

Laser safety

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I.Presentation

Module :

Lasers et optique non linéaire

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Abstract:

Lasers are more and more performant and diverse. Continuous and pulsed laser sources are now available, with wavelengths ranging from the visible spectrum to the infrared and UV. They also deliver powers ranging to the kilowatt. As a consequence, it is necessary for any user to take enormous precautions concerning laser safety, in order to prevent any injury. The aim of this course is to educate the potential users of laser sources about their risks and the adequate behaviour while manipulating them.

Keywords :

Laser, Laser safety

Prerequisites :

Knowledge of the Laser

Pedagogical objectives :

Educating people new to laser never worked on such sources, on how to behave when working with a laser.

Conception & production :

Le Mans Université

Licence :

Licence GNU¹

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II.Course

Laser sources emit both spatially and temporally concentrated light.

Spatial concentration corresponds to the possibility for laser light to be focused on very small surfaces, while carrying high powers. For example, one single Helium-Neon laser source, emitting 1 mW, can induce a bedazzlement ten times stronger than the one induced by sun light.

Temporal concentration corresponds to the possibility for laser light to carry a considerably high number of photons in a very short time. Laser pulses carrying energies of about one Joule during one nanosecond are common. The instantaneous power of the impulsion is in this case of the order of Gigawatt ! Still more powerful light pulses (up to the Petawatt, $10^{15}W$) are becoming more and more common. The effects induced on matter by such pulses are extremely violent : very fast absorption of the radiation, followed by high speed ejection of matter.

Laser is thus a dangerous tool as it can affect irreversibly both skin and eyes.

In the present context, where laser sources tend to be used for an increasing number of purposes, where their performances increase each year (sources emitting kilowatts continuously and Terawatts during pulses are becoming common), laser safety is a mandatory subject to study for laser users.

The purpose of this course is to present to the reader the main hazards related to laser sources and the way to prevent them. The structure is in three parts : after some reminders on lasers, the related hazards will be presented. Then follows the description of laser safety, including legal standards, physical quantities relevant for quantifying the hazard, and finally prevention. Case studies will finally analyze real laser accidents and thus show some good concrete behaviors for future laser users.

1. Reminders on lasers

A laser source is made of an amplifying medium (solid, liquid or gaseous) placed inside a resonant optical cavity (between mirrors, one of which is partially transmitting). Inside this cavity, light travels a certain amount of time and gets amplified each time it passes through the gain medium. Finally it escapes through the partially transmitting mirror. The geometrical characteristics of the whole system lead to a weak beam divergence (corresponding to spatial coherence) and a great spectral purity (temporal coherence).

1.1. Laser categories

A laser source can consequently be classified with respect to either one of the two following characteristics:

- The first classification compares **laser sources for which temporal properties differ**. One can distinguish continuous sources (corresponding to pulses longer than 0.25s, such as in the He-Ne case), and pulsed sources (gain-switched sources: $\tau = 10 \mu s$ to 0.1 s; Q-switched sources: $\tau = 10 ns$ to 10 ps; mode locked lasers: $\tau \approx 1 fs$ to few 10ps).
- The second classification compares **laser sources for which the amplifying mediums differ**. One can then distinguish four different gain medium classes :
 - Gaseous mediums, using for example neutral atoms (He-Ne, He-Cd, ...), ions (Argon Ar^+ , Krypton Kr^+), or molecules (CO_2 , excimers ...)

- Solid mediums, such as rubis (first historical laser), YAG...
- Dyes
- Semi-conductors

1.2. Laser radiation

For most of the continuous laser sources, laser radiation is made of multiple narrow frequency lines, at specific wavelengths corresponding to energetic transitions of the amplifying medium.

In the case of pulsed sources, light radiation is constituted of many frequencies contained in a spectral envelope, whose width can be of up to hundreds of nanometers.

For example, a source delivering light pulses of 10 fs emits a radiation whose spectral width is equal to 90 nm.

The light emitted by a laser is in the "optical" domain of the electromagnetic spectrum. It includes wavelengths from 180 nm to 1 mm. Optical radiation is conventionally classified as follows :

Domain	Acronym	wavelength
Ultraviolet C	UVC	180 – 280 nm
Ultraviolet B	UVB	280 – 315 nm
Ultraviolet A	UVA	315 – 400 nm
visible	/	400 – 780 nm
Infrared A	IRA	780 – 1400 nm
Infrared B	IRB	1,4 – 3 μ m
Infrared C	IRC	3 μ m – 1mm

Laser technology is still experiencing great innovations concerning simultaneously the beam characteristics, the high powers, but also the size of the source system. This explains the spread of laser technology to diverse domains, such as telecommunications, medicine, fundamental physics... Consequently to this diversity of applications, one understands the necessity to train laser sources users to laser safety.

1.3. Hazards

The main difficulty arising from this topic is related to the diversity of hazards experienced by the different people involved in laser utilization (users, researchers or maintenance staff).

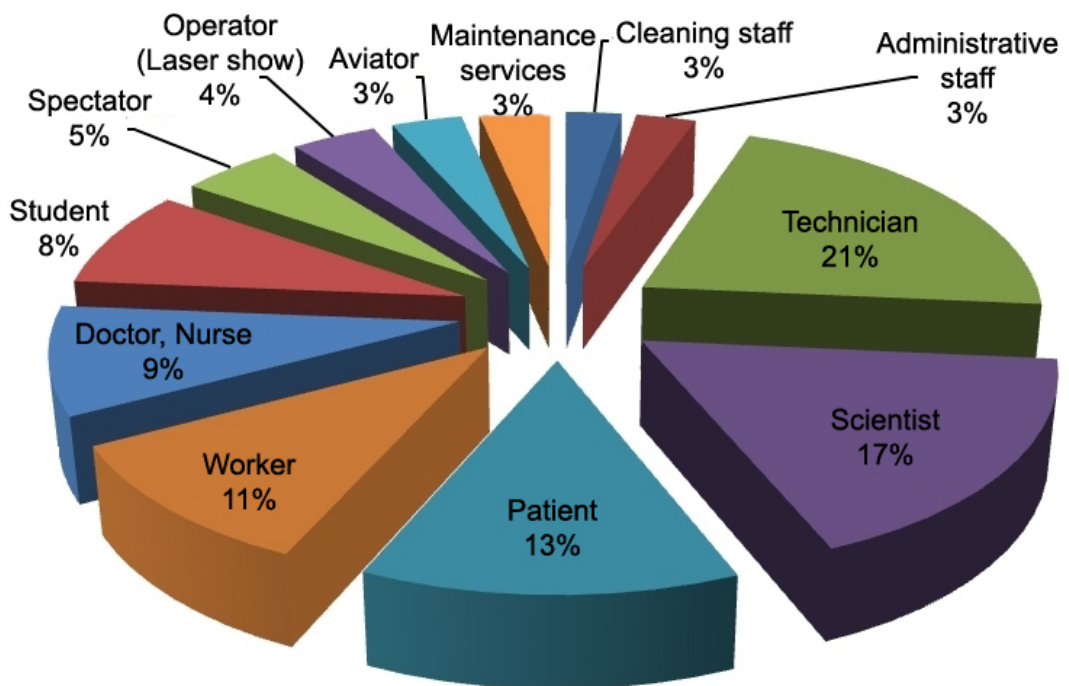
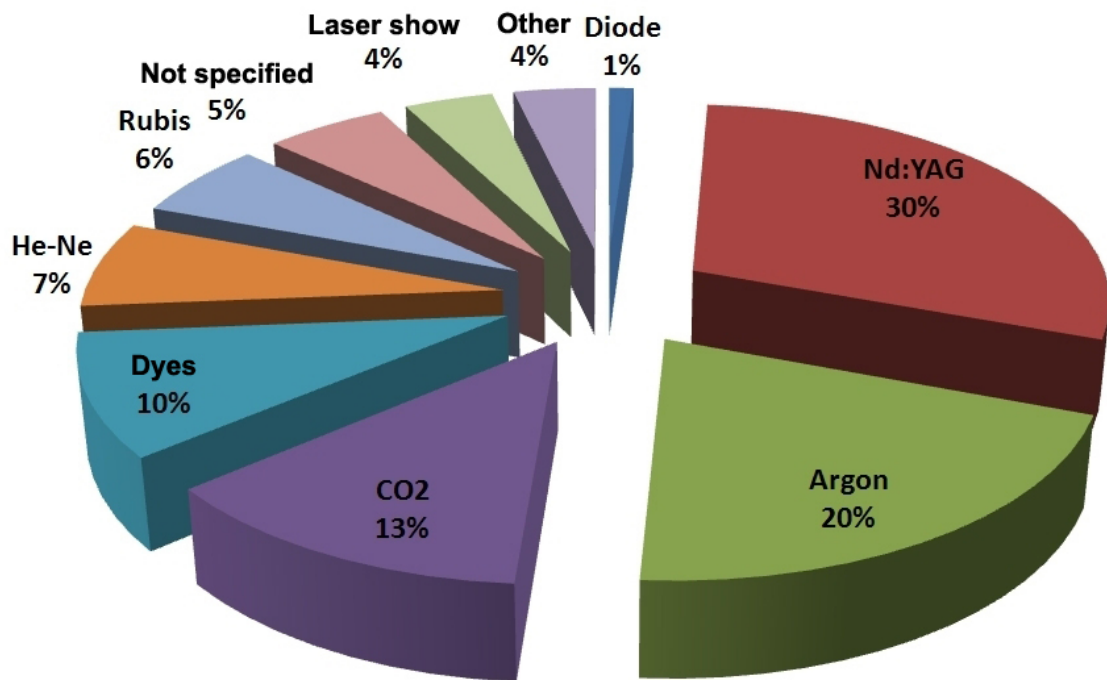
This difficulty is even increased by the fact that a laser system not only presents hazards related to

- The optical beam, characterized by a high energy density on a small surface, ("spatial concentration")

But also risks related to :

- The adjoining systems :
 - High voltage power supplies : electric hazard
 - Chemical hazard, specifically in the case of dye lasers
 - Acoustic hazards
 - Hazard related to pressurized gas bottles.

Before going into the hazards presentation, here are some statistics which compare the laser sources provoking most of the accidents, and the most hazard-exposed peoples.



2. Health issues

2.1. Biological effects of laser radiation

Before we describe the specific dangers of laser radiation on different human organs, it is useful to present the various effects it can have on organic tissues. One can easily understand that laser radiation, while meeting an obstacle to its free space propagation, provokes some physical effects depending on its power and on the surface on which it is focused.

- **Thermal effects** occur when laser radiation is absorbed by the obstacle (skin). They induce tissue reaction, related to the organism temperature elevation and to the duration of the heating process. Depending on the temperature elevation, different reactions can occur :
 - *Hyperthermia* : The temperature rises of only a few degrees. A 41°C temperature during a few tens of minutes can induce cellular death.
 - *Coagulation* : It corresponds to an irreversible necrosis without immediate tissular destruction. During this process, the tissue temperature can reach temperatures between 50°C and 100°C during about 1s. This induces dessication, whitening and retraction of tissues due to protein and collagen denaturation. Tissues will afterwards be eliminated (detersion processes) and the wound will scar.
 - *Ablation* : it corresponds to matter loss. This process occurs at temperatures higher than 100°C. In these conditions, the cell constituting elements evaporate within a relatively brief time. At the borders of the ablated area, one observes a necrosis coagulated area, as the temperature decreases continuously from the injured to the healthy tissues.
 - Hazard related to the use of pressurized gas bottles.
- **Mechanical effects** : They are caused by the creation of a plasma, by an explosive vaporisation, or by a cavitation phenomenon. These effects are mainly related to the expansion of a chock wave (created consequently to thermal effects), which in turns has destructive effects. Indeed, when ejecting matter from the substrate, the latter moves backward. This movement is due to the energy/momentum conservation, and to the fact that a part of the electromagnetic energy is converted into kinetic energy.

