time and are related to the wavelength of the radiation, the pulse duration or exposure time, the tissue at risk and, for visible and near infra-red radiation in the range 400 nm to 1 400 nm, the size of the retinal image. Maximum Permissible Exposure levels are (in the existing state of knowledge) specified in clause 13. Annex A gives examples of the calculations of MPE levels

minimum angular subtense (α_{min})
the value of angular subtense of the apparent source above which a source is considered an extended source. MPEs and AELs are independent of the source size for angular subtenses less than α_{min}

radiance
quantity defined by the formula

$$L = \frac{d\Phi}{dA \cdot \cos\theta \cdot d\Omega}$$

where

$d\Phi$ is the radiant flux transmitted by an elementary beam passing through the given point and propagating in the solid angle $d\Omega$ containing the given direction;

dA is the area of a section of that beam containing the given point;

θ is the angle between the normal to that section and the direction of the beam

Symbol: L

Unit: $W \cdot m^{-2} \cdot sr^{-1}$

See figure 2.

$$dP = L_e \, d\Omega \, A \cos\theta$$

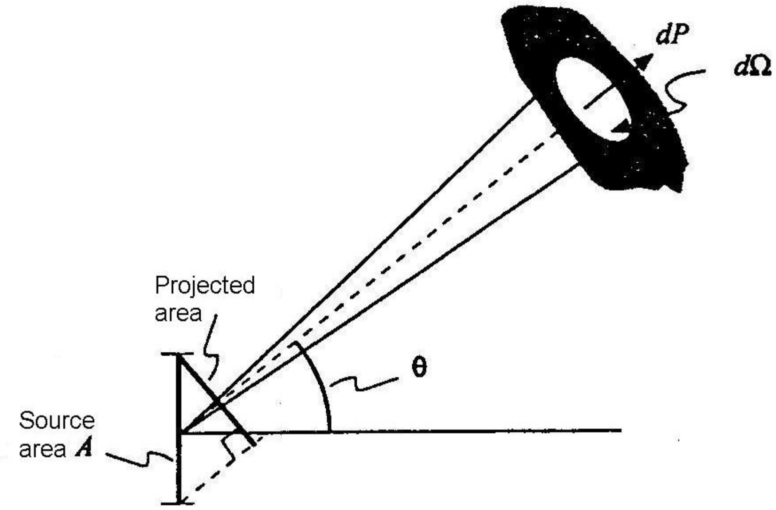


Fig. 2 Radiance of source

radiant energy
time integral of the radiant flux over a given duration Δt
(IEV 845-01-27):

Symbol: Q $\quad Q = \int_{\Delta t} \Phi \mathrm{d}t$
SI unit: joule (J)

radiant exposure
at a point on a surface, the radiant energy incident on an element of a surface divided by the area of that element

Symbol: H $\quad H = \frac{\mathrm{d}Q}{\mathrm{d}A} = \int E \mathrm{d}t$
SI unit: joule per square metre ($\mathrm{J \cdot m^{-2}}$)

radiant power; radiant flux
power emitted, transferred, or received in the form of radiation
(IEV 845-01-24)

Symbol: Φ, P $\quad \Phi = \frac{\mathrm{d}Q}{\mathrm{d}t}$
SI unit: watt (W)

small source
source with an angular subtense α less than, or equal to, the minimum angular subtense α_{min}

solid angle
the two-dimensional opening angle Ω of a conical surface is denoted solid angle. Think of the intersection of a cone and a sphere with radius R, having its centre at the apex of the cone. The intersection on the surface of the sphere has the area A. If A is equal to the surface of the whole sphere, $A=4\pi R^2$, then $\Omega=4\pi$ steradians. For a circular opening angle W we have $\Omega=4\pi \sin^2(\alpha/4)$ where α is the planar diameter angle.

