## Comments on the Radiation Protection Authority's regulations (SSI FS 2005:4) on lasers

In these comments the MPE-values according to Swedish Standard SS EN 60825-1, edition 3, 2003 are given. The Swedish standard is identical with the international standard IEC 60825-1, edition 1.2, 2001. The comments also contain an overview of the principles and hazard evaluations that form the base for the laser classes.

## Maximum permissible exposure (MPE)

The MPE-values ensure that damages do not occur according to the best available experimental data. The exposure limits have inherent safety margins and shall not be considered as sharp borders between harmless and harmful exposures.

The eye is the most sensible organ for laser radiation in particular regarding wavelengths that reach the retina, i.e. within the wavelength range 400 – 1400 nanometres (nm). The retina per se is not more sensible than other tissues but the optics of the eye focus the radiation at the retina so that the power density may increase by a factor of $10^5$ compared to outside the eye. The MPE-values take the focusing effect into account and are valid in front of the eye.

To compare with the MPE-values the power density or the energy density should be measured or calculated perpendicularly to the beam path as mean values over circular areas having diameters as shown in table 1.

***Terms and symbols***

| | |
|---|---|
| *MPE* | stands for maximum permissible exposure according to Swedish and international standard. |
| *Exposure duration (t)* | is the total time (seconds) during which exposure goes on. This time may contain repeated radiation pulses. |
| *Pulse duration ($\tau$)* | is the time (seconds) in which the instantaneous power exceeds half the peek power. |
| $\lambda$ | is the symbol for wavelength in nanometres (nm = $10^{-9}$ m) |
| *Wavelength interval and time interval* | are written in the form as the wavelength interval 315 – 400 nm for an example. Hereby is meant $315 \leq \lambda < 400$ nm if not otherwise is indicated. |
| $\gamma$ | is the symbol for the less plane opening angle (milliradians, mr) of a circular cone within which a measuring instrument shall be able to record radiation (the angle of acceptance). |
| $\alpha$ | is the symbol for the plane visual angle (mr) that an extended source shows at the present viewing distance, for instance an irradiated spot at a matte surface. Thus $\alpha$ is the angle that has its vertex at the cornea and its sides diametrically opposed to the fringes of the source. For an oblong source $\alpha$ is the arithmetic mean of the length and the width. $\alpha_{MIN}$ is 1.5 mr. $\alpha_{MAX}$ is 100 mr. If the visual angles are less than 1.5 mr or larger than 100 mr, $\alpha$ should be replaced by these angles prior to calculating the mean. $\alpha$ should not be mixed up with the divergence angle of the beam. |

## MPE-values

***Table 1: Measurement area***

| Spectral range λ (nm) | Exposure duration t (s) | Measurement area diameter (mm) eye | skin |
|---|---|---|---|
| 180 – 400 | all durations | 1 | 3,5 |
| 400 – 1400 | all durations | 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 durations | 11 | 11 |

If the cross section of the beam is less than the measurement area the total power in the beam or the total energy in a pulse should be considered to be even distributed over the measurement area. If the cross section of the beam is larger than the measurement area the maximum power density or energy density in the beam should be taken into account.

***Exposure to the eye for repeated pulses shorter than 0.25 seconds in the wavelength range 400 – $10^6$ nm***

The MPE tables regard one single pulse that may be short or long during an 8 hours period of time. If the laser emits repeated pulses or if the laser is scanning so that the eye is hit once per scan MPE for each pulse in the pulse train is calculated as follows.

If several pulses with duration longer than $10^{-9}$ seconds occur within the time $T_i$, the energy density of the pulses should be added in the time $T_i$. The number of those joint pulses should then be counted giving the number N and their energy density should then be compared to the calculated MPE for pulses with duration $T_i$. The values of $T_i$ to be used are shown in table 2.

***Table 2: $T_i$***

| Spectral range λ (nm) | $T_i$ (s) | Spectral range 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 | $10^{-3}$ | $2600 – 10^6$ | $10^{-7}$ |

Moreover applies to a pulse train:

a) The energy density of a single (joint) pulse in the pulse train must not exceed the applicable MPE-value for such a pulse.

b) The added up energy density in a pulse train or the mean power density of a pulse train respectively in the exposure duration t must not exceed the MPE for a single pulse with duration t.

c) MPE for each pulse in the pulse train is calculated by the following procedure:

* Determine MPE for a single pulse in the pulse train according to tables.
* Count the number of such pulses in the exposure time. This number is N. In the wavelength range 400 – 1400 nm N should be counted during the exposure time, however not longer than $T_2$, (See note under table 4). For longer wavelengths N is counted during 10 seconds.
* MPE for each pulse in the pulse train = MPE for a single pulse multiplied by $N^{-1/4}$.