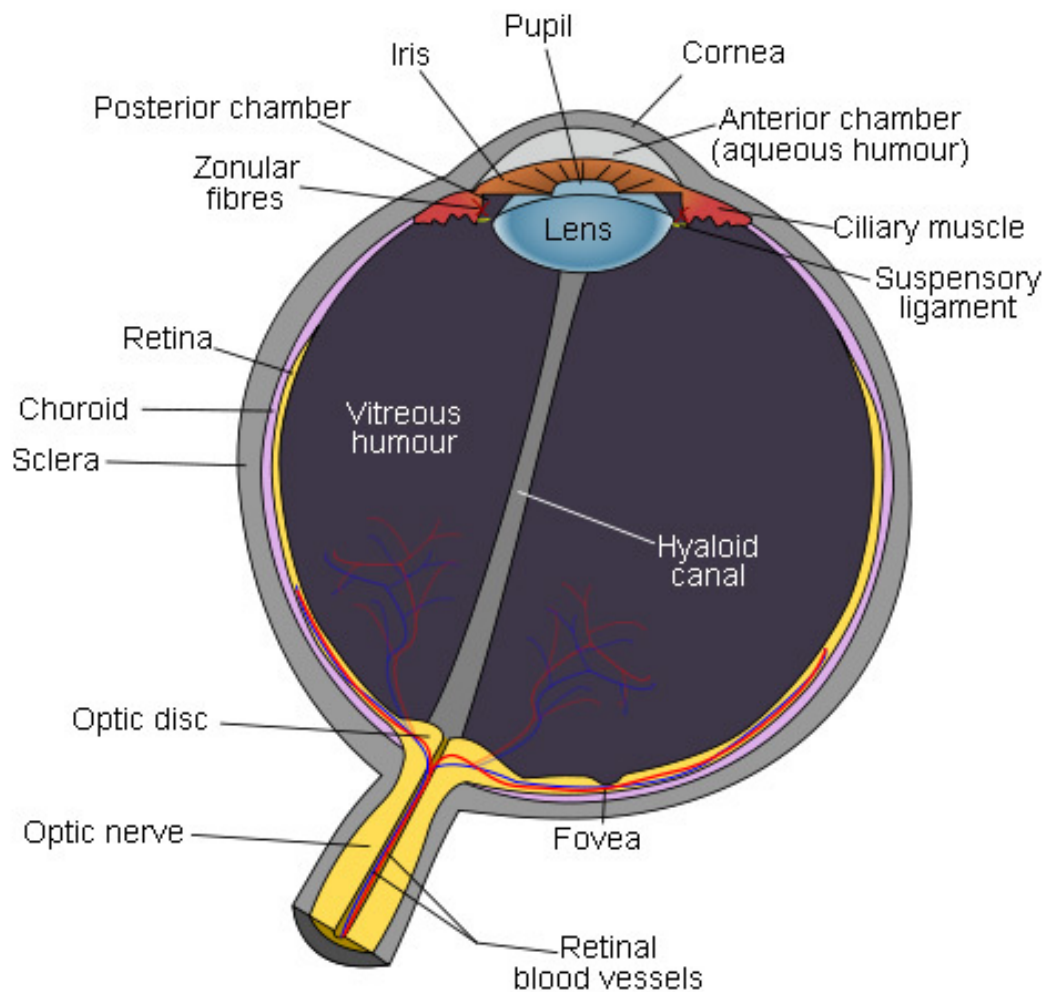
These effect can be seen from two opposite perspectives. When they accidentally happened, consequently to a lack of precautions, they are harmful. However, when used appropriately, they can have therapeutic effects. The chock wave can for example be used in ophthalmology, or in the industry.

2.2. Laser Hazard

a) Eye Hazard

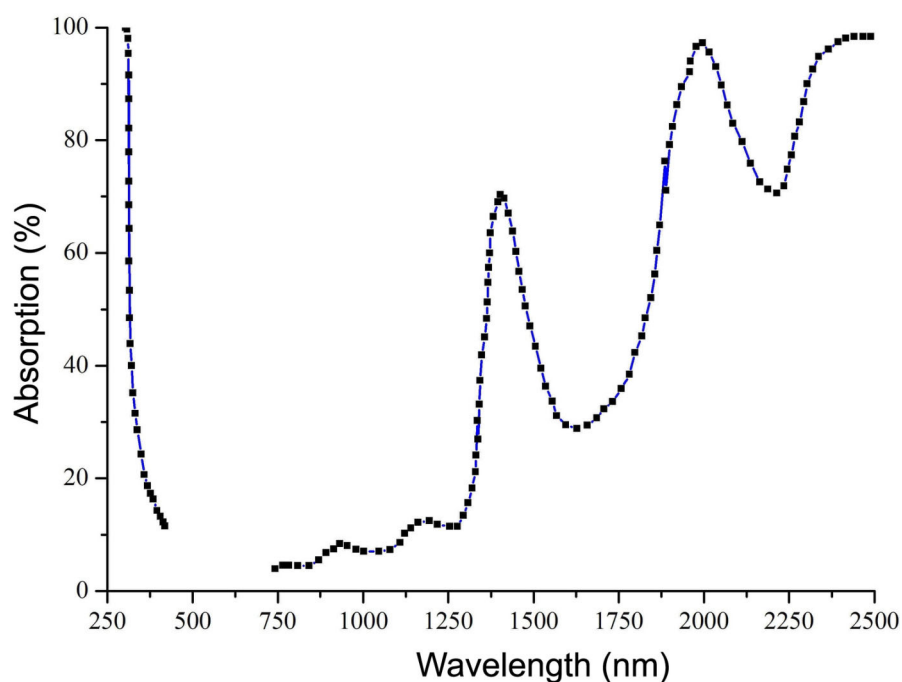
The radiation from a laser source is constituted of light rays, which can be considered as quasi-parallel. The eye, due to its function, can be assimilated to a converging lens. When a high-power laser-beam travels through the eye, its power gets focused on a smaller spot, localized on the retina. This power concentrated on a small diameter spot creates irreversible damages to the eye. However, the power is in itself not the only danger for the eye. Indeed, some factors are as relevant as the power concerning the potential damages : wavelength, exposure duration and continuous/pulsed nature of the exposition.

As can be seen on Fig. 2, the eye is a complex organ constituted of many different biological and optical elements, with different refractive indexes. Thus, while propagating through the eye, the light ray encounters mediums with different optical index and transparencies. Depending on the medium and on the wavelength of the beam, the effect will be very different.



i Cornea

Cornea has a refractive index of 1.377. Its absorption spectrum is presented on Fig. 3. Cornea does not contain blood vessels, is about 1 mm thick, and has a diameter of about 12 mm. It is isolated from ambient air by a lachrymal film.

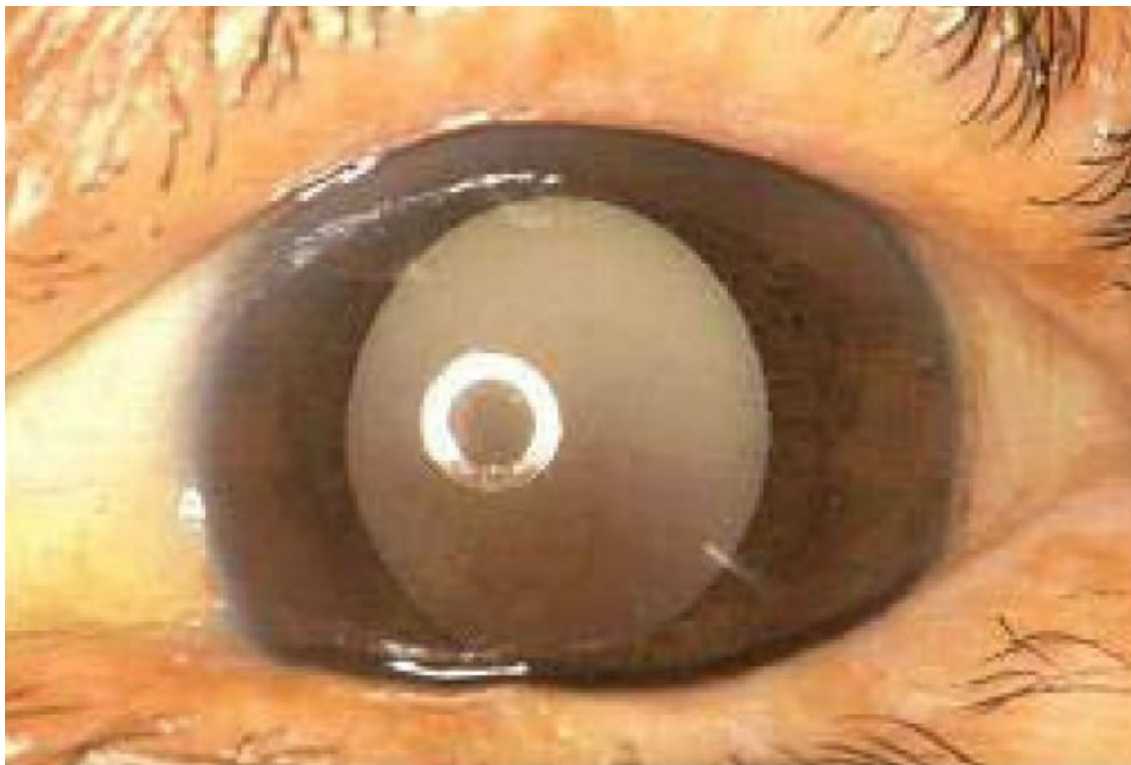


The plot in Fig. 3 shows that the most absorbed wavelengths are located in the far infrared domain (800 to 2400 nm) and in the ultraviolet domain (less than 300 – 400 nm). These wavelengths will thus provoke the most severe damages on this complex optical element.

Moreover, these injuries will have different aspects depending on the frequency of the absorbed light. Weak ultraviolet rays UV-B, UV-C provoke conjunctivitis, epithelium photokeratitis and latencies. These lesions come with red blotches and lacrimation, and are not irreversible. They disappear after a maximum of 48 hours due to the natural recovery process of the eye.

Strong ultraviolet UV-B, UV-C mostly provoke damages on the Bowman membrane and on the cornea's stroma. The Bowman layer never recovers from any lesion. The thickness of the Cornea is mostly due to the stroma. It is constituted of collagen fibers with a precise diameter (35 nm) and precise spacing (59 nm). These fibers are grouped in layers parallels to the surface of the cornea.

Previously mentioned UV rays provoke neo-vascularization of the cornea, characterized by the appearance of blood capillaries. This process can lead to a worsening of the damages and finally to an oedema associated with the production of lactic acid. The accumulation of this acid is responsible for a milky aspect of the cornea leading to a loss of transparency (see Fig. 4). These lesions are irreversible, and the cornea is lost. One can proceed with surgery, but it leads to an opaque scar. In order to get the eye functional again, the only solution is to transplant a new cornea.



Weakly energetic infrared rays slightly burn the epithelium and can create astigmatism. The lesions lead to an opacity having the same diameter as the beam. When the energy delivered by the beam is higher than a certain level (typically 30 J/cm^2), infrared rays can damage the stroma in the same manner as UV rays do (loss of transparency of the cornea). At such powers, this type of radiation is absorbed and converted into heat, thus creating a hole in the cornea and leading to a flow of aqueous humor. These damages are irreversible and require surgery, generally leading to either an opaque scar, or a transplantation.

ii Iris

As shown on fig 2, Iris is at the interface of the anterior and posterior chambers. It is constituted of colored pigments, and is thus responsible for the eye color. The pupil is located at its center. Iris is a muscle, dilating or contracting the pupil in order to regulate the light flow through the eye, thus playing the role of a diaphragm (its diameter varies from 1.5 to 9 mm). Laser radiation does not create irreversible lesions, but only pigmented areas. They appear after a laser impact, leading afterwards to an oedema and to the apparition of a miosis. However, lesions of this kind gradually disappear within 2 to 3 weeks.

Nevertheless, in case of repeated impacts, the pigments may migrate towards the anterior chamber, and the iris may atrophy or even tear.

