FOI, Swedish Defence Research Agency, is a mainly assignment-funded agency under the Ministry of Defence. The core activities are research, method and technology development, as well as studies conducted in the interests of Swedish defence and the safety and security of society. The organisation employs approximately 1000 personnel of whom about 800 are scientists. This makes FOI Sweden's largest research institute. FOI gives its customers access to leading-edge expertise in a large number of fields such as security policy studies, defence and security related analyses, the assessment of various types of threat, systems for control and management of crises, protection against and management of hazardous substances, IT security and the potential offered by new sensors.

FOI
Defence Research Agency
Information Systems
Box 1165
SE-581 11 Linköping

Phone: +46 13 37 80 00
Fax: +46 13 37 81 00

www.foi.se

IED-Logistics report, June 2011

UV-Laser safety in connection with IED detection

JOHAN ÖHGREN, SÖREN SVENSSON AND CESAR LOPES

FOI-R--3223--SE Base Data Report **Information Systems**
ISSN 1650-1942 June 2011

Johan Öhgren, Sören Svensson and Cesar Lopes

IED-Logistics report, June 2011

UV-Laser safety in connection with IED detection

Titel	Rapport för IED-Logistics, juni 2011 — UV-laser-säkerhet i samband med IED-detektion
Title	IED-Logistics report, June 2011 — UV-laser safety in connection with IED detection
Rapportnr/Report no	FOI-R--3223--SE
Rapporttyp Report Type	Underlagsrapport Base Data Report
Sidor/Pages	46 p
Månad/Month	Juni/June
Utgivningsår/Year	2011
ISSN	
Kund/Customer	FM
Projektnr/Project no	E26454
Godkänd av/Approved by	Lars Bohman

FOI, Totalförsvarets forskningsinstitut

Avdelningen för informationssystem

Box 1165

581 11 Linköping

FOI, Swedish Defence Research Agency

Information Systems

Box 1165

SE-581 11 Linköping

Sammanfattning

Hemmagjorda sprängladdningar (IED:er, från engelskans ’improvised explosive device’) utgör ett stort hot mot såväl det civila samhället som militära operationer och det finns ett behov av att detektera och identifiera sådana sprängladdningar där de förekommer i dag. Ett sätt är att spåra upp och angripa det nätverk som producerar, hanterar och placerar ut laddningarna. Vid hantering av sprängämnen blir det ofta spårpartiklar kvar och syftet med det här projektet är att vidareutveckla ett sensorsystem som kan finna dessa spårpartiklar. Systemet bygger på hyperspektral avbildande ramanspektroskopi och innehåller en UV-laser; det kommer att bli mobilt och lämpligt för användning i fält.

Användandet av en ytskannande laser väcker frågor om lasersäkerhet och vi redovisar medicinska effekter av UV-bestrålning av hud och ögon i rapportens inledande del. Ett centralt gränsvärde när det gäller strålningsexponering är ”maximalt tillåten exponering” (MTE, på engelska MPE).

Större delen av rapporten behandlar olika konfigurationer för lasern och redovisar, utgående från MTE:n, beräkningar för maximal tillåten pulsenergitäthet (PED), exponeringstid och ackumulerad energitäthet (PTAED). Konfigurationerna skiljer sig åt med avseende på våglängd (355 respektive 266 nm), pulslängd (30 ps respektive 5 ns) och pulsrepetitionsfrekvens (PRF) (10 Hz respektive 10 kHz; i viss utsträckning har även 1 kHz behandlats).

Beräkningsresultaten presenteras i diagram, som visar relationen mellan PED, exponeringstid och PTAED. PTAED redovisas för tidsintervallet 0–100 s (typisk tidsrymd för en mätning i fält) och även för den maximala tillåtna exponeringstiden. Maximal tillåten PED sträcker sig från 0,9 J/m^2 för 30 ps-pulser till 47 J/m^2 för 5 ns-pulser. Den PTAED som är möjlig att uppnå efter 100 s exponering är avsevärt större vid 355 nm än vid 266 nm; den går från 30 J/m^2 till hela 10 000 J/m^2. I de flesta fall innebär en låg PED, korta pulser och långa våglängder att PRF:en kan ökas och exponeringstiden förlängas. Fördelar och nackdelar med att använda maximal tillåten PED diskuteras.

Om strålningsexponeringen har närmat sig MTE:n, bör ytterligare exponering undvikas under de följande 16 timmarna. Exponeringen bör emellertid alltid hållas så låg som möjligt.

Avslutningsvis tar vi upp frågor om laserstrålens form, strålgång och stråldivergens, spridning, reflektioner och risken att bli bestrålad vid eller i närheten av det undersökta objektet. Lämplig taktik vid användandet och sätt att bestråla bör också övervägas.

