University of Chicago
Office of Radiation Safety

Calculating MPE and NHZ

This document provides the laser user with formula's to perform the MPE and NHZ calculations for lasers and laser systems used at the University of Chicago. The results from these calculations will assist the user in establishing the engineering and administrative controls for each laser and laser system used in their laboratory.

Am I Safe? The Important Definitions

Given the enormous range of wavelengths, power levels and exposure times that may be experienced with laser, how do you know when a given exposure is dangerous? The answer lies in the large amount of experiments that have been performed by researchers like you to determine the effect of laser radiation on the eye for various wavelengths, power levels, and exposure times. This has provided detailed knowledge of what total energies will, under a particular set of conditions, cause a biological effect.

This vast store of information has been collated by a number of government and non-government organizations to produce tables of information. They have also been the source for the American National Standard for the Safe Use of Lasers (ANSI Z136.1). Unfortunately, like most technical standards, the information in this standard is difficult to assimilate at first reading. To begin to use the information that is provided for your benefit, you must first understand the following definitions.

The Accessible Emission Limit (AEL)

The primary measurement of a laser's hazard potential is the Accessible Emission Limit (AEL), which defines the maximum total power of radiation that can be emitted from a laser of a particular class. Assuming a linear additive effect for radiation absorbed by the, the minimum irradiance known to cause a biological effect is converted into a power level for the length of time defined by a given class.

As AELs are mainly used for classification of a laser, they are not immediately useful to a user who wants to know if his/her particular setup is safe. However, you can use the classification scheme to help you make very simple decisions. For instance, if you always keep your power level below that required of a class II device, you can be assured that accidental exposure to the beam will not be hazardous to you. For visible lasers, this means keeping the average power below 1 mW for start up or alignment procedures.

The Maximum Permissible Exposure (MPE)

The single most useful number in laser safety calculations is the Maximum Permissible Exposure (MPE). This is the minimum irradiance or radiant exposure that may be **incident upon the eye** (or the skin) without causing biological damage. The MPE is related to the AEL by the limiting aperture of the eye, which is itself a function of wavelength and exposure time. To make things simple, the MPE is tabulated separately: for a specific safety calculation it should be the first table you turn to. One caution: the actual value of the MPE is occasionally dependent on some correction factors, which are separately tabulated.

The Nominal Hazard Zone (NHZ)

The other major definition for laser safety calculations is the Nominal Hazard Zone (NHZ). This is a distance within which the irradiance of a beam is greater than the MPE. Besides being specific to a given wavelength and time of exposure, a different NHZ can be defined for the beam's path to your eye – direct viewing, specular reflectance, or diffuse reflectance.

The NHZ is a practical definition; it has a specific shape around your particular laboratory apparatus (for instance, assuming your lab has no windows and a solid door, the NHZ will in the worst case scenario be the floor area of the lab itself). In other words, the NHZ for you will be derived at the end of your safety calculations, and thereafter will be most useful to you for planning control measures in you laboratory. Formulas for calculating the NHZ are listed below.

Principle of Laser Safety Evaluation

The basic method for evaluating the safety (or otherwise) of your specific laser system is to calculate the maximum irradiance that an unprotected eye might experience while the system is operating in a particular manner, and check whether it is less than the MPE. This involves thinking about all the different circumstances that may occur – accidentally viewing the beam directly while aligning an optic, catching a chance reflection while changing the optical setup, and so on. This might sound tortuous, but is really quite simple if you quickly determine what are the worst-case scenarios for any exposure.

Assuming you find that the irradiance in a particular situation is greater than the MPE. You then determine the NHZ for that particular situation. For example, the NHZ for a diffuse reflectance may be within 1 m of the laser itself, but the NHZ for direct viewing may include the entire laboratory. Within the NHZ, you then calculate the necessary OD for a set of laser goggles that will reduce the irradiance at the eye below the MPE. You can also take action to reduce the NHZ, such as enclosing the beam path or changing the design of the laser system. Finally, you should develop a set of consistent set of lab practices with your colleagues to ensure that everyone operates the system in a manner that is safe for both themselves and others.

Before proceeding, let us summarize right now the most common causes of accidents in research labs (as obtained from actual case histories). They are:

(1) not wearing appropriate safety goggles,
(2) not reducing power for alignment procedures, or unintended power increase,
(3) stray beams left uncontained by beam stops or other barriers.

If you are not addressing the three items above, you are currently operating you laser in an unsafe manner. Don't wait until after the accident to make excuses or blame someone else. Change your work practices now!