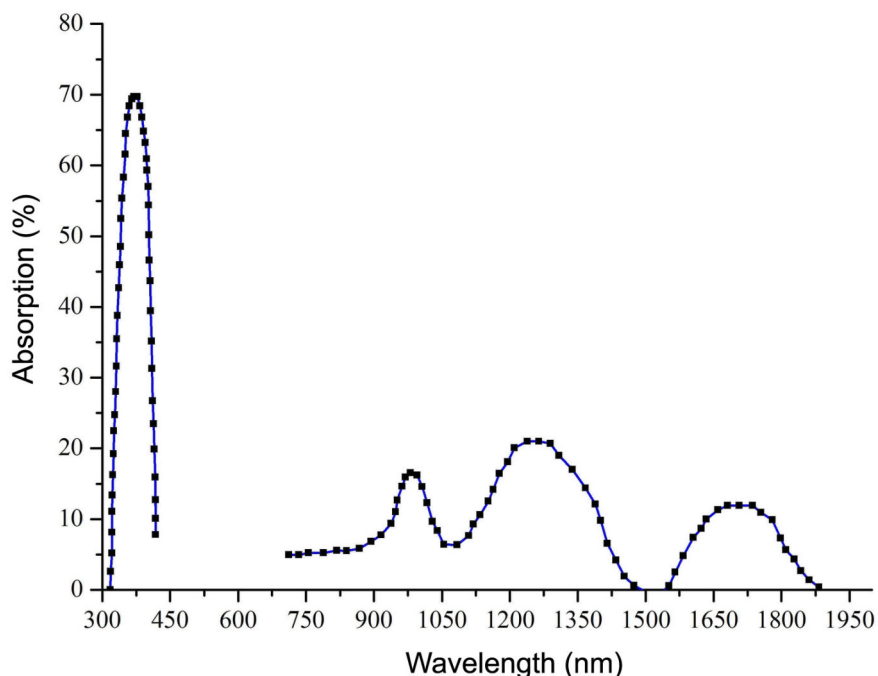
At high powers, the Iris loses its color on the impact site, and in the worst case gets paralyzed and finally necrosed.

As previously written, the Iris plays the role of a diaphragm. However, its aperture is dynamically varying and depends mainly on the radiation wavelength. For example, the diameter of the pupil exposed to UV rays is of the order of 1 mm, while it is around 7 mm if exposed to visible and near-IR radiations. In the case of still higher wavelengths, its aperture can reach 11 mm. Thus, the iris does not play its protecting role any more against visible and near-IR radiations for the deepest eye structures, bringing upon them major hazard.

iii Crystalline lens

Situated behind the pupil, the crystalline lens separates aqueous humor from vitreous humor. This optical element plays the role of a transparent biconvex lens. Using its accommodation

ability, it focuses the light rays from any object on the retina. In order to obtain a neat image on the retina of an object placed at any distance from the eye, the ciliary muscle can distort the crystalline lens and consequently modify its curvature. As any transparent medium, its absorption depends on the light wavelength. (See Fig. 5)



The crystalline lens, as any converging lens, focuses all the light rays parallels to the optical axis (presently the line of sight) on the focal point situated on the fovea (area located at the centre of the retina) – as long as the eye does not present optical defects such as myopia, astigmatism... Light rays parallels one to the other but tilted with respect to the optical axis will be focused on another point of the retina.

The wavelengths presenting the biggest hazard for the crystalline lens are near-ultraviolet and far-infrared. The damages consist either in ovoid opaque grey/white areas situated along the trajectory of the incident laser beam, or in permanent lesions where thermal effects lead to cataract.

iv Retina

The retina is a 0.5 mm thick surface situated at the back of the eye. It is the screen on which the crystalline lens focuses the light rays coming from the observed objects. One understands then quickly that retina is the sensitive part of the eye.

The retina contains the neuroreceptors responsible for the sight. It plays the role of a photographic film. It transforms the inverted image of the observed object into an analogical signal for the neurons. This transformation is done as follows : the light focused on the retina travels through the retinal layers and through the pigmented epithelium adherent to the choroid. The role of the epithelium is to protect the retinal receptors. The filtered light then activates photoreceptors, which can be either rods or cones. The latter then transmit a signal through synapses to the bipolar cells. This signal then propagates by chemical diffusion inside the bipolar cells and through synapses towards the ganglion cells, which constitute the optical nerve. All these cells thus transport the visual information from the eye to the brain. These different complex steps of sight allow us to see a detailed image of the observed object.

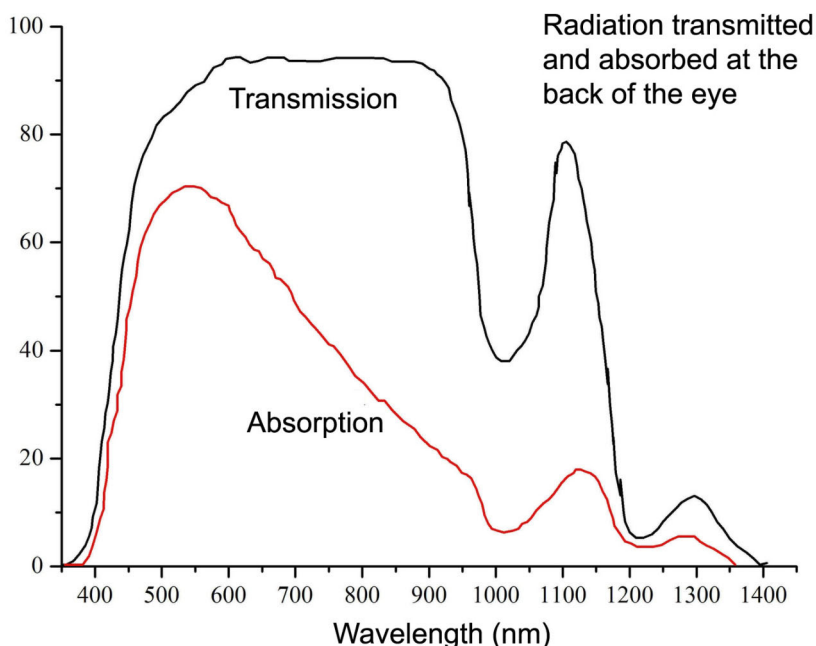


Fig. 6 presents the absorbed and transmitted wavelengths along their trajectories towards the back of the eye. One can notice that visible and infrared rays are the most transmitted wavelengths to the retina. These frequencies correspond to a maximal aperture of the pupil, which indeed partially explains this maximal transmission to the back of the eye. One then quickly understands that visible and infrared (IR-A) rays will cause maximal damages on the retina. However, the seriousness of the lesions can vary, depending on their localization and diameter on the surface of the retina.

The most commonly observed lesions are burns with coagulation and destruction of the tissues. They are mostly located on the pigmented epithelium, being very absorptive. The diagnosis is the apparition of a central unpigmented area encircled by a pigmented ring, whose diameter depends on the image size. In many cases, the epithelium then separates from the choroid.

An injury of the retina is accompanied with a physiological bedazzlement leading to a non-negligible decrease of visual perception. It can also be joint to a significant decrease of the retinal sensibility. This loss is characterized by a difficulty to adapt to obscurity and by a loss of chromatic perception.

The localization of these lesions on the retina depends on the angle between the incident ray and the line of sight (see Fig. 2). Indeed, the radiation can be focused on a spot on the macula and destroy the area. Then appears a scotoma - namely an area deprived of sight. The macula lutea (yellow spot) is mainly constituted of cones on a ~ 2 mm wide area. A small 0.2 mm diameter depression is located at its center - perfectly on the optical axis. Its name is fovea, and it contains a high density of cones. This area thus corresponds to the maximal visual acuteness used for diurnal vision.

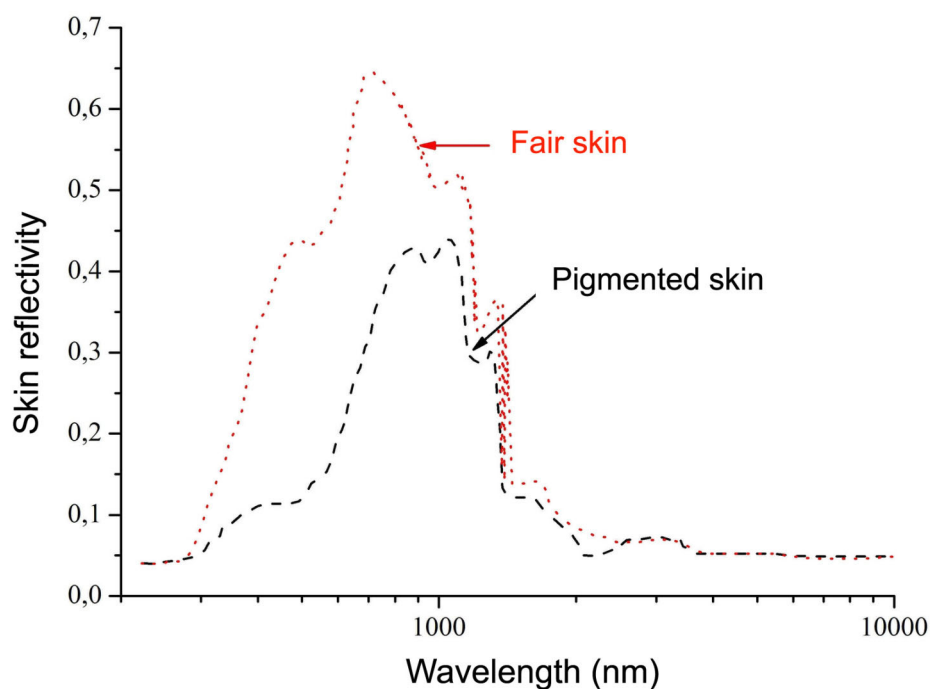
Laser rays propagating along the line of sight will be perfectly focused on the macula. If the spot is small enough, the fovea alone will be damaged. In this situation, the visual acuteness will be reduced by a factor of two. If the spot size is larger, the radiation can destroy the whole macula, leading to the loss of $\frac{3}{4}$ of the visual acuteness. Fine details won't be perceptible any more and images will become blurred.

Light rays tilted with respect to the line of sight provoke lesions on the retinal periphery, thus only altering the peripheral vision.

Remarque

The fovea does not contain blue-light-sensitive cones and is thus particularly insensitive to blue radiation.

b) Skin Hazard



As shown in Fig.7, the epidermis is made of different layers. The penetration length of a laser radiation will strongly depend on its wavelength.

The effects of laser radiation are less important on skin than on the eye. The power is generally not concentrated (in the absence of any optical element), and the pain perception is quicker.

The skin mostly undergoes thermal damages, as the epidermis cannot stand thermal powers higher than a few 0.1 W/cm^2 continuously or a few W/cm^2 during short pulses (peak power). As a reference, a clear weather sunlight exposes skin to 0.14 W/cm^2 .

Of course, the thermal effect not only depends on the beam power, but also on the skin pigmentation type. Indeed, the skin pigmentation protection efficiency depends on its coloration (see Fig. 5). For example, a 5 to 10 Joules pulse has no effect on a (reflective) white skin, while it burns a pigmented skin – this stresses the role of melanin and haemoglobin in the radiation absorption process. According to Fig. 7, visible and near infrared ($<1.4 \mu\text{m}$) are mostly reflected by the skin, while the other frequencies are mostly absorbed. The latter frequencies will thus be responsible for most of the skin injuries.

The skin constitutive layers have different resistances to radiation. The thick hyperkeratotic layers are resistant while the thinner layers in the dermis, closer to the surface, are more sensitive.

The observed lesions will then depend on the radiation frequency and are described in the following lines:

- UV rays, depending on their type (UV-A or UV-B), penetrate at different depths inside skin layers. UV-B rays are absorbed in the external layer - the epidermis - and are responsible for red blotches similar to sun burns. UV-A rays penetrate more deeply than the previous ones, and are responsible for many skin diseases. Both types are responsible for skin affections including ageing, erythema (red blotches), pigmentation increase, light-sensitization or even cancer.
- Visible and infrared radiations act on deeper layers through thermal effects. These radiation types can then induce vessels dilatation and red blotches, leading to skin burns from the surface to deeper layers.