Symbol: Ω $\quad \Omega = \frac{A}{R^2}$

SI unit: steradians (sr)

See figure 3

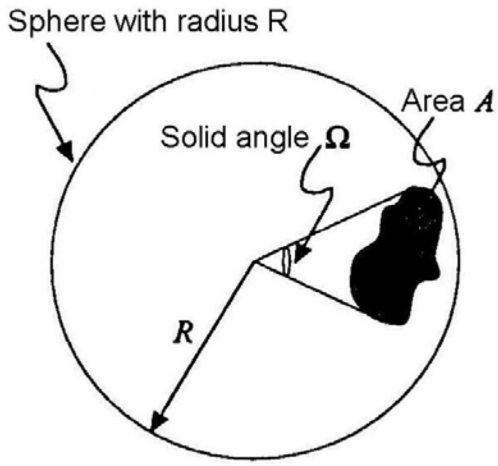


Figure 3 Solid angle

specular reflection
a reflection from a surface which maintains angular correlation between incident and reflected beams of radiation, as with reflections from a mirror

transmittance (optical) density
logarithm to base ten of the reciprocal of the Transmittance τ
(IEV 845-04-66)
Symbol: D $D = -\log_{10} \tau$

Imaging in the eye

In order to judge the risk of injury to the eye or skin in each specific exposure situation one can calculate or measure the irradiance at the cornea of the eye or at the skin, and compare it to the maximum permissible exposure, MPE.

In the eye, one can define two very different radiation geometries, either the laser beam is focused to a single point on the retina or an image of the radiant source is formed on the retina. See figure 4. In the second case, the irradiated area on the retina is larger than that from a parallel ray bundle. The smallest possible irradiated area on the retina is approximately 10 µm in diameter, determined by the diffraction limit.

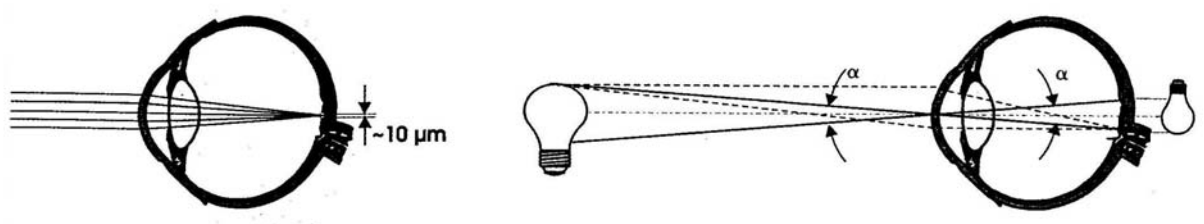


Figure 4 Intrabeam viewing and extended source viewing

Extended source or large diffuse reflection:

Assume that one is observing a radiant surface of area A. The pupil aperture area B and irradiated area C on the retina are also shown in figure 5, with the focal length of the eye as f.

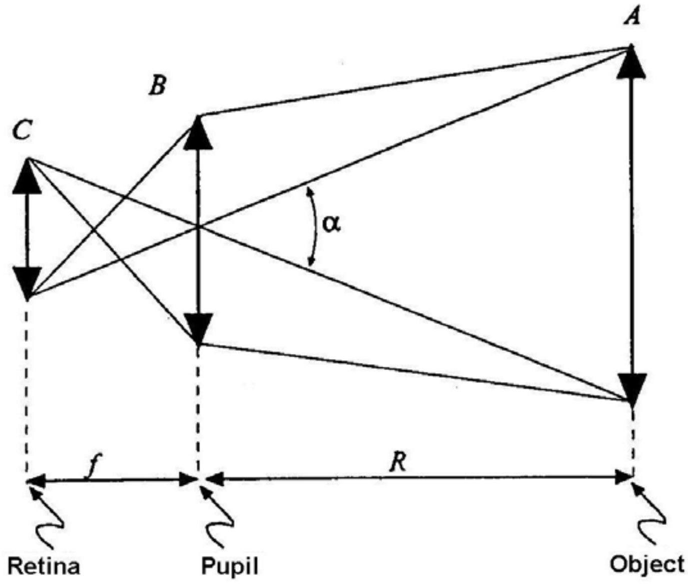


Figure 5. Imaging of an extended source on the retina.