Nyckelord: improviserade sprängladdningar, IED-detektion, mobil detektor, avbildande hyperspektral ramanspektroskopi, UV-laser, lasersäkerhet, standarder, maximalt tillåten exponering, MTE

Summary

Improvised explosive devices, IEDs, are a common threat to the civilian society and military operations and there is a need to detect and identify such explosive charges in real environments. One way is to find and attack the network behind the production, handling and placement of the charges. The handling of explosive material often leaves trace particles behind and the aim in this project is to further develop a sensor system for finding these trace particles. The system will be based on hyperspectral imaging Raman spectroscopy, utilising a UV laser; it will be mobile and suitable for field applications.

The use of laser to scan the surfaces raises the question on laser safety aspects and we have investigated the medical effect from UV radiation on eyes and skin in the first part of this report. A central exposure limit is the maximum permissible exposure (MPE).

The bulk part of this report analyses different configurations of the laser and, considering MPE, determines the maximum allowed pulse energy densities (PEDs), exposure times and accumulated energy densities (PTAEDs). Our configurations differ by wavelength (355 or 266 nm), pulse length (30 ps or 5 ns) and pulse repetition frequency (PRF) (10 Hz or 10 kHz; 1 kHz has been considered to a smaller extent).

The results are presented in diagrams, showing the relation between PED, exposure time and PTAED. The PTAED is stated for the time interval 0–100 s (typical value for a field measurement) and for the maximum allowed exposure time. The maximum allowed PED ranges from 0.9 J/m^2 for 30-ps pulses to 47 J/m^2 in some cases for 5-ns pulses. The PTAED that can be achieved after an exposure time of 100 s is much higher with 355 nm than with 266 nm; in fact it changes from 30 J/m^2 to 10,000 J/m^2. In most cases a lower PED, shorter pulses and longer wavelengths will allow for a higher PRF and a longer exposure time. Advantages and disadvantages of running the laser at the maximum allowed PED are discussed.

If the radiation exposure approaches MPE, further exposure should be avoided at least 16 hours. The exposure should, however, always be kept as low as possible.

Finally we discuss considerations to be made when designing the shape of the laser beam and the beam path, including beam divergence, scattering, reflections and risk of irradiation at or around the examined object. There are also considerations to be made about tactical use and irradiation method.

Keywords: improvised explosive devices, IED detection, mobile detector, hyperspectral imaging Raman spectroscopy, UV laser, laser safety standards, maximum permissible exposure, MPE

Contents

1 Introduction with background

1.1 IED-Logistics and UV lasers

Improvised explosive devices, IEDs, are a common and a growing threat to the civilian society as well as to military operations. Detecting and identifying explosive charges and IEDs in real environments is a very challenging and in many cases hazardous task.

One way to tackle the IED problem is to find and attack the network behind the production, handling and placement of the charges. The handling of explosive material often leaves trace particles behind, for example on cars or outside the production site buildings. Within the project IED-Logistics, the aim is to further develop a sensor for detection and identification of these trace particles. The detection system will be based on hyperspectral imaging Raman spectroscopy, and the project will result in a mobile detector prototype, suitable for field applications, which can be used to examine non-moving targets (such as vehicles, clothing, luggage, buildings et cetera.).

The system uses laser to scan the surfaces, which raises the question on laser safety aspects in order to avoid injuries to people in the area where a scanning process is being pursued and to equipment operators. One of the goals of the IED-Logistics project is to investigate the effect on eyes and skin of different laser wavelengths, and to design and modify the system accordingly to meet the safety requirements. One step in doing so is to move towards ultraviolet (UV) wavelengths, since it in comparison with the previously used green light has a less damaging effect on the human eye.

In this project the wavelength region of interest is between 200 and 400 nm with special interest in 266 and 355 nm. Table 1 summarises the operational modes (wavelengths, pulse repetition frequencies and pulse lengths) of interest in this report. These have been chosen as typical values and as boundary values of the interesting frequency and pulse length ranges.

Table 1 Wavelengths, pulse repetition frequencies and pulse lengths of interest in this project.

Wavelength	Pulse repetition frequency (PRF)	Pulse length
355 nm	10 Hz	30 ps
355 nm	10 Hz	5 ns
355 nm	1 kHz	30 ps
355 nm	1 kHz	5 ns
266 nm	10 Hz	30 ps
266 nm	10 Hz	5 ns
266 nm	1 kHz	30 ps
266 nm	1 kHz	5 ns

The UV-wavelength band spans from 10 nm to 400 nm, that is, shorter wavelengths than the human eye can see. The UV-wavelength band between 100 and 400 nm is normally divided into 3 parts; UV-A (315–400 nm), UV-B (280–315 nm) and UV-C (100–280 nm). The type of injury that can occur differs somewhat depending on the wavelength (UV-A, UV-B and UV-C), especially when the eye is considered.