MPEs and Safety Calculations

Useful Approximations:

For each laser in use, we are interested in identifying the maximum safe energy that may be incident upon the eye. This energy is a often a rather complicated function of wavelength and the duration of exposure. In some places a single value suffices for a broad range of conditions. In other cases, notably those of visible and near-infrared radiation during ordinary time-periods of exposure, the MPE should be calculated on a case-by-case basis. For these purposes, it is worth using the following assumptions:

1 Limiting time of inadvertent exposure to visible radiation = 0.25 s (the blink reflex)
2 Limiting time of inadvertent exposure to UV or NIR radiation = 10 s (natural eye motion)
3 Limiting time of exposure for intentional viewing = 10^{2} s (i.e. during laser alignment)
4 Limiting time of long-term exposure = $3\bullet 10^{4}$ s (24 hrs)

You might think the estimated exposure time of 100 s for a procedure such as alignment is ridiculous. However, even if you are wise enough to use indirect methods such as burn paper of power meters to align your beam, it is entirely possible that you will look in the same direction for 100 s during an alignment procedure. The 100 s exposure time includes the possibility of unbeknownst exposure to a stray beam while performing an operation on your laser system. Once you have determined MPE relevant to particular application, you must calculate the level of incident radiation at your eye under a variety of circumstances. Important parameters for such calculations are the optical path length from laser output to the eye, the beam diameter and divergence, the limiting aperture of the eye, whether the beam is viewed as a point or extended source, and whether a reflection is considered specular or diffuse.

Important Conventions

Before calculating actual numbers, you have to be sure you have the right starting values and units. The three big numbers found in laser manuals are the beam diameter *a*, the beam divergence *f*, and the radiant energy *Q* or radiant power Φ. These values appear in safety calculations, where they have the units of cm, radians, J and W respectively. The central quantities in a laser safety calculation however, are the radiant exposure *H* (measured in $\mathrm{J\}cm}^{-2}$) and the irradiance *E* (measured in $\mathrm{W\}cm}^{-2}$). These values are less common in the front of laser manuals. There may also be some confusion depending on the profile of your beam and the choice of beam diameter.

The most common profile of a laser beam is a Gaussian profile. The diameter *a* of a Gaussian beam be specified according the 1/*e* or $1/e^{2}$ point. Laser manufacturers may often use the $1/e^{2}$ definition since this area encompasses 90% if the total beam energy. However, safety calculations use the 1/*e* diameter, so check which one you are using. The two diameters have a simple relation

$$a(1/e^2) = \sqrt{2a(1/e)}$$

Your beam may not have a Gaussian profile. Another common profile is the top hat, in which the beams radiant exposure is equal for all points within the beam diameter. This mode makes the beam diameter very easy to define, and also the irradiance. For a beam with a top hat profile, beam diameter *a*, and radiant powerΦ :

$$E_0 = \frac{4\Phi}{\pi a^2}$$

The subscript for *E* identifies it as the maximum irradiance, i.e. at zero distance from the lasers exit port. The radiant exposure is calculated from this by dividing *H* by the appropriate exposure time or pulse duration.

For a Gaussian beam, the central irradiance will be different from the average irradiance over the area within the beam diameter. However, the MPE is not determined according to the peak irradiance of the beam, it is determined by averaging the incident power of the beam over an area defined by the *limiting aperture* of the eye. For visible light this limiting aperture is the diameter of a fully dilated pupil, which is 7 mm. For non-visible radiation other limiting apertures are defined as follows:

Spectral Region	Period of Exposure (s)	Aperture Diameter (mm)
180 to 400 nm	10^{-9} to 0.25	1.0
	0.25 to $3 \times 10_4$	3.5
400 to 1400 mm	10^{-9} to $3 \times 10_4$	7.0
1400 nm to 100 μm	10^{-9} to 0.25	1.0
	10 to $3 \times 10_4$	3.5
100 to 1000 μm	10^{-9} to $3 \times 10_4$	11.0

If the diameter of your beam is similar to the limiting aperture for your wavelength, you may calculate the irradiance assuming your beam has a top hat profile, using the following equation:

$$E_0 = \frac{4\Phi}{\pi[\max(a, D_f)]^2}$$

In which Φ is the total radiant power of the beam, a is the beam diameter (measured at 1/*e* of the peak irradiance), and D_f is the limiting aperture at the appropriate wavelength.

1. CW and Single Pulse MPEs

Example 1.1:

Q: Determine the MPE for accidental direct exposure to a visible laser.