The power entering the pupil depends on the radiance of the surface A according to:

$$P_B = L_e \; d\Omega \; A \; \text{[W]}$$

Where L_e is the radiance of the source in the direction towards the eye and $d\Omega = B/R^2$. This power is distributed over the area C on the retina giving the irradiance of the retina:

$$E_C = \frac{L_e \; d\Omega \; A}{C} \; [\text{W/m}^2]$$

Using the geometrical relation for the magnification:

$$\frac{C}{A} = \frac{f^2}{R^2}$$

Gives the irradiance of the retina as:

$$E_C = \frac{L_e \; B}{f^2} \; [\text{W/m}^2]$$

Note that the irradiance of the retina is solely determined by the radiance of the source, L_e and the eye constants B and f, so long as the source A is imaged as a spot on the retina with an area larger than the minimum area. We can also do the same calculation for the time-integrated quantities. Imaging is, of course, only relevant in the wavelength region in which the eye has low attenuation, the visible and near IR.

Direct parallel beam or small source:

When a parallel beam is incident on the eye, it is focused to a minimum spot size. Due to diffraction, a source of angular subtense $\leq \alpha_0$ will also be focused to the same minimum spot size. The area of this minimum spot is given by:

$$C_{\min} = \frac{\pi\ f^2\ \alpha_o^2}{4} \quad [\mathrm{m}^2]$$

where α_0 is the resolution limited angle for the eye. If the energy H_eB is deemed safe when concentrated to this minimum spot, then the same energy distributed over a larger area

$$\frac{\pi\ f^2\ \alpha^2}{4} \quad [\mathrm{m}^2]$$

should also be deemed safe. Here, α is the angular subtense of the source.

The energy density on the retina can then be written as:

$$\frac{4\ H_e\ B}{\pi\ f^2\ \alpha^2} \qquad \alpha \geq \alpha_o\ [\mathrm{J/m}^2]$$

$$\frac{4\ H_e\ B}{\pi\ f^2\ \alpha_o^2} \qquad \alpha \leq \alpha_o\ [\mathrm{J/m}^2]$$

The criterion for an extended source stipulates that the time-integrated radiance of the source, measured at the cornea, should be L_et [J/(m2 sr)], where t is the exposure time. This gives the retinal dose:

$$H_C = \frac{L_e \cdot t \cdot B}{f^2} \quad [\mathrm{J/m}^2]$$

Both criteria describe a safe situation and we can therefore choose that criterion which allows the highest irradiance on the retina. Figure 6 gives a sketch of the energy density on the retina as a function of the angle of subtense of the source, showing the criteria for direct and extended sources together. We can see that one should change criteria at $\alpha = \alpha$min. In the figure, the cross-hatched region denotes the safe energy density on the retina. The allowed levels are in general a function of the exposure time. αmin can be found from the intersection of the two lines corresponding to the two criteria. αmin is thus, as seen in the figure, a function of exposure time. Previous laser safety regulation standards included tables of α_{min} as a function of exposure time, but the new, updated regulations are simplified in this aspect. αmin is set to 1.5 mr in the new standards.