1.2 UV Laser induced injuries to eyes and skin

UV-A and UV-B radiation penetrates into tissue, while UV-C radiation is absorbed at the surface layers of eye and skin. Although UV-A and UV-B can penetrate into tissue, the radiation is absorbed before it is focused on the eye retina[1]. This means that the maximum permissible exposure (MPE) values for eyes and skin are the same. The MPE values are defined in a way that exposures below the MPE are considered safe. Only in rare cases have exposures below MPE lead to abnormal effects[2]. The MPE values are mainly based on animal experiments, but also include human volunteers.

The types of injury caused by the high-energy UV photons are photochemical and thermal in nature. Photochemical injuries also have a cumulative effect to consider and can take some time to appear even after MPE is exceeded. Therefore in cases where there is a cumulative effect, the MPEs are given as a constant radiant exposure which, thus, does not depend on duration time.

Photochemical injuries dominate for continuous-wave lasers, while thermal injuries dominate for short-time pulsed lasers (either single pulsed or in a repetetive pulse mode). In cases when tissue is heated up rapidly, thermo-mechanical injury also has to be considered. A thermo-mechanical injury can occur when short-time pulsed lasers are used, which causes a thermal expansion of the area exposed, leading to stress waves that propagate or even to ablation of tissue. Also, UV radiation might cause skin cancer. In most cases, except for cancer, the skin is able to repair itself.

Regarding the eye, the cornea and lens can be photo-chemically, thermally and thermo-mechanically injured. UV-A radiation is absorbed to a higher extent by the lens than the cornea which can lead to thermal injury to the lens. UV-B radiation can cause injury to both the cornea and the lens. In the case of the lens, cataract is formed. UV-C causes injury to the cornea. As for the skin, the eye has, in many cases, the ability to heal itself.

1.3 Laser safety standards

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) leads the work on laser safety by publishing guidelines on exposure limits[3]. These guidelines are used in the publications of the International Electrochemical Commission (IEC). The IEC 60825-1, the main international standard for laser safety[4], is one of a series of publications by IEC. In Europe (including Russia) the IEC standard is published as EN 60825-1. In USA the ICNIRP standards are published by the American National Standards Institute (ANSI)[5].

The adopted MPEs are identical in Europe and USA except for a few special cases.

Besides the EN and ANSI publications there are two more international documents of interest published by the International Labour Office[6] and the World Health Organization[7]. These documents also follow the ICNIRP standards.

---

[1] Radiation with wavelengths between approximately 400 and 1400 nm are focused on a very small spot on the retina giving an irradiance increase of approximately 100 000 times.

[2] R. Henderson, K. Schulmeister, ”Laser Safety”, Institute of Physics publ., Bristol UK, 2004.

[3] ICNIRP Guidelines, Health Phys. 87 (2): 171–186; 2004. http://www.icnirp.org/PubOptical.htm#top.

[4] (a) IEC 60825-1 ED. 2.0, ”Safety of Laser Products-Part I: Equipment Classification and Requirements”, IEC Geneva 2007, (b) http://www.iec.ch/dyn/www/f?p=103:105:0::::FSP_LANG_ID:25.

[5] ANSI Z136.1–2007 , “American National Standard for Safe Use of Lasers”, Laser Institute of America, Orlando, USA, 2007.

[6] International Labour Office, ”Use of lasers in the workplace — A practical guide”, ILO Geneva 1993.

[7] World Health Organization, ”Environmental health criteria 23 — lasers and optical radiation”, WHO Geneva 1992.

2 The use of MPE values with continuous and pulsed lasers

2.1 Dependence on wavelength and time

The maximum permissible exposure (MPE) is expressed as either an irradiance with units W/m^2 or an energy density (the irradiance integrated over time) with units J/m^2. Any of these aspects can be translated into the other (considering time) and both aspects are equally valid and important.

The MPE value is based on a single laser pulse with constant irradiance level (rectangular in time). The pulse duration can be shorter than 1 ns or as long as 10,000 s or anywhere in between. Thus it is straightforward to use the MPE with continuous wave lasers, whose radiation during some time could be regarded as a single pulse . The next section of this report (2.2) explains how to use MPE with pulsed lasers.

The MPE value will depend on how long a person is exposed to the radiation and the wavelength of the radiation as well. In general, a long exposure time or a short wavelength will lower the MPE. In fact, all wavelengths in the UV-A domain have the same MPE value, while in the UV-B the MPE is successively lowered for shorter wavelengths. Then, once more, all wavelengths in the UV-C have the same MPE (which is lower than for UV-A and UV-B).