* If the described procedure implies that the peak power density in a pulse should be lower than the power density allowed in the continuous case during the total exposure time, the pulse power density does not need to be reduced under the continuous level.

***Table 3: MPE for exposure of the eye to a single pulse concerning damages by ultraviolet radiation and photochemical damages in the retina***

| Wavelength $\lambda$ (nm) | Exposure duration t (s) | MPE | | |
|---|---|---|---|---|
| 180 – 302,5 | $10^{-13} - 10^{-9}$ | $3 \cdot 10^{10}$ | | W/m² |
| | $10^{-9} - 3 \cdot 10^{4}$ | 30 | | J/m² |
| 302,5 – 315 | $10^{-13} - 10^{-9}$ | $3 \cdot 10^{10}$ | | W/m² |
| | $10^{-9} - T_1$ | $5600 \cdot t^{0,25}$ | | J/m² |
| | $T_1 - 3 \cdot 10^{4}$ | $10^{0,2(\lambda - 295)}$ | | J/m² |
| 315 – 400 | $10^{-13} - 10^{-9}$ | $3 \cdot 10^{10}$ | | W/m² |
| | $10^{-9} - 10$ | $5600 \cdot t^{0,25}$ | | J/m² |
| | $10 - 10^{3}$ | $10^{4}$ | | J/m² |
| | $10^{3} - 3 \cdot 10^{4}$ | 10 | | W/m² |
| Photochemical damage in the retina: | | | | |
| 400 – 450 | $10 - 10^{2}$ | 100 | ($\gamma$ = 11 mr) | J/m² |
| | $10^{2} - 10^{4}$ | 1 | ($\gamma = 1,1 \cdot t^{0,5}$ mr) | W/m² |
| | $10^{4} - 3 \cdot 10^{4}$ | 1 | ($\gamma$ = 110 mr) | W/m² |
| 450 – 600 | $10 - 10^{2}$ | $100 \cdot 10^{0,02(\lambda-450)}$ | ($\gamma$ = 11 mr) | J/m² |
| | $10^{2} - 10^{4}$ | $10^{0,02(\lambda-450)}$ | ($\gamma = 1,1 \cdot t^{0,5}$ mr) | W/m² |
| | $10^{4} - 3 \cdot 10^{4}$ | $10^{0,02(\lambda-450)}$ | ($\gamma$ = 110 mr) | W/m² |
| 400 – 484 | $1 - 3 \cdot 10^{4}$ | $100 \cdot 10^{0,02(\lambda-450)}$ | ($1,5 \le \alpha < 82$) | J/m² |

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

In the wavelength range 400 – 600 nm there are dual limits concerning photochemical damages (table 3) and thermal damages (table 4) respectively. The limit is set by the most restrictive condition. In the wavelength range particular conditions apply if the exposure duration is longer than 1 second and $\alpha \geq 1.5$ mr.

*Table 4: MPE for exposure of the eye to a single pulse concerning thermal damages of the retina*

| Wavelength $\lambda$ (nm) | Exposure duration 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 | ($\alpha \leq 1,5$ 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$^2$ |
| | $T_2 – 3 \cdot 10^{4}$ | $10 \cdot C_4$ | ($\alpha \leq 1,5$ 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$^2$ |
| | $T_2 – 3 \cdot 10^{4}$ | $50 \cdot C_7$ | ($\alpha \leq 1,5$ 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 | for $\alpha \leq 1,5$ mr |
| $T_2 = 10 \cdot 10^{((\alpha - 1,5) / 98,5)}$ s | for $1,5 < \alpha \leq 100$ mr |
| $T_2 = 100$ s | for $\alpha > 100$ mr |
| $C_4 = 10^{0,002 (\lambda - 700)}$ | |
| $C_6 = 1$ | for $\alpha \leq 1,5$ mr |
| $C_6 = \alpha / 1,5$ | for $1,5 < \alpha \leq 100$ mr |
| $C_6 = 66,7$ | for $\alpha > 100$ mr |
| $C_7 = 1$ | for $1050 < \lambda \leq 1150$ |
| $C_7 = 10^{0,018(\lambda - 1150)}$ | for $1150 < \lambda \leq 1200$ |
| $C_7 = 8$ | for $1200 < \lambda \leq 1400$ |

*Table 5: MPE for exposure of the eye to a single pulse concerning thermal damages of the lens and vitreous*

| Wavelength $\lambda$ (nm) | Exposure duration 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$^2$ |