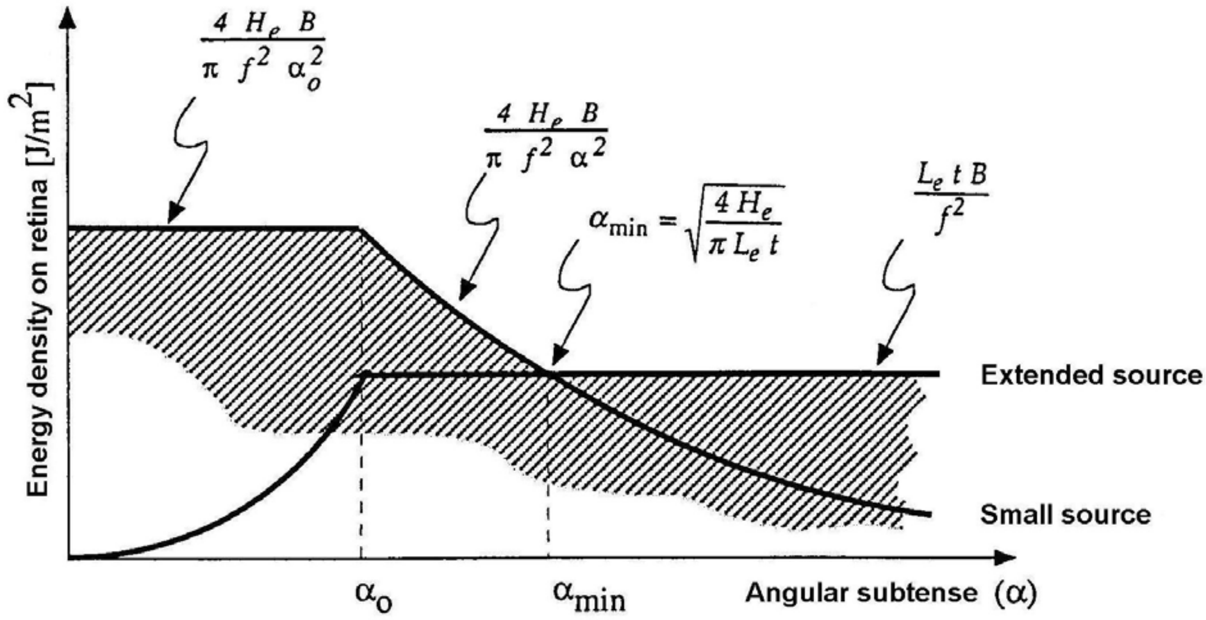


Figure 6. Permissible energy density on the retina as a function of angle of subtense of source.

Risk calculations

Maximum permissible exposure (MPE)

The allowed irradiance (power density) or radiant exposure (energy density) of the cornea or the skin is tabulated as Maximum Permissible Exposure (MPE) values in four tables:

Table 3	UV outer eye damage and photochemical retinal damage
Table 4	thermal retinal damage
Table 5	IR thermal outer eye damage
Table 6	skin damage

The criteria in Table 3 and Table 4 are overlapping in certain wavelength regions, and the strictest criterion is to be applied.

Note that MPE values depend on wavelength, exposure time, and angle of subtense. Extended sources are handled with a simple correction factor, C_6 in Table 4 (thermal retinal damage).

Limiting apertures

The worst case power density on the retina is obtained for a parallel beam completely filling the largest possible pupil aperture (7 mm), with smaller diameter beams resulting in larger illuminated spots on the retina (due to diffraction). This consideration leads to the stipulation that, in the visible and near IR region of the spectrum, the corneal irradiance is to be averages over a 7 mm pupil aperture before comparison with the tabulated MPE values. The apertures for averaging are given in Table 1.

Extended sources

All sources with angular subtense, α, between α_{min} = 1.5 mr and α_{max} = 100 mr are treated as extended (intermediate) sources. Above 100mr, the sources are classified as large sources. (See notes below Table 4.)

Repetitively pulsed lasers

Since there are only limited data on multiple pulse exposure criteria, caution must be used in the evaluation of exposure to repetitively pulsed radiation. The following methods should be used to determine the MPE to be applied to repetitive exposures to repetitively pulsed radiation.

The MPE for ocular exposure for wavelengths from 400 nm to 10^6 nm is determined by using the most restrictive of requirements a), b) and c). Requirement c) applies only to the thermal limits and not to the photochemical limits.