The various MPE values that will be presented in the following have been calculated from tables in the Swedish standard for laser and optical radiation[8], which are based on the ICNIRP standards.

Figure 1 shows the MPE for different wavelengths and exposure times. Shown are the important laser wavelengths 355 and 266 nm and two intermediate wavelengths, 310 and 305 nm. It should be noted that the MPE for 355 nm is valid for all wavelengths in the interval 315–400 nm (UV-A), and that the MPE for 266 nm is valid throughout the interval 180–302.5 nm (UV-C and part of UV-B). The wavelengths 305 and 310 nm belong to the intermediate wavelength region 302.5–315 nm (part of UV-B), where the MPE gradually changes to lower values for shorter wavelengths. For pulses of very short duration, less than 1 ns, all UV wavelengths have the same MPE 3×10^{10} W/m^2. As the duration increases, the MPE drops.

[8]AFS 2009:7, ”Artificiell optisk strålning”, Arbetsmiljöverket, Stockholm, Sweden, 2009 and AFS 1994:8, ”Laser”, Arbetarskyddsstyrelsen, Solna, Sweden, 1994.

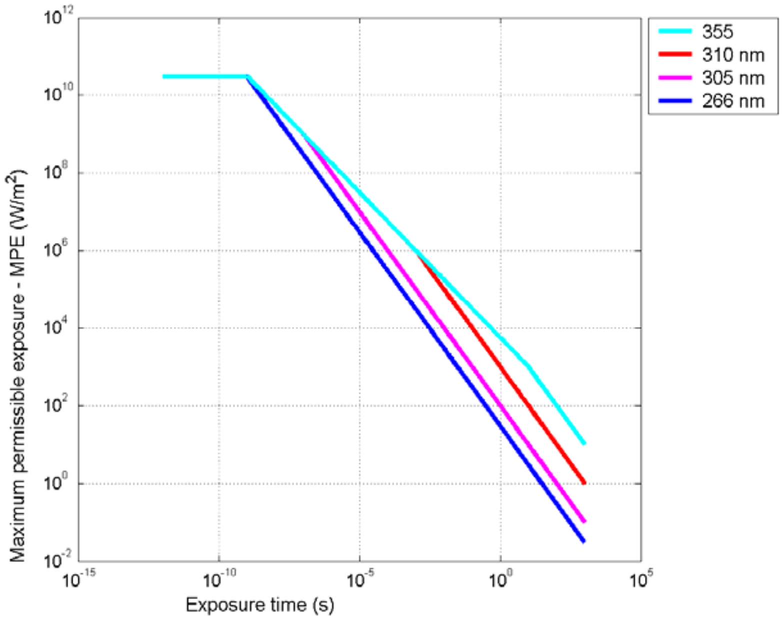

Figure 1 MPE as a function of exposure time. All curves join and coincide when going leftwards in the diagram, but for practical reasons only one of the overlayed curves can be shown. The curve for 355 nm represents all wavelengths in the range of 315–400 nm. Likewise, the curve for 266 nm represents all wavelengths in the range 180–302.5 nm. Two representative curves, 305 and 310 nm, are shown for the intermediate wavelength region (302.5–315 nm). Note the logarithmic scales on both the time and the MPE axis.

Figure 2 also shows the MPE for different wavelengths and exposure times, although in another fashion.