2.3. Other laser - related hazards

a) Electric Hazard

Any laser source needs a primary energy source responsible for the population inversion on which laser (stimulated) emission relies. For most of the lasers, this source is electric. Of course, some lasers are optically pumped, either by another laser (for example, Argon laser is commonly used to pump Titanium-doped Sapphire lasers), or by other light sources (flash lamps). In any case, electric energy comes as the original source.

The mean conversion efficiency of laser sources, from electric power to optical power, is low (typically a few 10%). To illustrate this, one can look at the example of Argon laser, delivering an optical power of up to a few tens Watts continuously. The electric pumping source delivers a few hundreds Watts, and consequently presents some hazard to the laser user. Moreover, such laser sources commonly need a water-cooling system. One has thus to be extremely cautious in order to isolate the electric source from the cooling system.

b) Chemical pollution Hazard

There are different chemical hazard types:

- The first one can be directly related to the laser, and more specifically to its amplifying medium. Indeed, inside the wide spectrum of laser sources, there are very different mediums. Solid mediums lead to moderate hazard. Liquid mediums (used for example in dye lasers) are generally very toxic, and special care must be taken to prevent any contact between the medium and the skin. Finally, gaseous mediums lead to moderate hazard as the gas is confined inside a hermetically closed tube. Thus, one mainly needs to be cautious during maintenance operations.
- The second one is related to the exposition of materials to laser radiations in order to voluntarily trigger chemical transformations. These activities can create some chemical pollution. Indeed, the layers on the surface of these materials (corrosion protective layer, stain removal solvents), when exposed to high intensity optical fields, can be damaged by thermal effects and emit toxic gases.

3. Laser safety

3.1. (NF) EN 60825 standard

Europe applies the European standard (NF) EN 60825-1/A2 : "Safety of Laser Products – Part 1: Equipment classification, requirements and user's guide ". Every program applying laser safety to industry, medicine and research is based on this standard. It is referenced in France by the ministers of work, health, and by the "Caisses Primaires d'Assurance Maladie".

The EN 60825-1/A2 standard for laser safety contains informations on the classification of lasers with respect to safety, the useful safety-related calculations, hazard prevention activities, and the main advices to the persons in charge for laser safety and to the firm security-and-health-comity. These standards have been written in order to give all required informations to the users and to help the understanding of the laser safety programs.

This standard is the reference concerning the conformity of the equipments of laser-sources-production industries. Every laser source sold in Europe must be conform to this standard and be labelled CE.

3.2. Limits

To assure laser safety, we can distinguish two limitation types : the Maximum Permissible Exposure (MPE), and the Maximum Accessible Emission Level Limit (AEL). These limits were defined taking into account the main parameters characterizing laser sources : wavelength, exposure or emission duration.

a) M.P.E. : Maximum Permissible Exposure

M.P.E. is the maximal radiation level one can be exposed to before undergoing immediate or long term injuries. This maximum permissible exposure was established from the energy density limits, or the power-per-surface-unit (intensity) limits, that can be admitted on the cornea and on the skin. They were obtained by extrapolating to mankind the experimental M.P.E. measured on animals.

Thus, the M.P.E. levels were calculated as functions of the radiation wavelength, of the pulse duration, of the exposure duration of the exposed tissue (skin or eye), and of the size of the image on the retina. Table 2. summarizes a few M.P.E. limits. More details and M.P.E. values can be obtained from the (NF) EN 60825-1/A2 standard in Appendix 1 (after the exercises). In order to evaluate the M.P.E. to repeated pulses, see the exercises, section B.

LASER SOURCES	TEMPORAL MODE	EYE M.P.E.	SKIN M.P.E.
Excimers	Pulsed	30 J/m ²	30 J/m ²
He-Ne	Continuous (t=2,25 s)	25 W/m ²	3.10 ⁴ J/m ²
Nd:YAG	Pulsed (t=1ms)	0,5 J/m ²	9780 J/m ²
CO ₂	Continuous (t>10s)	1000 W/m ²	1000 W/m ²

Remarque

In any cases, whatever the operation on the source or on the beam (adjustment, maintenance...), the exposure must be maintained at its lowest possible level in order to be always far under the M.P.E. limits.

b) A.E.L. : Accessible Emission Limit , and laser classes

These limits were defined according to the EN 60825-1/A2 standard. They enable to define a laser classification according to the related hazard, depending on their characteristics. The limits were defined on the powers and energies emitted by the laser and accessible to the user – this explains the acronym A.E.L. Each laser class is labeled by a maximum accessible emission that must not be exceeded.

A.E.L. limits are based on the laser emission, while M.P.E. limits are based on the radiation received by the eye or the skin – directly from the beam or after reflection.

Because of the wide range of wavelengths, energies, pulse durations... accessible by laser technologies, they are the source of very different hazards. Due to the impossibility to treat laser sources as one unique group with common safety limits, laser sources were finally

classified according to their accessible emission limits (A.E.L.). The EN 60825-1/A2 standard defines four classes, as long as the laser sources are used in their specifications.

- **Class 1** : The sources of this class do not present hazard, due to their performances. The beam carries energies and intensities inferior to the lowest M.P.E. values. A class 1 laser becomes of a higher class when not used accordingly to the manufacturer's instructions (thus exceeding the M.P.E.)
- **Class 1M** : This class contains laser sources whose spectrum is comprised between 302.5 nm and 4000 nm. Compared to Class 1 sources, Class 1M sources may carry higher powers but still low intensities, as they are either diverging, or collimated with a large diameter – so that the energy carried through the area of a pupil is lower than class 1 limits. As any class 1 source, they are harmless in standard conditions of use, but can present a danger when the user inserts some optical elements in the beam trajectory, ether to collimate a diverging beam, or to focus a collimated source. A diverging class 1 source becomes class 1M when optical elements are inserted in the beam trajectory at less than 10 cm from the source output port.
- **Class 2** : This class contains the low power sources whose spectrum is fully in the visible range (400 nm – 700 nm), with powers up to 1 mW. These sources are harmless for the eye because of the action reflex (i.e., when the eye is hit with a bright light, the eye lid will automatically blink or the person will turn their head to escape the bright light). This reaction to visible light ensures a sufficient protection in standard conditions of use, even if the user needs optical instruments to look at the beam.
- **Class 2M** : Like class 1M laser sources, class 2M sources may carry higher powers but still low intensities, as they are either diverging, or collimated with a large diameter – so that the energy carried through the area of a pupil is lower than class 2 limits. They are dangerous if the user inserts some optical elements in the beam trajectory, ether to collimate a diverging beam, or to focus a collimated source. A diverging Class 2 source becomes Class 2M when optical elements are inserted in the beam trajectory at less than 10 cm from the source output port.
- **Class 3** : This class contains laser sources carrying medium powers. A short skin exposition does not lead to any damage. This class is divided in two subclasses :
- **Class 3R** : These sources emit powers between 1 and 5 mW in the wavelength range from 302.5 nm to 10^6 nm, where direct beam eye exposure is dangerous but still presents a risk inferior to the one related to Class 3B sources exposure. The Accessible Emission Limit is five times higher than for class 2 sources in the range 400 – 700 nm, and five times higher than for class 1 sources at any other wavelength.
- **Class 3B** : This class is made of medium power laser sources, from 5 mW to 500 mW. The direct vision of the beam of these lasers is always dangerous. On the contrary to class 3A, diffused radiations or diverging sources are dangerous if the exposure duration is higher than 10 s and if the eye is situated at less than 13 cm from the source. Continuous sources of this class emit powers of up to 500 mW, and the maximal energy per surface carried by a single pulse of a pulsed source must be inferior to 10^5 J.m⁻². Compared to 3R laser sources, the manufacturers have more obligations and more control measurements must be done by the user.
- **Class 4** : For every source of this class, not only the direct vision of the beam but also diffused radiations are dangerous for the eye. These laser provoke skin injuries and can light a fire. Their use thus requires to be very cautious. A continuous source of this class emits more than 500 mW.

Remarque

Any manufacturer's machine including a class 4 laser source must be used following class 1 specifications : this means that the M.P.E. for the eye and for the skin of the user must always be lower than defined in class 1 sources specifications. The manufacturer must define a Nominal Ocular Hazard Area (N.O.H.A.) and a Nominal Ocular Hazard Distance (N.O.H.D.) that must be respected.

Wavelength(nm)	For values expressed in powers (W) or energies (J)				For intensities (W/m ²) or energy per surface unit (J/m ²)	
	Condition 1		Condition 2		Limit diaphragm (mm)	Distance (mm)
	Diaphragm (mm)	Distance (mm)	Diaphragm (mm)	Distance (mm)		
<302,5 nm	-	-	7	14	1	0
302,5 to 400 nm	25	2000	7	14	1	100
400 to 1400 nm	50	2000	7	R	1	100
1400 to 4000 nm	25	2000	7	14	1 for < 0.35s 1.5 t ^{3/8} for 0.35s<t<10s 3.5 for t > 10s	100
4000 to 10 ⁵ nm	-	-	7	14	1 for < 0.35s 1.5 t ^{3/8} for 0.35s<t<10s 3.5 for t > 10s	0
10 ⁵ to 10 ⁶ nm	-	-	7	14	11	0

3.3. Nominal Ocular Hazard Distance and Area

a) Nominal Ocular Hazard Distance (N.O.H.D.)

This is the distance from the source at which the intensity or the energy per surface unit becomes lower than the Maximum Permissible Exposure (M.P.E.) on the cornea and on the skin. The laser beam can thus be considered as dangerous if the operator is closer from the source than the N.O.H.D.

Like the M.P.E., this distance depends on several parameters :

- the beam characteristics : output power, diameter and divergence
- the M.P.E. value on the cornea
- eventually, the optical system inserted in the beam trajectory

For example, this distance can be extremely long for class 3B and 4 laser sources (see exercises). It is thus necessary to stop the beam at the end of the optical system.

When looking at the beam with an optical system, one has to consider the possible higher intensity entering the eye, and thus to expand the evaluated N.O.H.D. (called afterwards expanded N.O.H.D.)

As long as the beam propagates freely, this distance can be evaluated according to the following expression :

$$N.O.H.D. = \frac{1}{\theta} \sqrt{\frac{4 \cdot P_0}{\pi \cdot M.P.E.} - (2 \cdot w)^2}$$

In this formula, N.O.H.D is the Nominal Ocular Hazard Distance (in meter), P_0 the power of the source (in Watts) or eventually the total energy carried by one pulse (in Joules), M.P.E the Maximum Permissible Exposure (in W/rad or J/m²) , w the waist of the Gaussian beam (m), and θ the divergence of the beam.

When using an optical system to look at the beam, one has to take into account the beam focusing induced by the system. Defining f the focal length f of the optical system and α the half-aperture angle of the beam, the expression turns to :

$$N.O.H.D. = f + \frac{1}{\tan(\alpha)} \sqrt{\frac{P_0}{\pi \cdot M.P.E.}}$$

b) Nominal Ocular Hazard Area (N.O.H.A.)

Inside this area, the intensity or the energy per surface unit is higher than the M.P.E. on the cornea. The size of this area is defined by the N.O.H.D. However, it is very difficult to define

this area as it depends on the environment (dusty or not,...) and on the objects than can be on the beam trajectory – in other words, one has to take into account the specular reflections.

3.4. Individual protection

a) Training course

A laser safety course is mandatory for any person likely to use laser sources of classes higher than 1.

Of course, the maintenance staff must have a more complete formation. Indeed, these people may not only work directly on the laser source, but also on every peripheral systems, such as the electric high voltage supplies for example. More specific training courses can be found, depending on the concerned laser system. For example, a chemical hazard course should complete the laser safety course for gas and dye lasers users.

b) Medical ability

As for most employees, the laser operator must have regular medical consultations in order to evaluate his ability to occupy his position. The doctor makes a somehow general consultation, and if required mandates the employee to a complementary consultation to a specialised doctor. The employer must then give to the doctor every information on the employee's position. When a high power laser source is to be used, the employer must ensure that the working conditions form has been established and transferred to the doctor.