A: The time to use for “accidental exposure” in the visible region is 0.25 s, the blink reflex. Visible lasers are those that emit light of wavelengths between 400 and 700 nm. From Table 3, we find:

$$MPE = 1.8t^{3/4} \text{ x } 10^{-3} \text{ J-cm}^{-2}$$

For $t = 0.25$ s, this is equal to a radiant exposure $H = 0.636$ mJ }cm^{-2}. If we want the MPE in terms of irradiance, we use the formula:

$$E = \frac{H}{t}$$

$$= \frac{0.636}{0.25}$$

$$= 2.55 \text{ mW / cm}^{2}$$

Finally, if we consider the limiting aperture of the eye in the visible region, 7 mm, then the area over which the visible radiation will be viewed is $\pi/4\times0.7^2 = 0.385$ cm^2. Hence the maximum flux of a visible laser to avoid harm due accidental exposure should be 2.55×0.385 = 1.0 mW. As you may recall, this is the upper power limit for a class II laser device.

Example 1.2:

Q: Calculate the MPE for intentional, direct ocular exposure to the fundamental mode of a CW Nd:YAG laser.

A: The fundamental mode of a Nd:YAG laser is at 1064 nm. The appropriate value is read directly from Table 3: For intentional viewing, take the time of exposure to be 100 s, so the MPE is $5C_C \bullet 10^{-3}$ W / cm^2, or 5 mW / cm^2 ($C_C = 1.0$ for 1050 to 1150 nm).

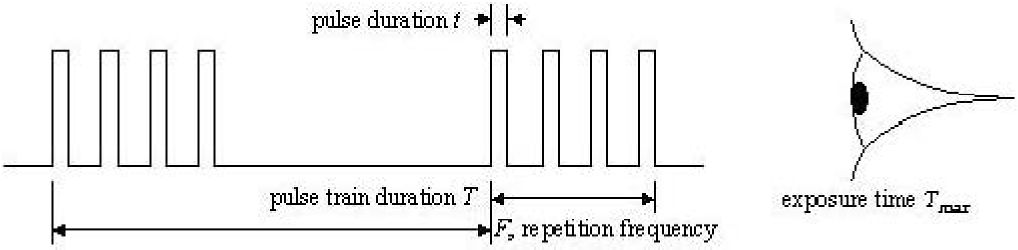
Example 1.3:

Q: Calculate the MPE for accidental exposure to a Xe:Cl excimer laser.

A: The wavelength of emission from a Xe:Cl excimer is 308 nm. Since this is invisible to the human eye, the time period for accidental exposure should be take as 10 s. From Table 2, the MPE is 40 mJ }cm^{-2}. Note from Table 2 that this MPE applies to all exposure times. Unlike the visible and near-IR region, where the eye can tolerate a small but constant irradiance, in the UV radiation damage is cumulative. Thus the longer the exposure time, the lower the safe operating power.

2. Repetitively Pulsed Lasers

The most common lasers in research today are pulsed lasers, due to their higher peak energies. Because of its high peak intensity, the MPE from a pulsed laser is more complicated than for .an equivalent continuous source. To determine the correct MPE for a f=given train of pulses you must know the pulse repetition frequency (F), the duration of a single pulse (t), the total duration of a train of pulses (T), and the total exposure time T_{max}.



There are three rules that limit the MPE per pulse for a train of laser pulses:

1 The MPE/pulse is limited to the MPE for any single pulse (single pulse limit).
2 The MPE/pulse is limited to the MPE for all exposure times between T and T_{max}, divided by the number of pulses n during that time period (average power limit).
3 The MPE/pulse is limited to the MPE for a single pulse multiplied by $n^{-1/4}$, where n is the number of pulses that occur during the period of exposure T_{max} (repetitive pulse limit).

Above a critical frequency (>55 kHz for visible lasers) rule 2 gives the lowest value. In other cases all three limits should be checked.

Ex. 2.1

Q: Calculate the MPE for a XeCl excimer laser (308 nm), with a pulse length t = 20 ns, operating at a frequency F = 120 Hz.

A: Assume an exposure time of 10 s (no blink reflex). Now check each of the three limits:

1. The MPE for a single pulse of 20 ns at 308 nm, found in Table 2, is the lower of 0.56 $t^{1/4}$ and 40 mJ / cm^2. In this case, the MPE for a single pulse is given by $0.56\cdot(2\times10^{-8})^{1/4}$ = 6.7 mJ / cm^2.