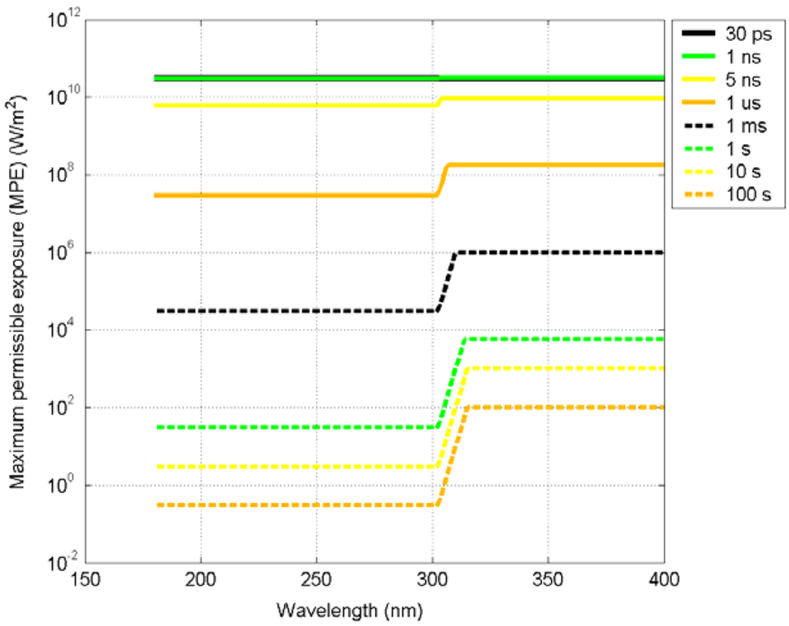

Figure 2 MPE as a function of wavelength. Short pulses have a relatively high MPE (in W/m^2), while long pulses have a relatively low MPE. The curves representing 30-ps pulses and 1-ns pulses coincide at wavelengths below 302.5 nm and almost coincide for wavelengths above 302.5 nm. Note the logarithmic scales on the MPE axis.

2.2 Pulsed lasers and MPE

A pulsed laser emits a pulse train with individual constituent pulses. In the simple case, each pulse has a rectangular shape in time (sharp rise, then constant radiation level, then sharp decline), all the pulses look the same and the pulses are evenly spaced in time. The duration of a pulse is also called pulse length and the pace at which they arrive is the pulse repetition frequency, PRF. The duration of the whole pulse train will often be referred to as exposure time in this report, because the intention is that the whole pulse train from its beginning to its end should impinge on the examined object.

The irradiance of an individual pulse will be called PI ('pulse irradiance'). Integrating the PI over the pulse length results in an energy density, which will be called PED ('pulse energy density'). PI and PED can be used interchangeably, as long as the pulse length is known.

The pulse train's mean irradiance over time will be called PTMI ('pulse train mean irradiance') in this report. The accumulated energy density from all pulses under the exposure time will be called PTAED ('pulse train's accumulated energy density ').

As explained in the previous section, the MPE is stated for continuous laser radiation during some exposure time. When using a pulsed laser, on the other hand, things get slightly more complicated. There are now two restrictions, which both must be fulfilled:

1. The PI of an individual pulse must not exceed the MPE related to a continuous pulse with the same irradiance and duration. (In some circumstances, PED is considered instead of PI.)

2. The PTMI of the pulse train must not exceed the MPE related to a continuous pulse with the same mean irradiance (time averaged) and duration. (In some circumstances, PTAED is considered instead of PTMI.)

2.3 Implications for pulsed lasers

Before analysing the actual laser system used in this project, some general remarks for pulsed lasers can be made. Four modes with either 355 or 266 nm wavelength and either 30-ps or 5-ns pulses are analysed in figure 3. The relation between exposure time and PRF is presented under the conditions that PED is maximal and equals MPE of the pulse and also that PTMI must not exceed the MPE of the pulse train.

Here is a clarifying example of the calculations made: Assume wavelength 266 nm and pulse length 30 ps. MPE for a pulse length of 30 ps is 3×10^{10} W/m^2. The maximum allowed PED is thus (pulse length) × (MPE) = (30 ps) × (3×10^{10} W/m^2) = 0.9 J/m^2. Now assume an exposure time of 1 s. The MPE for the whole pulse train during this time is 30 J/m^2. Therefore PTMI must not exceed (MPE) / (exposure time) = (30 J/m^2) / (1 s) = 30 W/m^2. As (PTMI) = (PED) × (PRF), this means that maximum PRF is (PTMI) / (PED) = (30 W/m^2) / (0.9 J/m^2) = 33.3 Hz (truncated value).[9]

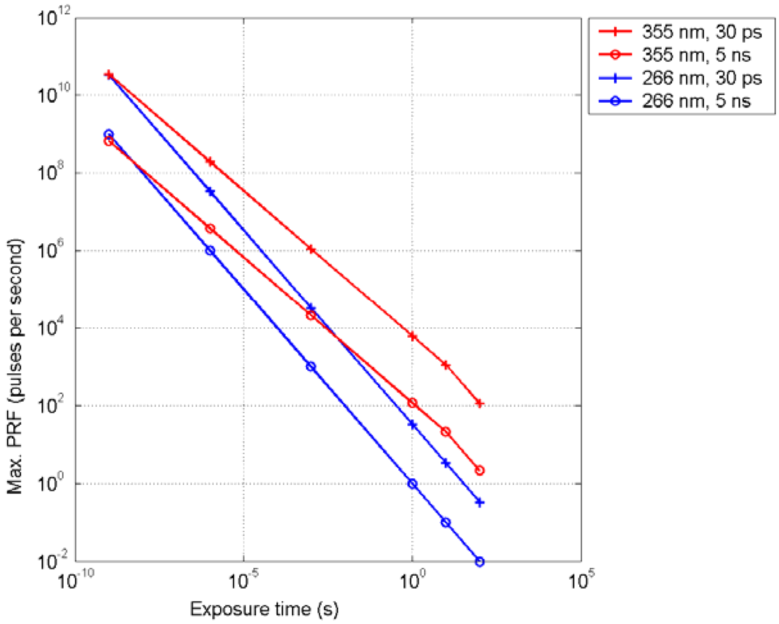

Figure 3 Relation between the maximum allowed pulse repetition frequency (PRF) and the maximum allowed exposure time for four modes of wavelengths and pulse durations.