The medical surveillance is mostly required for class 3A, 3B and 4 laser source users. When hired, the employee must not only have the standard medical consultation, but also do an ophthalmologic checkpoint every 2-3 years and after any accident or ocular symptom.

c) Individual protection

The subject of this paragraph is the protection of one individual by fully or partially isolating him from the laser radiation. This protection generally concerns the eyes, and sometimes the skin.

Its purpose is to attenuate any incident radiation, so that the eye exposure always stays under the M.P.E. that is defined in the standard for the considered wavelength. This protection is mandatory when it is impossible to confine by some way the laser beams and the eventual parasitic reflections (which commonly occur in laboratory experiments, and during maintenance operations). This individual protection mostly consists in safety goggles.

These goggles are subjected to the safety standards (NF) EN 207 [[Norme NF-EN 207]] and (NF) EN 208 [[Norme NF-EN 208]]. Why two different standards? Depending on the protection required by the user (ordinary safety goggles or adjustment goggles), they must obey to one of these two standards.

Ordinary safety goggles are subjected to the standard (NF) EN 207, and must have the following informations written on them :

- First, a letter specifying the laser type :
 - D for continuous sources
 - I for pulsed sources
 - R for giant pulses
 - M for mode-locked pulsed sources
- A number indicating the wavelength(s) or the spectral domain on which the goggles ensure a protecting filtering.
- A "L number" (L1 to L10), quantifying the filtering.
- The name of the manufacturer
- Eventually, the certification label
- And eventually the standard reference.

Adjustment safety goggles are subjected to the standard (NF) EN 208. They must have the following informations written on them :

- The maximal power of the source, or the maximal energy carried by the pulses
- The wavelength or the spectral domain
- A "R number" (R1 to R5), quantifying the protection
- The manufacturer
- The certification label
- The explicit notification "Adjustment goggles" on the mount (in France, it must be written in French : "lunettes de réglage")
- Eventually, one of the codes specifying the mechanical resistance as defined in the standard (NF) EN 166

3.5. Preventive displays

Preventive displays can belong to two different types :

- Integrated display or protection
- Complementary protection

a) Displays or integrated protection

The following displays are made mandatory to the manufacturers by the standard (NF) EN 60825-1/A2. They consist in warning panels placed on every laser system or source, specifying all the details concerning its maximum output power, wavelength, temporal mode (continuous or pulsed, with eventually the duration and repetition rate of the pulses).

Moreover, every laser class must be labelled as follows :

- **Class 1**

Any class 1 system must carry a warning label :

CLASS 1 LASER PRODUCT

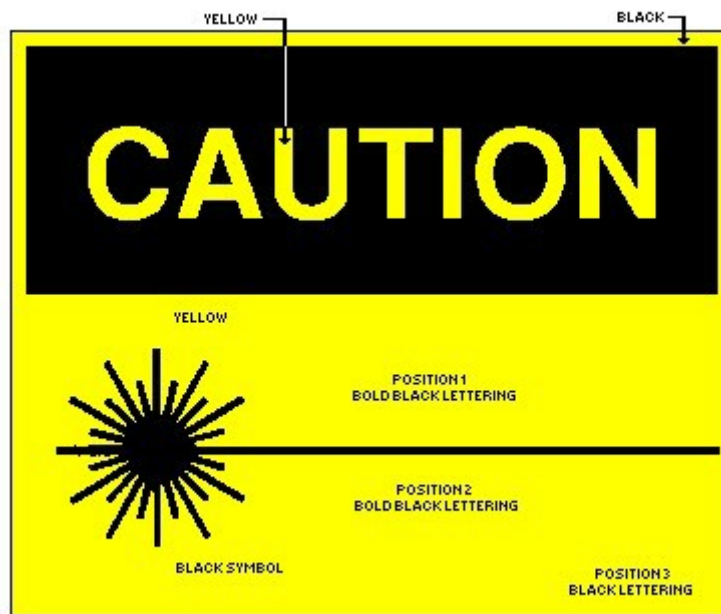
Any class 1M system must carry the following warning label :

LASER RADIATION
DO NOT VIEW DIRECTLY WITH OPTICAL INSTRUMENTS
CLASS 1M LASER PRODUCT

- **Class 2**

A warning label (as shown in fig 6a.) must be fixed on any class 2 laser, with the following text :

LASER RADIATION
DO NOT STARE INTO THE BEAM
CLASS 2 LASER PRODUCT



Any class 2M system must carry an explicative text :

LASER RADIATION
DO NOT STARE INTO BEAM
OR VIEW DIRECTLY WITH OPTICAL INSTRUMENTS
CLASS 2M LASER PRODUCT

- **Class 3R**

Any class 3R system emitting between 400 and 1400 nm must carry a warning label as in fig. 6A, and a warning panel with the following text :

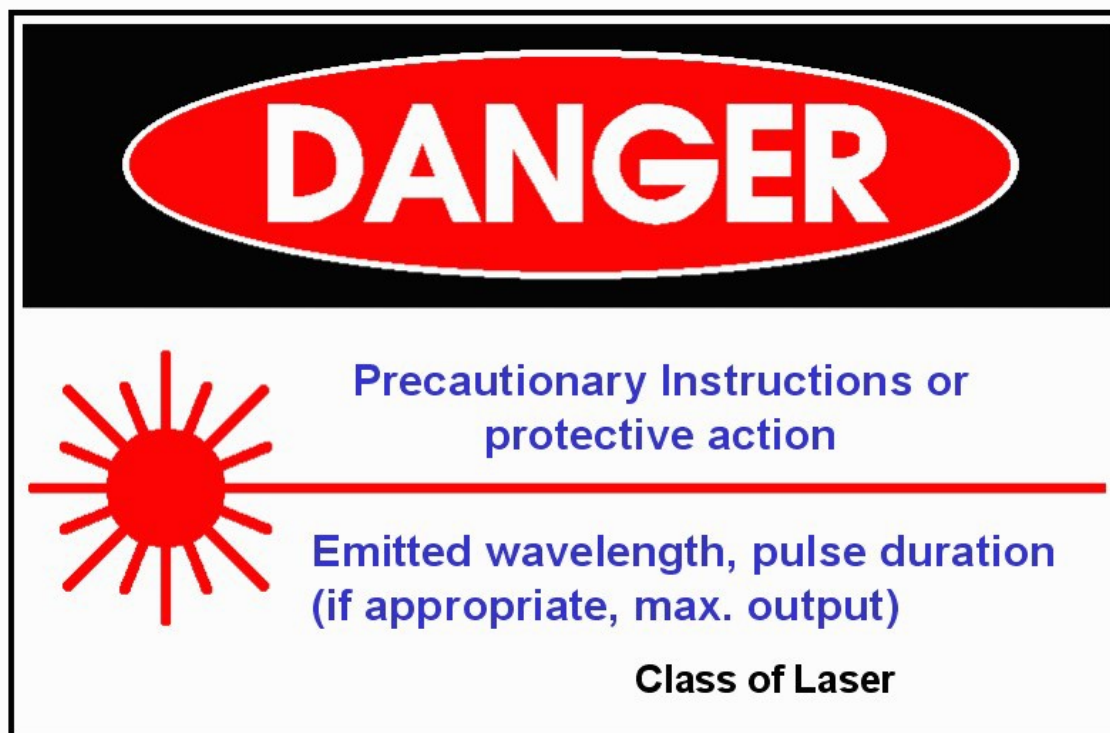
LASER RADIATION
DO NOT STARE INTO THE BEAM OR VIEW
DIRECTLY WITH OPTICAL INSTRUMENTS
CLASS 3A LASER PRODUCT

Moreover, a panel carrying the text " **Laser output**" must be placed next to the output(s) of the beam(s).

- **Class 3B**

A warning label (as shown in fig 6b.) must be fixed on any class 3B laser emitting between 400 and 1400 nm, next to a sign with the following text :

LASER RADIATION
AVOID DIRECT EYE EXPOSURE
CLASS 3B LASER PRODUCT



Moreover, a sign carrying the text "**Laser output**" must be placed next to the output(s) of the beam(s).

- **Class 4**

A warning label (as shown in fig 6b.) must be fixed on any class 4 laser, next to a sign with the following text :

LASER RADIATION
AVOID DIRECT EYE OR SKIN EXPOSURE TO
DIRECT OR SCATTERED RADIATION
CLASS 4 LASER PRODUCT

Moreover, a sign carrying the text "**Laser output**" must be placed next to the output(s) of the beam(s).

Remarque

If the radiation is not inside the spectral domain 400 – 700 nm, the display must contain the following text : "invisible laser radiation".

b) Complementary protection

In order to ensure a better protection of the users or laser operators, the firm or the laboratory can apply a supplementary protection. It consists in one of the following examples :

- Delimiting a laser area whose access can be controlled. One can use various ways to delimit the area : either by placing at its border permanent clearly visible displays and signs, presenting the different hazards, or by installing the laser system in a closed room, whose access is restricted to the competent staff.
- Writing marks on the floor, in order to prevent anyone to cut the beam's trajectory
- Installing a minimal permanent lightning (500 lux). This can prevent the pupil to get wide opened, and thus limits the radiative power entering the eye.

* *

*

As seen previously, the great efficiency and directionality of laser beams is the source of an extremely high hazard for the eye. Moreover, the wavelengths responsible for damages on the eye (cornea excepted) at the lowest intensities are in the domain 400 to 1400 nm. Indeed, if one considers that the image of a collimated beam on the retina has a width of about 10 mm, and that the diameter of a dilated pupil is of about 7mm, then a pulse carrying a few μJ or a continuous He-Ne laser beam of 1 mW are powerful enough to create permanent lesions on the retina.

In order to find the spectral domain where the damage threshold on the eye is the highest, and therefore the hazard the lowest, one has to find a compromise between the absorption spectra of the different parts of the eye.

Thus, concerning a laser emitting between 1.5 and 1.55 μm , the absorption is negligible in the crystalline lens, 75% occurs inside the cornea, and 25% inside the aqueous humor. We see that most of the energy is absorbed inside the cornea. The absorption is distributed along the relatively high thickness of this optical element, and thus the energy absorbed per volume unit is too weak to provoke important damages. The cornea is as resistant to radiations as the skin. Moreover, it has a very high regeneration ability. But outside of the previously defined wavelength range, the eye faces high hazard levels...

Laser sources emitting in the so-called "ocular safety domain" (1.5 to 1.55 μm) can freely propagate without inducing laser hazard. These are so-called "**ocular safety laser sources**". This spectral domain presents many other advantages : it is commonly used for telecommunications through optical fibers, because it corresponds to the minimum of the absorption spectrum of the silica, and is situated in a spectral domain transmitted by the atmosphere.

III. Case Study

The common point between all the laser accidents presented in the following pages is their location in research laboratories. Why uniquely in laboratories? Because these are the places where the beams are the most often directly worked on (laser development research). In Laser technology development, the M.P.E. can indeed often exceed the authorized M.P.E. When looking at Fig. 1, one can notice that the populations mostly exposed to laser accidents are scientists and laser-specialized technicians, who, unlike the other categories, develop and optimize laser systems instead of simply using them. According to the standard (NF) EN 60825, people using laser systems as tools must only use class 1 systems. Then, these users are mostly exposed to radiation levels inferior to the M.P.E.

1. First Case

In a French laboratory, a researcher was exposed to the diffused radiation from a class 4 laser source.

The research institute had nevertheless taken some precautions in order to prevent laser accidents. Indeed, the source was situated in a closed room, whose access was restricted to a few trained persons. The accident occurred in a neighbouring room. The beam was sent from one room to the other through a small hole through the wall. By this mean, the same source could be used simultaneously for several experiments (presently, two other rooms were connected). However, these holes were not protected by protective caps allowing to shut the beam off when the experiments were not in use. So, the room was never freed from laser hazard.