2. The MPE of a continuous source for a 10 s exposure, found in Table 2, is 40 mJ/cm^2. The total number of pulses n = 1200, so the

$$\text{MPE per Pulse} = \frac{40}{1200} = 33\ \text{uJ/cm}^2$$

3. Using the MPE for a single pulse = 6.7 mJ/m^{-2} (from limit 1), and the number of pulses in 10 s n = 1200 (from limit 2), the calculated

$$\text{MPE per Pulse } = \frac{6.7}{\sqrt[4]{1200}} = \frac{6.7}{5.89} = 1.1 \text{ mJ/cm}^2$$

So the MPE/pulse is defined by limit 2, and is 33 $mJ\}\mathrm{cm}^{-2}$. To express this in terms of irradiance, multiply the result by the repetition frequency F:

$$E = \frac{H}{t}$$

$$= 3.3 \text{ x } 10^{-5} \text{ x } \frac{120}{1}$$

$$= 4 \text{ mW / cm}^2$$

Ex. 2.2

Q: Calculate the MPE for accidental

exposure to a pulsed Nd:YAG laser operating in its doubled mode of 532 nm, with an pulse length t = 1 ns and a repetition frequency F = 20 Hz.

A: Assume an exposure time of 0.25 s (blink reflex)

1. The MPE for a single pulse of 1 ns at 532 nm, found in Table 3, is $0.5\ m\text{J / cm}^2$.

2. The MPE of a continuous source for a 0.25 s exposure, found in Table 2, is 0.636 mJ / cm^2 . The total number of pulses n = 5, so the

$$\text{MPE per Pulse } = \frac{0.636}{5} = 0.13 \text{ uJ / cm}^2$$

3. Using the MPE for a single pulse = 0.5 mJ / cm^2 (from limit 1), and the number of pulses in 0.25 s n = 5 (from limit 2), the calculated

$$\text{MPE per Pulse } = \frac{0.5}{\sqrt[4]{5}} = 0.33 \text{ uJ / cm}^2$$

Hence the MPE/pulse is defined by limit 3, and is 0.33 mJ / cm^2. To express this in terms of irradiance, multiply the result by the repetition frequency F:

$$E = \frac{H}{t}$$

$$= 3.3 \times 10^{-4} \times \frac{20}{1}$$

$$= 6.7 \text{ uW / cm}^{2}$$

Note that the magnitude of this MPE is several hundred times lower than for an equivalent CW laser (compare to exercise 1.1).

3a. Extended Source Viewing

If a laser beam has a high divergence, or is viewed at a close distance relative to the beam diameter, the image formed by the beam upon the retina may not be a point. In this case, the laser is an extended source and the MPE should be corrected accordingly. Extended source MPEs are applied only in the spectral region 400 to 1400 nm, and where the angle subtended by the eye to capture the entire beam is greater than a minimum angle specified for differing exposure times:

Exposure Time (s)	Angle α_{min} (mrad)
= 0.7	1.5
0.7 – 10	$2t$¾
= 10	11

If the laser beam subtends and angle greater than the minimum for particular viewing circumstances, then the MPE should be multiplied by the factor α/α_{min}. Extended source viewing may apply in cases such as viewing a beam after passing through an optic, or viewing a diffuse reflection at close distance. However, since an extended source correction factor increases the MPE, it is generally sufficient to perform your calculations simply assuming a point source (worst case scenario).

3b. Diffuse Reflections

The major feature of class IV lasers such as those found in research laboratories is the fact that even diffuse reflections can be hazardous. Thus it is important to understand how to calculate the power of a diffusely reflected laser beam.

The flux of energy through a point at a given distance and angle from a diffusely reflecting surface is:

$$H = \frac{P_{\lambda} Q \cos \Phi_{\nu}}{\pi r^{2}}$$

where P_{λ} is the reflectance at the wavelength in question, Q is the energy of the incident beam, Φv is the angle of observation with respect to the normal, and r is the distance from the point of reflection to the point of observation. For safety calculations this equation can be greatly simplified by assuming $P_\lambda = \cos \Phi v = 1$.

Ex. 3.1

Q: A user (sans safety glasses) observes a diffuse reflection from a CW Nd:YAG laser operating at 532 nm with an energy of 2 W. The distance is 40 cm and the angle of observation 20º to the normal. Is the user safe?

A: Assuming an exposure time of 0.25 s, the MPE = 0.636 mJ / cm^2. Assume a perfect reflector (*r* = 1) and ignore the angle of observation. The energy observed by the user is:

$$\mathrm{H} = \frac{0.5}{3.14x(40)^2} = 9.95x10^{-5} = 0.1 \text{ mJ / cm}^2$$

Yes, the user is safe.