In many cases a shorter exposure time allows for a higher PRF, each balancing the other to produce the associated MPE. The different curves are not entirely separated, but intersect. Nonetheless a tendency can be noted, that longer wavelengths permit a higher PRF (due to a higher MPE for longer wavelengths) and that shorter pulses also permit a higher PRF (due to lower PTMI).

[9] The observant reader will have noted that the first MPE is given as an irradiance, while the second is given as an energy density; this comes from the fact that a separate pulse and the whole pulse train belongs to totaly different time scales and that the standard uses different MPEs for different time scales.

Let us next assume that the PED is lower than MPE. Then a longer exposure time will be allowed. This is illustrated by figure 4.

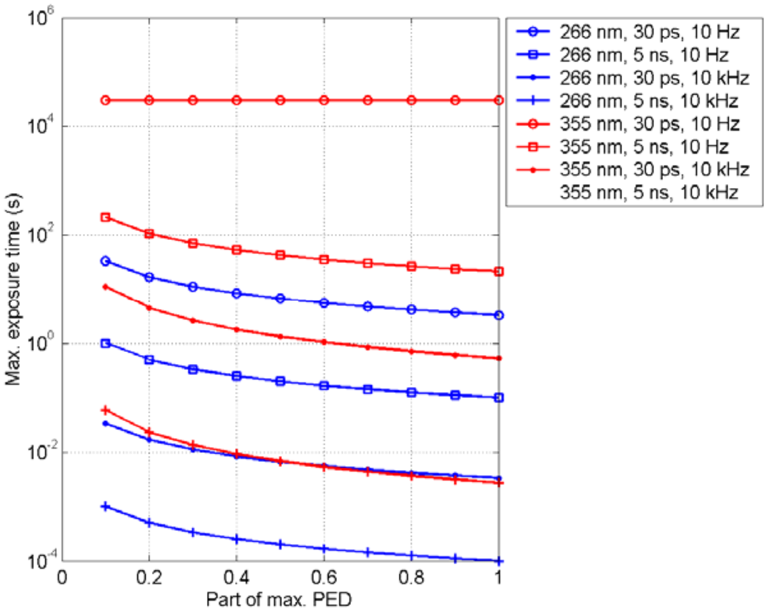

Figure 4 The maximum allowed exposure time is shown for eight operational modes. In the far right end of the horizontal scale, it is assumed that PED equals MPE. Going to the left, PED amounts a smaller part of MPE, as stated by the fractional numbers.

A lower PED permits a longer exposure time, but whether this is useful or not will be discussed in section 4.2.

2.4 Computational considerations

For pulses shorter than 1 ns, the standard explains that 'due to poor data ... ICNIRP recommends using 1 ns as limit value for irradiance'[10] and provides not an energy density value, but the irradiance value 3×10^{10} W/m^2 for the MPE. Therefore we use this irradiance value throughout this report when calculating the maximum allowed PED for short pulses. For instance would the maximum PED of a 30-ps pulse be (30 ps) × (3×10^{10} W/m^2) = 0.9 J/m^2. (This computation was made also in previous section.)

The standard also provides an aperture, defined as 'a circular area, on which the average exposure of irradiance and radiation is to be calculated'[11]. The value of the diameter of this aperture varies from 0.7 to 3.6 mm depending on the circumstances. This aperture has no effect on the calculations in this report, but it provides a mean to measure the irradiance in the real laser beam. It is also adviced, that the diameter of the laser beam always is larger than 3.6 mm for valid comparison with the results in this report.

[10] AFS 2009:7, "Artificiell optisk strålning", Arbetsmiljöverket, Stockholm, Sweden, 2009. Page 41 including footnote c.

[11] AFS 2009:7, "Artificiell optisk strålning", Arbetsmiljöverket, Stockholm, Sweden, 2009. Pages 39, 41,42 and 44.

3 Evaluation of the current UV-laser system

3.1 Operational modes

The UV laser system in this project can be configured by setting various parameters to different values. The three main parameters and their two typical values are

- laser wavelength 355 or 266 nm
- pulse length 30 ps or 5 ns
- pulse repetition frequency (PRF) 10 Hz or 10 kHz

In total this gives us eight different operational modes (OPs) of wavelength, pulse length and PRF (compare table 1 in chapter 1.1.). The parameters could also have intermediate values, but these are regarded as limiting values.