In the present case, a researcher was retrieving experimental data in one of the rooms, without intending to work on the experimental setup. However, he never thought that somebody may be working in the other room, and that the laser may thus be working. He wasn't wearing his safety goggles, although they were correctly placed at the entry of the laboratory.

The laser beam sent to his room was regrettably being reflected by a mirror towards a plastic poster. When the researcher came near this poster, he observed two circular spots on it. The first one was due to the laser beam itself, which he thus didn't look at for long, while he was intrigued by the second one, from unknown source, and then observed it a longer time. After having observed this white spot more than ten seconds, he got bedazzled. Four hours later, a bright spot had appeared in his left eye sight.

We need to remember the following points concerning this accident :

- The research institute had isolated the source in order to prevent that kind of accidents. Still, a protective cap should have been placed on each hole, allowing one to close it when the beam was not in use.
- A **light signal** should have been placed at the entry of the room, allowing one to be immediately aware of the presence of laser radiation in the room. If this had been done, the researcher would have been wearing the protective goggles adapted to the wavelength and power of the laser beam.
- The present accident could have happened even if the researcher were aware of the presence of a laser beam in the room he was entering. Indeed, the highly diffusing poster shouldn't have been placed at the same level as the laser beam, but should have been isolated from it.
- The laser power should be tunable, so that the operator doesn't bring hazard upon himself when not necessary.

2. Second case

While adjusting an experiment involving a class 4 Titanium-doped Sapphire laser oscillator, a PhD student got briefly exposed to the beam.

In order to facilitate the alignment procedure by directly observing the beam with the naked eye – instead of a more complicated procedure implying a camera or an infrared sensor, the student worked in continuous mode at full power (700 mW), in the dark, without safety goggles.

As he had to elevate the beam to the same height as the rest of the experiment, he first adjusted a periscope with the two mirrors as close as possible, and tightly fixed the bottom mirror – sending the beam to the ceiling. On the contrary, as he knew he would still have to move the upper mirror, he didn't tightly fix it. During the adjustment procedure, the student bent over the desk, thus placing his eye precisely over the periscope. His hand accidentally ran into it, the upper mirror moved away from the beam, which briefly entered the student's eye. The retina was damaged, nervous cells of the macula were burnt. This led to a permanent and irreversible trouble of his sight angle without loss of visual acuteness.

This accident could have been avoided if the following precautions had been applied:

- The student should have been wearing his safety goggles adapted to the pulsed laser, which were placed next to him.
- While working with a laser, the **ambient light** must always be over a certain level, in order to prevent the pupil from getting wide opened.
- Always work at **minimum power** when adjusting an optical system.
- In order to trace the trajectory of the beam, always use a camera or a visualization card which transforms the invisible beam into a visible spot.
- Always tightly fix the optical elements, even if their positions must be optimized later.

3. Third case

This is an example of a very unlucky person. During some experiments involving a femtosecond pulsed laser, the researcher was measuring the beam width using a camera specially designed for this kind of measurements. The detection head was placed on a stand in order to be at the center of the beam, but was badly fixed. He acquired his measurements, and then wanted to copy the results on his lab book, placed on a desk next to the experiment. A computer was situated on this desk. The experimentalist sat down on a chair, turning his back to the experiment, aware that the beam was behind him. While he was writing on the book, the detection head ripped and the beam was now aimed at the computer. The beam then got reflected on the computer screen situated at the same height. The experimentalist then straightened up and his eye got briefly exposed to the reflected beam. He was instantly bedazzled. Hopefully, due to the blink reflex of his eye, he didn't experience permanent lesions. He only experienced headache during a few days related to the bedazzlement.

This accident, which finally ends pretty well, could have been easily avoided simply by correctly fixing the detection head. Then, the the beam would have been stopped all along the data acquisition and copying. But this protection was still not sufficient. The laser should have been isolated from the desk by an opaque partition – at least opaque to the laser wavelength. Such a partition permits to isolate the experiment part of the room from the “paper work” part. Nonetheless, if the screen had been placed at higher than the beam, the reflection would never have occurred.

4. Fourth Case

In a British university, a student was aligning two pulsed lasers with different wavelengths for his experiment. The first one was a dye laser emitting at 720 nm, delivering 10 ns pulses carrying 10 mJ with a repetition rate of 10Hz. The second one was a pulsed Nd:YAG laser emitting at 266 nm, delivering pulses of same duration and at the same repetition rate but carrying 50 mJ. In this experiment, the beam emitted by the first laser was passing through a dichroic mirror, fully reflecting at 266 nm and highly transparent at any other wavelength. Unfortunately, the back side of the mirror was reflecting about 5% of the 720-nm-beam towards the ceiling. As he couldn't see the beam at 266 nm, the student briefly worked without safety goggles – and then the accident occurred. As he had totally forgotten the presence of the parasitic beam at 720 nm, he bent over the mirror and received a laser pulse from this reflection. He immediately noticed a blind spot in the central sight of his eye while looking at some object in the laboratory. Still, as any operator aware of the laser hazard, he was most of the time wearing safety goggles at 266 nm...

He was immediately sent to the hospital in order to make ophthalmologic exams. The doctor then noticed a small burn on the fovea. The student was aware of the presence of the beam and had placed some obstacles along its trajectory during the previous experiments. However, every obstacle had been removed for this new experiment.

One must emphasize the following characteristics of this accident :

The safety goggles must never be removed. In the present case, although there were two different wavelengths, the operator should have been wearing his safety goggles : even if they were specified for one precise wavelength, they would nevertheless have protected the eye against other wavelengths – with a lower efficiency, but still. For any new experiment, the operator must evaluate the new hazard sources he will be exposed to.

Consequently to a laser accident, the eye injuries are often irreversible, except in some precise situations : it is thus very important to be subjected to **medical exams** as soon as possible, **within the next 24 hours**. One can also use a class 1 laser during the adjustment, harmless to the eye.

5. Fifth case

In a United States laboratory, an undergrad French student was beginning his internship on a Titanium:Sapphire laser emitting around 800 nm. The student had never been sent to a laser safety course, nor had he been told about laser hazard. His advisor had only told him he must wear safety goggles, without specifying how to choose them or even telling him the meaning of the informations written on the goggles.

Thus, during an experiment, the student, as any good student, took the first goggles he found : they were orange colored. Having not been to any laser safety course, he thought he was protected against every laser radiation, while his safety goggles were in fact only specified for 532 nm radiation.

Then, while aligning the beam of his experiment, the student bent over the desk to look at the beam and placed his eye in the propagation axis of the beam. All along the adjustment, he observed some blue light in his eye due to the non-linear interaction between the 800 nm radiation and the eye. He did not get alerted by this and continued his adjustment likewise.

After his work and while taking the bus to come home, he noticed that he couldn't read the display panel of the bus station any more. The day after, he immediately made a report to his laboratory, which sent him in emergency to do some ophthalmologic exams. It revealed that the crystalline lens was partially burned, and that a dark spot had appeared on the fovea – characteristic of the nervous cells destruction.

The student should have been to laser safety courses before he worked on lasers, in order to be aware of their hazard. This formation would have prevented him from making two mistakes.

First, he wouldn't have taken the first safety goggles passing by : he would have chosen goggles precisely specified for the near-infrared radiation of the Ti:Sapph laser and for pulsed emission. The second and biggest mistake was to place his eye in the beam propagation axis. If he had been to a laser safety training course, he would instead have used a visualization card or a camera, transforming the invisible radiation into a visible signal. But the worst mistake was made by the advisor, who should have immediately sent the non-specialist trainee to a laser safety training course – thus preventing the following accident from happening.

6. Sixth Case

In a French laboratory, a PhD student was making adjustments on an experiment, in which a beam was briefly directed perpendicularly to the desk by a 45° mirror. During the experiment, the operator had to adjust the beam to be perfectly vertical towards the ceiling, and then to propagate through a vacuum chamber. For this alignment, he closed the shutter at the output port of the laser in order to work perfectly safely. As he believed himself not subjected to any hazard, he took off his goggles and placed his eye right on the vertical of the vacuum chamber, in the trajectory of the beam. Due to a technical problem, the beam shutter briefly opened and sent one laser pulse, which propagated straight to the eye of the operator. Consequently, his macula was destroyed. After the accident, he went to ophthalmologic exams. The result was that he had lost about 30% of his visual acuteness, and that a blind area was situated at the center of his sight. These were irreversible injuries. However and with the help of time, the brain is able to correct this blind area.

Although this accident was due to a technical problem and not to a mistake by the student, it illustrates the fact that one must always be cautious, even if one believes oneself not exposed to any hazard. The student shouldn't have taken his safety goggles off, even in the absence of the beam.

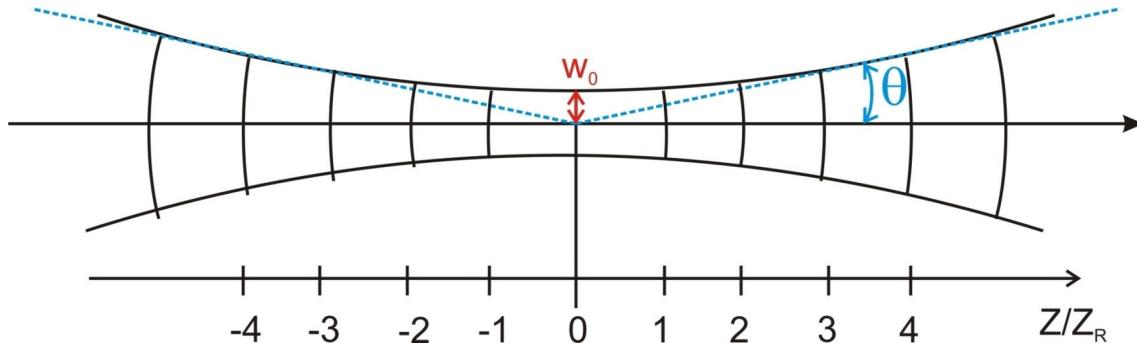
7. The perfect laser operator's guide

While working on laser of higher class than class 1, it is mandatory to :

- Have the perfect control over the beam, from the source to the detector :
 - Every fully or partially reflecting object must be tightly fixed
 - One must perfectly know his experiment and the exact trajectory of the beam. This knowledge allows one to find the accidental reflections and to stop them (using absorbing, non-reflecting shutters)
 - In order to stop the beam, one must minimize the diffused radiation consequent to, for example, the interception of a high power laser by some cardboard. It is much better to use an adapted tool, such as a beam dump or some diffusive foam inside an opaque tube.
- Take all the available precautions :
 - Make the adjustments at low power
 - Never place one's eyes in the laser propagation axis
 - Always work without wearing any reflecting object like a watch, bracelet, ring...
 - Always work with some minimal ambient lightning, in order to prevent the pupil from being wide opened
 - And of course, always wear adapted safety goggles

IV. Exercises

1. Basics on the Gaussian beams



The radiation emitted by a laser source can be considered as Gaussian. Why should we consider Gaussian waves instead of spherical or plane waves? This is because the considered waves exhibit non-negligible diffraction phenomena due to their finite extension transversally to their propagation axis.

A Gaussian wave, just like a spherical or plane wave, is a solution of the wave equation. The electric field has the following expression :

$$E(r, z) = A(z) \cdot \exp\left(-i \frac{k r^2}{2 R(z)}\right) \cdot \exp\left(\frac{-r^2}{2 w^2(z)}\right)$$

where $\mathbf{A}(\mathbf{z})$ is the complex amplitude of the field along the propagation axis \mathbf{z} . In this expression, the variations of the field \mathbf{E} with respect to the radial coordinate \mathbf{r} are expressed through the exponential terms.