The MPE for ocular exposure for wavelengths less than 400 nm and the MPE for skin exposure is determined by using the most restrictive of requirements a) and b).

a) The exposure from any single pulse within a pulse train shall not exceed the MPE for a single pulse.

b) The average exposure for a pulse train of exposure duration T shall not exceed the MPE given in tables 3 to 6 for a single pulse of exposure duration T.

c) The average exposure from pulses within a pulse train shall not exceed the MPE for a single pulse multiplied by the correction factor C_5.

NOTE 1 The exposures in a pulse train are to be averaged over the same emission duration which was used to determine N. Every averaged pulse exposure is to be compared to the reduced MPE_{train} as specified below:

$$\mathrm{MPE}_{\mathrm{train}} = \mathrm{MPE}_{\mathrm{single}} \times C_5^{*}$$

where

$\mathrm{MPE}_{\mathrm{train}}$ = MPE for any single pulse in the pulse train

$\mathrm{MPE}_{\mathrm{single}}$ = MPE for a single pulse

C_5 = $N^{-1/4}$

N = number of pulses expected in an exposure.

In some cases this value may fall below the MPE that would apply for continuous exposure at the same peak power using the same exposure time. Under these circumstances the MPE for continuous exposure may be used.

If pulses of variable amplitude are used, the assessment is made for pulses of each amplitude separately, and for the whole train of pulses.

The maximum exposure duration for which requirement c) should be applied is T_2 in the wavelength range from 400 nm to 1 400 nm (as defined in notes below Table 4 and 10 s for longer wavelengths.

NOTE 2 C_5 is only applicable to individual pulse durations shorter than 0,25 s.

NOTE 3 If multiple pulses appear within the period of T_i (see table 2) they are counted as a single pulse to determine N and the radiant exposure of the individual pulses are added to be compared to the MPE of T_i, provided that all individual pulse durations are greater than 10^{-9} s.

NOTE 4 The exposure from any group of pulses (or sub-group of pulses in a train) delivered in any given time should not exceed the MPE for that time.

NOTE 5 In cases of varying pulse widths or pulse intervals, the total-on-time-pulse (TOTP) method may be used in place of requirement c). In this case, the MPE is determined by the duration of the TOTP, which is the sum of all pulse durations within the exposure duration or T_2, whichever is smaller. Pulses with durations less than T_i, are assigned pulse durations of T_i. If two or more pulses occur within a duration of T_i, these pulse groups are assigned pulse durations of T_i. For comparison with the MPE for the corresponding duration, all individual pulse radiant exposures are added.

This method is equivalent to requirement c) when the average radiant exposure of pulses is compared to the MPE of a single pulse multiplied with C_5.

Protective eye-wear

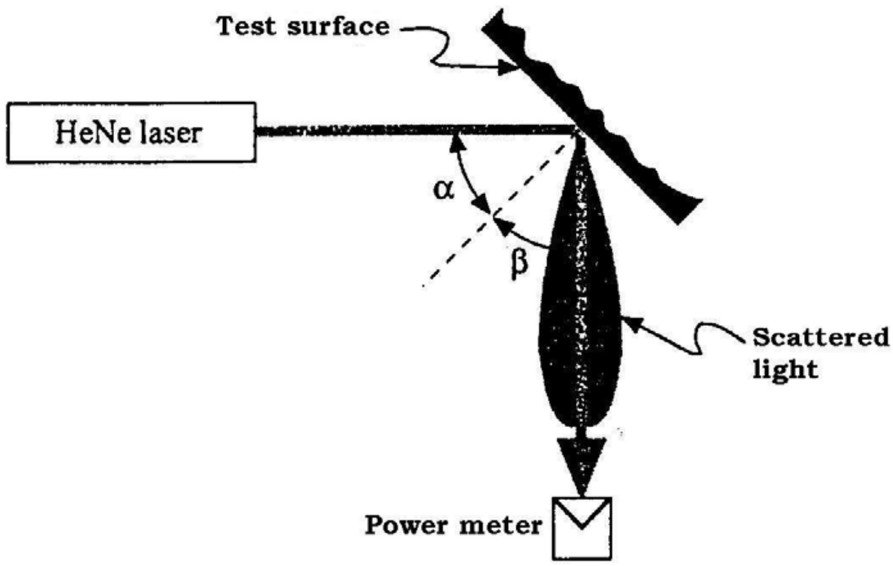
The spectral optical density D_λ of laser protective eyewear is normally highly wavelength dependent. Where protective eyewear is required to cover a band of radiation, the minimum value of D_λ measured within the band shall be quoted. The value of D_λ required to give eye protection can be calculated from the formula:

$$D_\lambda = \log_{10} \frac{H_0}{\mathrm{MPE}}$$

where H_0 is the expected unprotected eye exposure level.

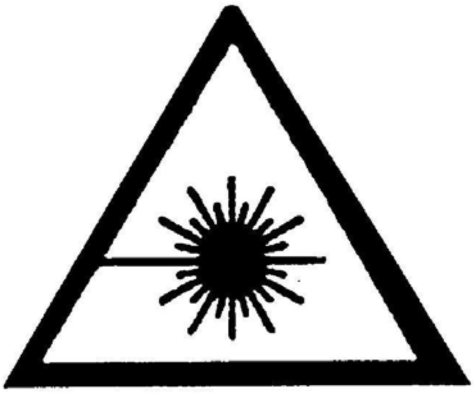
Non-diffuse reflections

Usually, the irradiation of a surface with a laser gives rise to reflections which can not be described as completely diffuse, that is, having constant radiance. The diagram and table below give data from measurements of reflections from a number of test surfaces. Note that a surface which gives a more or less diffuse reflection at visible wavelengths can function as a perfect mirror at longer wavelengths, e.g. for a CO_2 laser at λ = 10 µm.



$$F = L_e(\text{test surface})/L_e(\text{diffuse surface})$$

Test surface	F (α=β=10º)	F (α=10º, β=20º)
Shiny gray painted surface	300	0.3
Matt metal surface	10	1
Roughly polished metal	5	5
Matt white paper	0.8	0.8
Rusty iron plate	0.7	0.2
Matt black metal	0.6	0.2
Masonite (back side)	0.2	0.2
Black painted masonite (back side)	0.04	0.03
Black velvet fabric	0.003	0.003



Laser hazard warning symbol

Table 1. Measurement area

Spectral region λ (nm)	Exposure time t (s)	Aperture diameter (mm) for eye	for skin
180 - 400	all times	1	3,5
400 - 1400	all times	7	3,5
1400 - 10^5	≤ 0,35	1	3,5
	0,35 - 10	$1{,}5 \cdot t^{3/8}$	3,5
	≥ 10	3,5	3,5
10^5 - 10^6	all times	11	11

Table 2. T_i pulse grouping time

Spectral region λ (nm)	T_i (s)	Spectral region λ (nm)	T_i (s)
400 - 1050	$18 \cdot 10^{-6}$	1500 - 1800	10
1050 - 1400	$50 \cdot 10^{-6}$	1800 - 2600	10^{-3}
1400 - 1500	10^{-3}	2600 - 10^6	10^{-7}