Other parameters, which can be set freely (within reasonable bounds), include exposure time, pulse energy and geometry of the laser beam. In the following sections we will see how exposure time and PED are restricted by the condition thar MPE must not be exceeded. The pulse energy or geometry of the laser beam, however, will not be explicitly stated, because these two can be calculated and adapted to each other once the PED is known.

3.2 OP 1: Wavelength 266 nm, pulse length 30 ps, PRF 10 Hz

The first operational mode of the UV laser system to be studied in more detail uses the setting 266 nm wavelength, 30-ps pulses and PRF 10 Hz. For this wavelength and pulse length the MPE is 3×10^{10} W/m^2. The highest allowed PED is thus (pulse length) × (MPE) = $(30\times10^{-12}$ s) × (3×10^{10} W/m^2) = 0.9 J/m^2. Consequently, the highest allowed PTMI will be (PED) × (PRF) = (0.9 J/m^2) × (10 Hz) = 9 W/m^2. Of relevance to this PTMI is another MPE, namely 30 J/m^2, which limits the exposure time. The longest allowed exposure time will be (MPE) / (PTMI) = (30 J/m^2) / (9 W/m^2) = 3.3 s (truncated value).

If the PED would be lowered, the PTMI would also be lower and the exposure time longer, without violating the MPE. The relation between PED and exposure time is shown in figure 5. The curve ends to the right with the highest allowed PED 0.9 J/m^2 and the longest allowed exposure time for this PED, 3.3 s. The left side of the curve, with lower PED values, could have been continued with even lower PED values and longer exposure times, but for practical reasons it has been discontinued at 3×10^{-3} J/m^2, corresponding to an exposure time of 10^3 s.

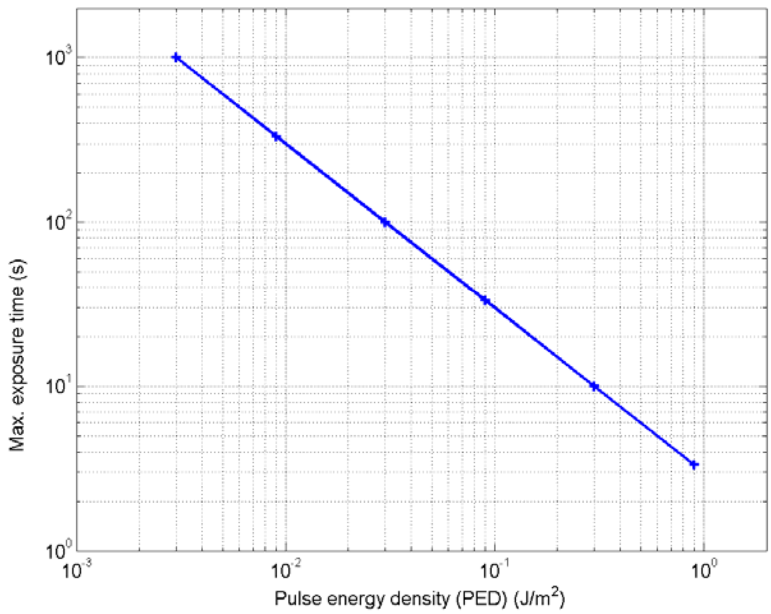

Figure 5 Relation between pulse energy density and maximum allowed exposure time for a 266-nm laser with 30-ps pulses and PRF 10 Hz. MPE for a pulse in the pulse train is 0.9 J/m^2; this is also the curve's right-most value.

It is now clear that our system could be operated with high PEDs (maximum 0.9 J/m^2) for short moments of time (maximum 3.3 s) or at lower PEDs for longer times. But of equal importance is what energy density that will have been accumulated in the target (the PTAED) after the allowed exposure time. In this case this value is known to be 30 J/m^2, which is the MPE on which the calculations of exposure time were based. The relation between PTAED and PED is presented in figure 6. The diagram in this figure is based on the same PEDs as in the last figure and consequently the curve ends with 0.9 J/m^2 to the right.