***to be continued***

*Table 5: (continuation) MPE for exposure of the eye to a single pulse concerning thermal damages of the lens and vitreous*

| Wavelength $\lambda$ (nm) | Exposure duration t (s) | MPE | |
|---|---|---|---|
| 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 exposure of skin to a single pulse*

| Wavelength $\lambda$ (nm) | Exposure duration t (s) | MPE | |
|---|---|---|---|
| 180 – 400 | all durations | 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 – 1050 | $< 10^{-9}$ | $2 \cdot 10^{11} \cdot C_4$ | $W/m^2$ |
| | $10^{-9} – 10^{-3}$ | $200 \cdot C_4$ | $J/m^2$ |
| | $10^{-3} – 10$ | $1,1 \cdot 10^4 \cdot C_4 \cdot t^{0,25}$ | $J/m^2$ |
| | $10 – 3 \cdot 10^4$ | $2000 \cdot C_4$ | $W/m^2$ |
| 1050 – 1400 | $< 10^{-9}$ | $10^{12}$ | $W/m^2$ |
| | $10^{-9} – 10^{-3}$ | $10^3$ | $J/m^2$ |
| | $10^{-3} – 10$ | $5,5 \cdot 10^4 \cdot t^{0,25}$ | $J/m^2$ |
| | $10 – 3 \cdot 10^4$ | $10^4$ | $W/m^2$ |
| $1400 – 10^6$ | all durations | same as for eye | |

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

At exposure of skin to repeated pulses the procedure used for eye exposure does not apply. In stead the mean power density or the total energy density in a pulse train should be compared to the MPE according to table 6 for the relevant exposure duration.

## Laser classes

***Introduction***

The IEC committee TC76 has since many years dealt with laser safety, exposure limits and laser classification at an international level. The exposure limits (maximum permissible exposure, MPE) form an important part of the standard IEC 60825 which has been up-dated and amended several times since 1984. The exposure limits are expressed as functions of, among others, wavelengths, time patterns, and retinal image sizes. Thus their use is not too easy for persons who have not particularly considered the matter. No higher mathematics is involved, but there are a number of things to think about.

To make things easier for the users, a system of classification of lasers and products containing lasers was invented. The user then easily gets an idea about the potential risks and how the work on safety should be designed.

***Description of the laser classes***

*Class 1*

Lasers are harmless even to long term exposure. Either the lasers are so weak that they are not capable of producing any health effects whatsoever, or we deal with products that contain lasers, which might be of higher classes, but are safely built-in and interlocked in such a way that no harmful radiation can be emitted from a product at normal use. The maximum radiation power or the maximum pulse energy in the class is directly related to the exposure limits. The upper class-limits of these parameters are of course strictly defined, but the complexity of the exposure limits does not permit a simple description.

*Class 1M*

This class contains lasers, emitting visible or invisible radiation (or both), with a total power or pulse energy that exceeds the class 1 limit, but the beam must be expanded so the MPEs are not exceeded. The philosophy is similar to the former class 3A but the cap (five times the class 1 limit) is removed. Thus lasers in the class are harmless provided no collecting optics are involved. M stands for magnifier.

*Class 2*

This class only contains lasers that emit visible radiation, defined in the standard as radiation in the wavelength interval 400 - 700 nanometres. (It is possible to see radiation of wavelengths for instance 380 nm or 750 nm as well, but in these spectral regions the relative vision response of the human eye is too low to guarantee a sensation of glare.) The sensation of glare is important. If an unprotected eye should be hit by a class 2 laser beam, natural mechanisms are provoked to avoid further exposure i.e. the eyelid closes. These mechanisms are fast enough (< 0.25 seconds) to prevent overexposure of the retina. For CW-lasers the upper class limit is 1 mW. CW stands for "continuous wave", and such lasers emit radiation with constant power from switched on to switched off.

*Class 2M*

The class contains lasers emitting visible radiation (400 - 700 nm). The limit of class 2 is exceeded, but the beam must be expanded to allow an exposure of duration 0.25 seconds. This means for CW-lasers a maximum power density of 25 $W/m^2$, as recognised from the obsolete class 3A in the visible region. The old 3A cap (five times the class 2-limit, i.e. 5 mW for CW-lasers) is also removed.

*Class 3R*
This class contains lasers in the lower end of the class 3B as defined in older standards. The class limits are defined as five times the upper limits of class 1 (invisible) or five times the limits of class 2 (visible), regardless of the geometric shape of the beam, unless the beam is expanded to meet the requirements of class 1M or 2M. It is possible to exceed the MPE-values, but they have inherent safety factors, so lasting damages on eyes or skin are extremely unlikely in reality, should a short term human exposure occur. R stands for restricted.

*Class 3B*
As soon as the class limits for class 3R are exceeded the class designation is 3B. Class 3B-lasers are considered to be hazardous for direct exposure of the eye and, at least in the upper region, of the skin. However, it is not hazardous to view diffuse reflexes, i.e. reflexes from matte surfaces. The upper limit for CW-lasers is 0.5 W.

*Class 4*
This class contains lasers that can be extremely dangerous. Direct exposure is dangerous for eye and skin and even diffuse reflexes may be hazardous at least under some circumstances. There might also be fire hazards. The class has no upper limit.