Table 3 MPE for eye regarding UV and photochemical retinal damage risk

Wavelength λ (nm)	Exposure time t (s)	MPE		
180 - 302,5	10^{-13} - 10^{-9}	$3 \cdot 10^{10}$		W/m^2
	10^{-9} - $3 \cdot 10^4$	30		J/m^2
302,5 - 315	10^{-13} - 10^{-9}	$3 \cdot 10^{10}$		W/m^2
	10^{-9} - T_1	$5600 \cdot t^{0,25}$		J/m^2
	T_1 - $3 \cdot 10^4$	$10^{0,2(\lambda - 295)}$		J/m^2
315 - 400	10^{-13} - 10^{-9}	$3 \cdot 10^{10}$		W/m^2
	10^{-9} - 10	$5600 \cdot t^{0,25}$		J/m^2
	10 - 10^3	10^4		J/m^2
	10^3 - $3 \cdot 10^4$	10		W/m^2
Photochemical damage to retina:				
400 - 450	10 - 10^2	100	(γ = 11 mr)	J/m^2
	10^2 - 10^4	1	($\gamma = 1,1 \cdot t^{0,5}$ mr)	W/m^2
	10^4 - $3 \cdot 10^4$	1	(γ = 110 mr)	W/m^2
450 - 600	10 - 10^2	$100 \cdot 10^{0,02(\lambda-450)}$	(γ = 11 mr)	J/m^2
	10^2 - 10^4	$10^{0,02(\lambda-450)}$	($\gamma = 1,1 \cdot t^{0,5}$ mr)	W/m^2
	10^4 - $3 \cdot 10^4$	$10^{0,02(\lambda-450)}$	(γ = 110 mr)	W/m^2
400 - 484	$1 - 3 \cdot 10^4$	$100 \cdot 10^{0,02(\lambda-450)}$	($1,5 \leq \alpha < 82$)	J/m^2

$T_1 = 10^{0,8(\lambda - 295)} \cdot 10^{-15}$ s

Table 4 MPE for eye regarding thermal and micro-mechanical retinal damage risk

Wavelength λ (nm)	Exposure time t (s)	MPE		
400 - 700	10^{-13} - 10^{-11}	$1{,}5 \cdot 10^{-4} \cdot C_6$		J/m^2
	10^{-11} - 10^{-9}	$2{,}7 \cdot 10^{4} \cdot t^{0{,}75} \cdot C_6$		J/m^2
	10^{-9} - $1{,}8 \cdot 10^{-5}$	$5 \cdot 10^{-3} \cdot C_6$		J/m^2
	$1{,}8 \cdot 10^{-5}$ -T_2	$18 \cdot t^{0{,}75} \cdot C_6$		J/m^2
	T_2 - $3 \cdot 10^4$	10	($\alpha \le 1{,}5$ mr)	W/m^2
	T_2 - $3 \cdot 10^4$	$18 \cdot C_6 \cdot T_2^{-0{,}25}$	($\alpha > 1{,}5$ mr)	W/m^2
700 - 1050	10^{-13} - 10^{-11}	$1{,}5 \cdot 10^{-4} \cdot C_4 \cdot C_6$		J/m^2
	10^{-11} - 10^{-9}	$2{,}7 \cdot 10^{4} \cdot t^{0{,}75} \cdot C_4 \cdot C_6$		J/m^2
	10^{-9} - $1.8 \cdot 10^{-5}$	$5 \cdot 10^{-3} \cdot C_4 \cdot C_6$		J/m^2
	$1{,}8 \cdot 10^{-5}$ - T_2	$18 \cdot t^{0{,}75} \cdot C_4 \cdot C_6$		J/m^2
	T_2 - $3 \cdot 10^4$	$10 \cdot C_4$	($\alpha \le 1{,}5$ mr)	W/m^2
	T_2 - $3 \cdot 10^4$	$18 \cdot C_4 \cdot C_6 \cdot T_2^{-0{,}25}$	($\alpha > 1{,}5$ mr)	W/m^2
1050 - 1400	10^{-13} - 10^{-11}	$1{,}5 \cdot 10^{-3} \cdot C_6 \cdot C_7$		J/m^2
	10^{-11} - 10^{-9}	$2{,}7 \cdot 10^{5} \cdot t^{0{,}75} \cdot C_6 \cdot C_7$		J/m^2
	10^{-9} - $5 \cdot 10^{-5}$	$5 \cdot 10^{-2} \cdot C_6 \cdot C_7$		J/m^2
	$5 \cdot 10^{-5}$ - T_2	$90 \cdot t^{0{,}75} \cdot C_6 \cdot C_7$		J/m^2
	T_2 - $3 \cdot 10^4$	$50 \cdot C_7$	($\alpha \le 1{,}5$ mr)	W/m^2
	T_2 - $3 \cdot 10^4$	$90 \cdot C_6 \cdot C_7 \cdot T_2^{-0{,}25}$	($\alpha > 1{,}5$ mr)	W/m^2