Ex. 3.2

Q: Let the diameter of the beam at the surface of the reflector *a* = 8 mm. Is the beam observed as an extended source?

A: To determine the angle subtended by the beam's image at the point of observation, we require the distance (*r* = 40 cm) the angle (θ = 20º) and the beam diameter (0.8 cm). The angle subtended is given by:

$$\alpha = = \frac{D\cos\Phi}{r} = \frac{0.8}{40} x0.94 = 19 \text{ mrad}$$

Yes, the beam does represent an extended source. The correct MPE is actually 0.636 × 19/1.5 = 8.06 mJ / cm^2. Note that the above equation only holds for small angle in which sin θ ˜ θ.

4. Nominal Hazard Zones

Having determined the MPE for a specific laser operating in a specific mode, you can now define a Nominal Hazard Zone (NHZ). The NHZ relates to the space within which the level of direct, reflected, or scattered radiation during normal operation exceeds the appropriate MPE. Exposure levels beyond the NHZ are below the appropriate MPE level, thus no control measures are needed outside the NHZ. The NHZ may be calculated using the following formula:

$$NHZ = \frac{1}{\phi}\left[\left(\frac{4\Phi}{\pi * MPE}\right)^{1/2} - a\right]$$

Where ϕ is the emergent beam divergence measured in radians; Φ is the radiant power (total radiant power for continuous wave lasers or average radiant power of a pulsed laser) measured in watts; and *a* is the diameter of the emergent laser beam, in centimeters.

Protective Eyewear

As the calculations above should demonstrate, the majority of applications of lasers in a research setting will involve levels of radiation that are extremely hazardous to ones eyes. One of the common ways a direct user of a laser system protects him/herself is by wearing protective eyewear, or laser goggles.

However, many people do not bother to check whether their eyewear is appropriate to their application. On one extreme, a user may wear goggles that are appropriate for alignment procedures but will not protect against intrabeam exposure at full power. At the other extreme, a user may wear goggles that have much higher optical density than is necessary. This can be just as hazardous, because the lack of vision while wearing such goggles will tempt users to take them off, or may cause the user to make other mistakes that endanger his health.

Fortunately, once you understand how to calculate the MPE for a particular situation, determining the correct eyewear is easy. Simply calculate the radiant exposure or irradiance of the beam under the circumstances of your experiment, calculate the corresponding MPE, and take the logarithm of the quotient:

$$OD = \log_{10} \frac{H}{MPE{:}H} = \log_{10} \frac{E}{MPE{:}E}$$

The OD obtained is the minimum required to protect your eyes. Round **up** to the nearest value that is commercially available. Laser goggles are expensive but your eyes are worth more. In some cases it may be appropriate to have two sets of goggles available, one with a low OD that provide maximum visibility during alignment and low power operation, and another with a high OD for full power applications.

Ex. 5.1

Q: Calculate the appropriate OD of laser goggles for use with the two Nd:YAG lasers in exercises 4.1 and 4.2.

A: The maximum irradiance for both these lasers was determined in exercise 4.1, $E_0 = 5.2\ \mathrm{W \cdot cm^{-2}}$. The MPE for each laser, in units of irradiance, were calculated in exercises 1.1 and 2.2 respectively.

For the CW case:

$$\log_{10} \frac{E}{MPE{:}E} = \frac{5.2}{2.55 \cdot 10^{-3}} = 3.3 \Rightarrow \mathrm{OD} = 4$$

For the pulsed case: E 5.2

$$\log_{10} == 5.9 \} \mathrm{OD} = 6$$
$$MPE{:}E\ 6.7 \cdot 10^{-6}$$

Laser goggles are not always sold at all optical densities. A pair of laser goggles with OD = 6 at 532 nm would be appropriate for both these lasers.

A common attitude amongst researchers is that laser goggles are the first line of defense against hazardous laser radiation. This is not true. The first line of defense against hazardous radiation is a solid opaque barrier, i.e. a wall! Although laser goggles are of great importance, there are a number of other ways in which you can, and should, make your laboratory a safe and efficient work environment. These will be discussed in the next chapter.

Finally, one should not forget that the high optical density of laser goggles is due to their capacity to absorb laser radiation, but laser goggles also have a specific heat capacity and a melting point. There have been several recorded cases where a user sustained drastic and permanent injury when the beam they chose to look at melted through their laser goggles! Treat laser goggles as a last line of defense against injury, not your one and only safeguard.