- The $\exp\left(\frac{-r^2}{2 w^2(z)}\right)$ term contains the Gaussian character of the beam : at a distance \mathbf{z} from the focus, the field amplitude decays transversally by a factor $1/e^2$ at the distance $\mathbf{r} = \mathbf{w}(\mathbf{z})$ from the optical axis. The radius, or waist, $\mathbf{w}(\mathbf{z})$ thus depicts the beam radial extension.
- Similarly to the paraxial spherical wave, the Gaussian beam is characterized by the curvature radius $\mathbf{R}(\mathbf{z})$ of its wave fronts.

On the Fig. 8, at $\mathbf{z} = \mathbf{0}$, one can define the waist at the focus \mathbf{w}_0 , which is the minimal value of the radius $\mathbf{w}(\mathbf{z})$ along the propagation axis. From this primordial parameter, one can express the following characteristic quantities :

$$R(z) = z \cdot \left(1 + \left(\frac{\pi w_0^2}{\lambda z} \right)^2 \right)$$

$$w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2}$$

$$z_R = \frac{\pi w_0^2}{\lambda}$$

The Rayleigh length z_R depicts the characteristic divergence length of the beam. Indeed, the smaller this value, the more divergent the beam. This divergence, as can be seen on Fig. 8, can also be measured using the asymptotic evolution of the radius $w(z)$:

When $z \gg z_R$, $w(z)$ tends to :

$$w(z) \simeq \frac{w_0 \cdot z}{z_R}$$

and the associated angle can be written as follows :

$$\theta \simeq \tan \theta = \frac{w_0}{z_R} = \frac{\lambda}{\pi w_0}$$

2. Section A : M.P.E. evaluation in the case of a unique laser pulse

Answer the three following questions :

Question 1

[Solution n°1 p 34]

Exercise 1.1 : The source is a Helium-Cadmium laser emitting a beam whose central wavelength is 325 nm . The pulse duration is 0.1 s . From the table in Appendix 1, what is the M.P.E. for the eye ?

Question 2

[Solution n°2 p 34]

Exercise 1.2 : The source is a Rubis laser emitting at 694 nm . Knowing that the exposure duration is 1 ms , what are the M.P.E. for the eye and for the skin ?

Question 3

[Solution n°3 p 34]

Exercise 1.2 : The source emits pulses of 100 ns , and its central wavelength is 905 nm . What is the M.P.E. for the eye ?

3. Section B : M.P.E. evaluation in the case or repeated laser pulses

Basics : It is much more difficult to evaluate the M.P.E. for a pulsed laser, because of the limited amount of existing data on the exposure to multiple pulses. One must thus be cautious when evaluating the exposure to repeated pulses. In order to determine the M.P.E. for repeated pulses, the method is the following :

The M.P.E. for wavelengths in the range 400 to 1400 nm must be determined using the most restrictive of the following instructions, depending on the specific case :

- the exposure to one isolated pulse of the pulse train mustn't exceed the M.P.E.

- the mean intensity for a pulse train of duration T mustn't exceed the M.P.E. defined in the tables for one isolated pulse of duration T.
- the exposure to one pulse from the pulse train mustn't exceed the M.P.E. specified for an isolated pulse, multiplied by the total number of pulses during the exposure duration to the power of $-1/4$:

$$EMP_{\text{train}} = EMP_{\text{isolated}} \cdot N^{-1/4} \quad \text{per pulse}$$

At any wavelength outside this range, the M.P.E. for skin and eyes must be determined using the most restrictive instructions.

Question

[Solution n°4 p 34]

Using both your own knowledge and the table given in appendix 3 (at the end of the exercises), what is the M.P.E. for an eye submitted to laser radiation at 488 nm from an Argon laser, emitting pulses of 10 ns at a repetition rate of 1 MHz ? The evaluation of this M.P.E. can be done using two different approaches. One will be less restricting, and the other one, more rigorous, will give the exact M.P.E. value.

4. Section C : Nominal Ocular Hazard Distance (N.O.H.D.)

Basics : The N.O.H.D. is the distance from the source at which the intensities and energies fall under the appropriate M.P.E.

The axial intensity (in W/m²) at a distance **z** from a laser source is given by the following formula :

$$I = \frac{4 P_0 \cdot \exp(-z\mu)}{\pi (2w + z\theta)^2}$$

This formula assumes a Gaussian beam with a power **P₀**, an $1/e^2$ intensity radius **w**(in m) at its waist, a divergence **θ** (in rad), and an absorption rate **μ** due to the atmosphere – commonly neglected. This is a general formula , where **z** depicts the distance from the source to the operator.

In order to evaluate the N.O.H.D., one replaces in the formula above z by the N.O.H.D. and **I** by the M.P.E.

Then, when neglecting the absorption by the atmosphere, one obtains the following expression :

$$NOHD = \frac{\sqrt{\frac{4 P_0}{\pi \cdot MPE}} - 2 \cdot w}{\theta}$$

This formula is valid if and only if the beam propagates freely. If any optical instrument is used in order to observe the laser radiation, then one must consider a higher N.O.H.D. in order to take into account the higher energy density, as the radiation may be collimated or concentrated by the optical instrument.

The increase of intensity due to the optical instrument can be evaluated according to the following parameter K :

$$K = \frac{\text{Entrance diameter of the instrument}}{\text{Pupil diameter of the eye}}$$

where the pupil diameter of the eye is of order 7 mm .

Question 1

[Solution n°5 p 35]

Exercise 3.1 : The considered laser source emits continuously at the central wavelength 400 nm . Its mean optical power is 4 W , the divergence of the beam is 0.7 mrad , and the beam diameter at the output port of the source is 1 mm .

1. The exposure duration is 2 hours. What is the appropriated M.P.E. ?
2. The beam propagates freely through the air. What is the N.O.H.D. of this source? The atmospheric absorption can be neglected.

Question 2

[Solution n°6 p 35]

Exercise 3.2 : In order to reduce the divergence of the beam, an afocal lens pair is placed in the beam, increasing its diameter and collimating it. After this optical system, the beam divergence is reduced down to 0.1 mrad , while the beam diameter is 7 mm . What is the new N.O.H.D. ?

Question 3

[Solution n°7 p 35]

Exercise 3.3 : A topography laser (He-Ne medium, emitting at 632 nm) emits a continuous radiation with a mean optical power of 3 mW . The beam leaves the cavity with a diameter of 13 mm and diverges along its free space propagation. Fifty meters away from the source, the beam diameter is 18 mm .

1. 65 meters away from the source, how long can one directly look at the beam without risking eye injuries?
2. For an exposure duration of 3 min , what is the minimum distance at which one can safely look at the beam ?

Question 4

[Solution n°8 p 36]

Exercise 3.4 : A telemetry laser using a Neodymium doped gain medium emits laser pulses at 1060 nm . Its peak optical power is 1.5 MW and each pulse carries 45 mJ . The repetition rate is 12 pulses per minute. The beam diameter is 10 mm at the output port of the source, and its divergence is 1 mrad .

1. What is the N.O.H.D for the naked eye exposed to this radiation ?
2. What is the N.O.H.D for the eye looking through a 60 mm diameter telescope ?

5. Section D : How to choose safety goggles ?

Question 1

[Solution n°9 p 37]

Exercise 4.1 : A student wants to use a Titanium : Sapphire laser emitting in the near infrared domain at 800 nm . This source emits pulses of 30 fs with a repetition rate of 10 Hz . Each pulse carries 2 J and the beam diameter is 5.5 mm . We assume that the divergence of the beam can be neglected. Which labels must be written on the safety goggles adapted to this source? (Use the table in appendix 4 – at the end of the exercises)

Question 2

[Solution n°10 p 37]

Exercise 4.2 : The considered source emits 10 W of continuous radiation at 647 nm. The beam diameter is 1.6 mm. Which labels must be written on the safety goggles adapted to this source?

6. Appendices

Exposure duration t (s)	< 10 ⁻⁹	10 ⁻⁹ to 10 ⁻⁷	10 ⁻⁷ to 10 ⁻⁶	10 ⁻⁶ to 1,8.10 ⁻⁵	1,8.10 ⁻⁵ to 5.10 ⁻⁵	5.10 ⁻⁵ to 10	10 to 10 ³	10 ³ to 10 ⁴	10 ⁴ to 3.10 ⁴
Wavelength (nm)									
From 180 to 302.5	$30 J.m^{-2}$								
From 302.5 to 315	$3.10^{10} W.m^{-2}$	$C1 J.m^{-2}$ if $t < T1$			$C2 J.m^{-2}$ if $t > T1$		$C2 J.m^{-2}$		
From 315 to 400		$C1 J.m^{-2}$				$10^4 J.m^{-2}$		$10 W.m^{-2}$	
From 500 to 550	$10^{11} W.m^{-2}.sr^{-1}$	$5.10^{-3} J.m^{-2}$			$18 t^{0.75} J.m^{-2}$		$100 J.m^{-2}$		$10^{-2} W.m^{-2}$
From 550 to 700							$18 t^{0.75} J.m^{-2}$ if $t < T2$		$C3.10^2 J.m^{-2}$ if $t > T2$
From 700 to 1050	$10^{11}.C4 W.m^{-2}.sr^{-1}$	$5.C4.10^{-3} J.m^{-2}$			$18 t^{0.75}.C4 J.m^{-2}$			$3,2.C4 W.m^{-2}$	
From 1050 to 1400	$5.10^{11} W.m^{-2}.sr^{-1}$	$5.10^{-2} J.m^{-2}$				$90.t^{0.75} J.m^{-2}$		$16.W.m^{-2}$	
From 1400 to 1530	$10^{11} W.m^{-2}$	$\frac{100 J.m^{-2}}{2}$	$5600.t^{0.25} J.m^{-2}$				$1000 W.m^{-2}$		
From 1530 to 1550		$1.10^4 J.m^{-2}$		$5600.t^{0.25} J.m^{-2}$					
From 1550 to 10 ⁶		$\frac{100 J.m^{-2}}{2}$	$5600.t^{0.25} J.m^{-2}$						
	$C1=5,6.10^3.t^{0.25}$	$C2=10^{0.2(\lambda-295)}$	$C3=10^{0.015.(\lambda-550)}$	$C4=10^{(\lambda-700)/500}$		$T2=10.10^{0.02.(\lambda-550)} s$		$T1=10^{0.8.(\lambda-295)}.10^{-15} s$	

Exposure duration t (s)	< 10 ⁻⁹	10 ⁻⁹ to 10 ⁻⁷	10 ⁻⁷ to 10	10 to 10 ³	10 ³ to 3.10 ⁴
Wavelength (nm)					
From 180 to 302.5	$30 J.m^{-2}$				
From 302.5 to 315	$3.10^{10} W.m^{-2}$	$C1 J.m^{-2}$ if $t < T1$		$C2 J.m^{-2}$	
From 315 to 400		$C1 J.m^{-2}$		$10^4 J.m^{-2}$	$10 W.m^{-2}$
From 400 to 1400	$2.10^{11} W.m^{-2}$	$200 J.m^{-2}$	$1,1.10^4 t^{0.25} J.m^{-2}$	$2000 W.m^{-2}$	
From 1400 to 10 ⁶	$10^{11} W.m^{-2}$	$100 J.m^{-2}$	$5600 t^{0.25} J.m^{-2}$	$1000 W.m^{-2}$	
	$C1=5,6.10^3.t^{0.25}$	$T1=10^{0.8.(\lambda-295)}.10^{-15} s$		$T2=10.10^{0.02.(\lambda-550)} s$	
	$C2=10^{0.2(\lambda-295)}$	$T2=10.10^{0.02.(\lambda-550)} s$			
	$C3=10^{0.015.(\lambda-550)}$				
	$C4=10^{(\lambda-700)/500}$				

Test conditions for the different laser types	Laser type	Exposure duration	Pulse number
D	Continuous	> 0.25 s	1
I	Long pulse	10 ⁻⁵ to 0.25 s	100
R	Q-switched	10 ⁻⁹ to 10 ⁻⁶	100
M	Mode locked	< 10 ⁻⁹	100