$T_2 = 10$ s	$\alpha \le 1{,}5$ mr
$T_2 = 10 \cdot 10^{((\alpha - 1{,}5)/98{,}5)}$ s	$1{,}5 < \alpha \le 100$ mr
$T_2 = 100$ s	$\alpha > 100$ mr
$C_4 = 10^{0{,}002(\lambda - 700)}$	
$C_6 = 1$	$\alpha \le 1{,}5$ mr
$C_6 = \alpha / 1{,}5$	$1{,}5 < \alpha \le 100$ mr
$C_6 = 66{,}7$	$\alpha > 100$ mr
$C_7 = 1$	$1050 < \lambda \le 1150$
$C_7 = 10^{0{,}018(\lambda - 1150)}$	$1150 < \lambda \le 1200$
$C_7 = 8$	$1200 < \lambda \le 1400$

Table 5 MPE for eye regarding IR thermal corneal and lens damage risk

Wavelength λ (nm)	Exposure time t (s)	MPE	
1400 - 1500	10^{-13} - 10^{-9}	10^{12}	W/m^2
	10^{-9} - 10^{-3}	1000	J/m^2
	10^{-3} - 10	$5600 \cdot t^{0,25}$	J/m^2
	$10 - 3 \cdot 10^4$	1000	W/m^2
1500 -1800	10^{-13} - 10^{-9}	10^{13}	W/m^2
	10^{-9} - 10	10^4	J/m^2
	$10 - 3 \cdot 10^4$	1000	W/m^2
1800 - 2600	10^{-13} - 10^{-9}	10^{12}	W/m^2
	10^{-9} - 10^{-3}	1000	J/m^2
	10^{-3} - 10	$5600 \cdot t^{0,25}$	J/m^2
	$10 - 3 \cdot 10^4$	1000	W/m^2
2600 - 10^6	10^{-13} - 10^{-9}	10^{11}	W/m^2
	10^{-9} - 10^{-7}	100	J/m^2
	10^{-7} - 10	$5600 \cdot t^{0,25}$	J/m^2
	$10 - 3 \cdot 10^4$	1000	W/m^2

Table 6 MPE for skin damage risk

Wavelength λ (nm)	Exposure time t (s)	MPE	
180 - 400	all times	same as for eye	
400 - 700	$< 10^{-9}$	$2 \cdot 10^{11}$	W/m^2
	10^{-9} - 10^{-3}	200	J/m^2
	10^{-3} - 10	$1,1 \cdot 10^4 \cdot t^{0,25}$	J/m^2
	$10 - 3 \cdot 10^4$	2000	W/m^2
700 – 1400	$< 10^{-9}$	$2 \cdot 10^{11} \cdot C_4$	W/m^2
	10^{-9} - 10^{-3}	$200 \cdot C_4$	J/m^2
	10^{-3} - 10	$1,1 \cdot 10^4 \cdot C_4 \cdot t^{0,25}$	J/m^2
	$10 - 3 \cdot 10^4$	$2000 \cdot C_4$	W/m^2
1400 - 10^6	all times	same as for eye	

$C_4 = 10^{0,002(\lambda - 700)}$ $\quad 700 < \lambda \le 1050$

$C_4 = 5$ $\quad 1050 < \lambda \le 1400$