Scale number	Maximum spectral transmittance for laser wavelength $\tau(\lambda)$	Maximum power (E) and energy (H) density in the wavelength range								
		180 nm → 315 nm			> 315 nm → 1400 nm			> 1400 nm → 1000 μm		
		For test condition / pulse duration in s								
		D > 3·10 ⁴ E _D W/m ²	I,R 10 ⁻⁹ bis 3·10 ⁴ H _{I,R} J/m ²	M < 10 ⁻⁹ E _M W/m ²	D > 5·10 ⁻⁴ E _D W/m ²	I,R 10 ⁻⁹ bis 5·10 ⁻⁴ H _{I,R} J/m ²	M < 10 ⁻⁹ H _M J/m ²	D > 0,1 E _D W/m ²	I,R 10 ⁻⁹ bis 0,1 H _{I,R} J/m ²	M < 10 ⁻⁹ E _M W/m ²
L1	10 ⁻¹	0,01	3·10 ²	3·10 ¹¹	10 ²	0,05	1,5·10 ⁻³	10 ⁴	10 ³	10 ¹²
L2	10 ⁻²	0,1	3·10 ³	3·10 ¹²	10 ³	0,5	1,5·10 ⁻²	10 ⁵	10 ⁴	10 ¹³
L3	10 ⁻³	1	3·10 ⁴	3·10 ¹³	10 ⁴	5	0,15	10 ⁶	10 ⁵	10 ¹⁴
L4	10 ⁻⁴	10	3·10 ⁵	3·10 ¹⁴	10 ⁵	50	1,5	10 ⁷	10 ⁶	10 ¹⁵
L5	10 ⁻⁵	100	3·10 ⁶	3·10 ¹⁵	10 ⁶	5·10 ²	15	10 ⁸	10 ⁷	10 ¹⁶
L6	10 ⁻⁶	10 ³	3·10 ⁷	3·10 ¹⁶	10 ⁷	5·10 ³	1,5·10 ²	10 ⁹	10 ⁸	10 ¹⁷
L7	10 ⁻⁷	10 ⁴	3·10 ⁸	3·10 ¹⁷	10 ⁸	5·10 ⁴	1,5·10 ³	10 ¹⁰	10 ⁹	10 ¹⁸
L8	10 ⁻⁸	10 ⁵	3·10 ⁹	3·10 ¹⁸	10 ⁹	5·10 ⁵	1,5·10 ⁴	10 ¹¹	10 ¹⁰	10 ¹⁹
L9	10 ⁻⁹	10 ⁶	3·10 ¹⁰	3·10 ¹⁹	10 ¹⁰	5·10 ⁶	1,5·10 ⁵	10 ¹²	10 ¹¹	10 ²⁰
L10	10 ⁻¹⁰	10 ⁷	3·10 ¹¹	3·10 ²⁰	10 ¹¹	5·10 ⁷	1,5·10 ⁶	10 ¹³	10 ¹²	10 ²¹

Solution des exercices

>Solution n°1 (exercice p. 29)

According to the table given in Appendix 1 (at the end of the exercises), the solution is "C1" J/m^2 . According to the expression of C1, the M.P.E. is $3.15 J/m^2$.

>Solution n°2 (exercice p. 29)

According to the table given in Appendix 1 (at the end of the exercises), the M.P.E. for the eye is $0.1 J.m^2$.

According to the table given in Appendix 2 (at the end of the exercises), the M.P.E. for the skin is $1956 J.m^2$.

>Solution n°3 (exercice p. 29)

The M.P.E. for this situation is $12.5 \times 10^{-3} J/m^2$.

>Solution n°4 (exercice p. 30)

First approach

As the laser source emits in the visible spectral domain, the exposure duration is limited by the blink reflex of the eye lid, thus approximately to $0.25 s$. Thanks to this reflex, a limited amount of pulses enters the eye. Indeed, the laser emits a new pulse every $1/(1MHz) = 1 s$; the total amount N of pulses penetrating the eye is thus 2.5×10^5 .

One now has to take into account the corrective factor for repeated pulses : $N^{-1/4} = 0,0447$. In order to evaluate the M.P.E. for the pulse train, one first needs to know the M.P.E. for one isolated pulse, given in Appendix 1 :

$$M.P.E._{Isolated} = 5.10^{-3} J/m^2$$

Using this value and the corrective factor, the final answer is :

$$M.P.E._{train} = M.P.E._{Isolated} \times N^{-1/4} = 2.24 \cdot 10^{-4} J/m^2 \text{ per pulse}$$

This calculation enables us to have a quick outlook at the reduced M.P.E. for the eye. But this calculation is not rigorous and gives a not very restrictive value.

Second approach :

A more rigorous way to proceed is to work on a long isolated pulse. For an exposure duration of $t = 0.25 s$, the M.P.E. for the eye is $18 \cdot t^{0.75} J/m^2$. The calculated value of this M.P.E. is $6.36 J/m^2$ for one long isolated pulse.

The mean intensity related to this M.P.E. is given when dividing the given energy per surface unit by the exposure duration :

$$I_{mean} = 6,36/0,25 = 25,5 W/m^2$$

One can now evaluate the peak intensity during the pulses associated to this mean intensity, using their duration $\Delta\tau$ and the repetition rate f_R :

$$I_{\text{pulse}} = I_{\text{mean}} / (\Delta\tau f_R) = 25,5 / (10^{-9} \cdot 10^6) = 2,55 \cdot 10^3 \text{ W/m}^2$$

And finally the M.P.E. is :

$$\text{M.P.E.} = I \cdot \Delta\tau = 2,55 \cdot 10^{-5} \text{ J/m}^2$$

Thus, the value of the M.P.E. for the eye given by the rigorous method based on the intensities ($M.P.E_{\text{train}} = 2,55 \times 10^{-5} \text{ J/m}^2$ per pulse) is much more restrictive than the first method ($M.P.E_{\text{train}} = 2,24 \times 10^{-4} \text{ J/m}^2$ per pulse)

>Solution n°5 (exercice p. 31)

1. According to Appendix 1, the M.P.E. is 10 W/m^2 .
2. One must simply apply the formula :

$$N.O.H.D = \frac{\sqrt{\frac{(4 \cdot 4)}{\pi \cdot 10}} - 0,001}{0,0007} = 1,02 \text{ km}$$

The operator should thus work approximately 1 km away from the source to be perfectly safe.

>Solution n°6 (exercice p. 31)

In this precise situation, one must notice that the optical system is not used to look at the optical beam : it thus doesn't concentrate more light into the eye. Then, one can use the same formula as previously :

$$N.O.H.D = \frac{\sqrt{\frac{(4 \cdot 4)}{\pi \cdot 10}} - 0,007}{0,0001} = 7,07 \text{ km}$$

We thus figure out the enormous importance of the beam divergence, as in this example the reduction of the divergence from $0,7 \text{ mrad}$ to $0,1 \text{ mrad}$ leads to an increase of the distance by a factor of 7.

>Solution n°7 (exercice p. 31)

1)

The first thing to do is to evaluate the beam divergence :

$$\theta = \frac{0,018 - 0,013}{50} = 0,1 \text{ mrad}$$

The He-Ne is a continuous laser. Consequently, the M.P.E. given in Appendix 1 is equal to : $M.P.E. = 18 \cdot t^{0,75} \text{ J/m}^2$.

One can use instead the formula giving the intensity as a function of distance and divergence to deduce the permissible exposure duration.

$$M.P.E. = \frac{4P_0}{\pi(2w+z\theta)^2} \quad \text{in } W/m^2$$

We need to convert these two expressions in the same unit : W/m^2 . We must thus divide the first expression by the pulse duration t .

$$18 \cdot t^{-0.25} = \frac{4 \cdot 0.003}{\pi \cdot (0.013 + 65 \cdot 0.0001)^2}$$

The equation is thus : leading to an exposure duration $t = 10$ s. The operator situated 65 meters away from the source is perfectly safe as long as he doesn't look at the beam longer than 10 s.

2)

If the operator needs to look at the beam during 180 s, one can use the same formula to determine the distance z .

After inverting the previously used formula, one obtains :

$$z = \frac{1}{\theta} \cdot \left(\sqrt{\frac{4 \cdot P_0}{\pi \cdot M.P.E.}} - 2 \cdot w \right)$$

Finally, $z = 149$ m.

>Solution n°8 (exercice p. 31)

1)

The duration of each pulse can be deduced from the power during a pulse and the energy per pulse. Thus, using $E = P_0 \cdot \Delta t$, the pulse duration is evaluated to be 30 ns.

Moreover, as this source emits repeated pulses, one must evaluate the number N of consecutive pulses to which one is susceptible to be exposed. In the present case, the repetition rate leads to $12/60 = 0.2$ pulses par second.

In Appendix 1, the M.P.E. related to this wavelength and pulse duration is $5 \cdot 10^{-2} J/m^2$ for one isolated pulse. As the repetition rate is inferior to 1 Hz, it is not necessary to use the corrective factor $N^{-1/4}$ on the M.P.E.

Finally, the N.O.H.D. can be evaluated as in Question 7 :

$$z = \frac{1}{\theta} \cdot \left(\sqrt{\frac{4 \cdot P_0}{\pi \cdot M.P.E.}} - 2 \cdot w \right)$$

$$N.O.H.D. = \frac{1}{0.001} \cdot \left(\sqrt{\frac{4 \times 1.5 \times 10^6 \times 30 \times 10^{-9}}{\pi \times 0.05}} - 0.01 \right) = 1060 \text{ m}$$

According to this value, the operator must work 1 km away from the source to be perfectly safe. As this is UNREALISTIC, the operator must wear safety goggles during any operation near the source.

2)

If an optical element of diameter 60 mm is used to look at the beam, then the N.O.H.D. must be corrected by a factor $K = 60/7$. (7 mm being the naked eye pupil diameter).

$$N.O.H.D._{\text{Optical system}} = N.O.H.D._{\text{Naked eye}} \cdot K = \frac{1060 \cdot 60}{7} \text{ m} = 9\text{ km}$$

>Solution n°9 (exercice p. 31)

The first letter on the protective goggles label is the letter **M**, because the Ti:Sa laser is a mode-locked pulsed laser emitting pulses shorter than 1 ns .

The next information on the label is the wavelength of the radiation, expressed in nanometers : **800**. If a source emits in a wide spectral range, the wavelength can be replaced by the two extremal wavelengths of the spectrum (600-900 for example).

The next information is the "L-number", as presented in Appendix 4. We need however the energy per surface unit :

$$H = \frac{E}{S} = \frac{E}{\frac{\pi \cdot (2w)^2}{4}} = 8.42 \cdot 10^2 \text{ J/m}^2$$

In Appendix 4, the relevant information is written in the column "wavelength : from 315 to 1400 nm" and laser type "M". The relevant line is the one with the nearest value higher than $8.42 \times 10^2 \text{ J/m}^2$. Presently, the L7 number corresponds to $1.5 \times 10^3 \text{ J/m}^2$.

Warning : the previous calculation does not take into account the repetition rate of the laser. In order to take this parameter into account and to respect the standard (NF)EN 207, one must consider a typical pulse number $N = 100$. (see the section on individual protection).

The value of H previously considered must thus be corrected by a factor $N^{1/4}$.

$H' = N^{1/4} \cdot H = 3 \times 10^3 \text{ J/m}^2$. Thus, the L-number must finally be L8.

To conclude, the label written on the goggles must be : **M 800 L8**

>Solution n°10 (exercice p. 32)

One must first evaluate the maximal intensity on the axis of this beam, using its power (10 W) and diameter ($2w = 1.6\text{ mm}$)

$$I = \frac{2P_0}{\pi w^2} = 9.9 \cdot 10^6 \text{ W/m}^2$$

Using Appendix 4 for a continuous (D) laser emitting at 647 nm , one can deduce the appropriate goggles label : **D 647 L6**.

Bibliographie

[Norme NF-EN 207] COMMUNAUTÉ EUROPÉENNE -, *Norme NF-EN 207*, -, -, 2000.

[Norme NF-EN 208] COMMUNAUTÉ EUROPÉENNE -, *Norme NF-EN 208*, -, -, 2000.