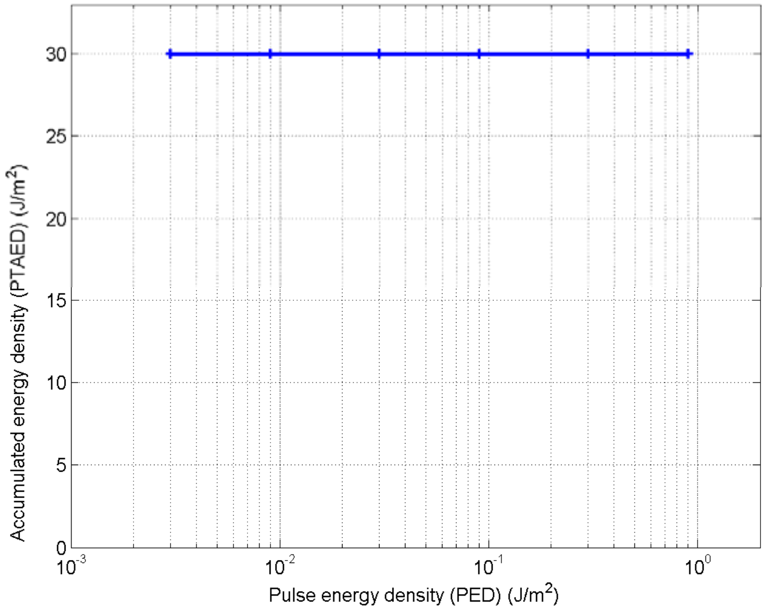

Figure 6 Accumulated energy density (PTAED) after maximum allowed exposure time for a 266-nm laser with 30-ps pulses and PRF 10 Hz. Following the curve to the right, the energy density of a pulse in the pulse train (PED) increases. The last value to the right is its MPE (0.9 J/m^2). Independently of high or low pulse energy densities, the PTAED is constant (30 J/m^2).

For the practical use of the laser system in this operational mode, we conclude that using a low PED during a long time will not give a higher PTAED than using the maximal PED during a short time. Thus there are arguments for using a high PED, but there are also arguments for using low PEDs; see section 4.2.for a discussion of this subject.

The examination of an object in field typically ends within a minute. It will therefore be of interest to know the achieved PTAED after this time, especially when maximum allowed PED is used, but also for smaller fractions of this value. Figure 7 shows the PTAED for exposure times up to 100 s when using different PEDs, including the maximum allowed PED.

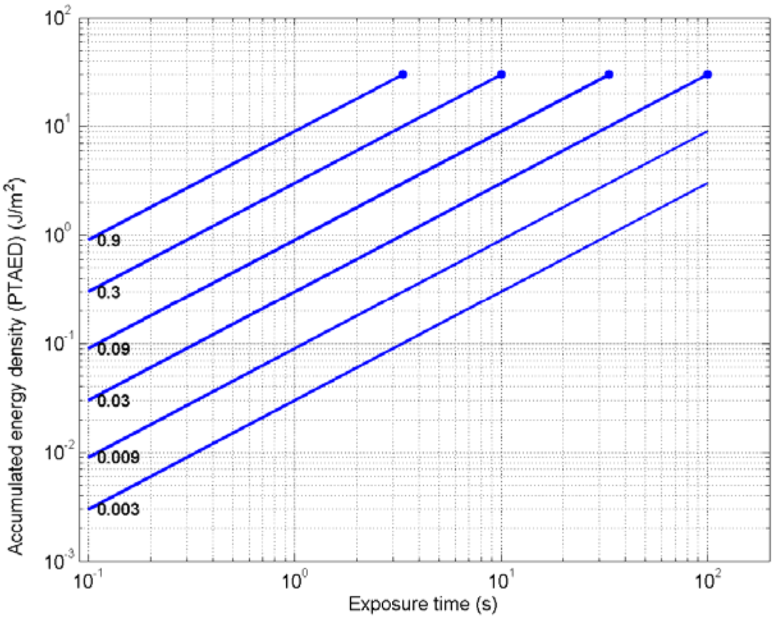

Figure 7 Accumulated energy density (PTAED) after exposure times up to 100 s for a 266-nm laser with 30-ps pulses and PRF 10 Hz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2.) Four curves are discontinued earlier than 100 s, because MPE is reached; this is shown by a dot.

From this figure, as well as from the initial calculations in this section, it is clear that the maximum allowed PTAED is reached after 3.3 s when using maximum allowed PED. It is also clear, that the PED must be reduced 30 times to 0.03 J/m^2 if an exposure time of 100 s should be used.

3.3 OP 2: Wavelength 266 nm, pulse length 5 ns, PRF 10 Hz

This mode differs from the foregoing only in the longer pulse length, 5 ns. As a consequence, the MPE of a pulse changes to 30 J/m^2. The relation between PED and maximum exposure time is shown in figure 8. It is essentially the same as in the last described mode, the difference being that higher PEDs can be used, although during shorter exposure times. (The maximum PED is 30 J/m^2 with corresponding maximum exposure time 1×10^{-1} s. That is, just one single pulse!)

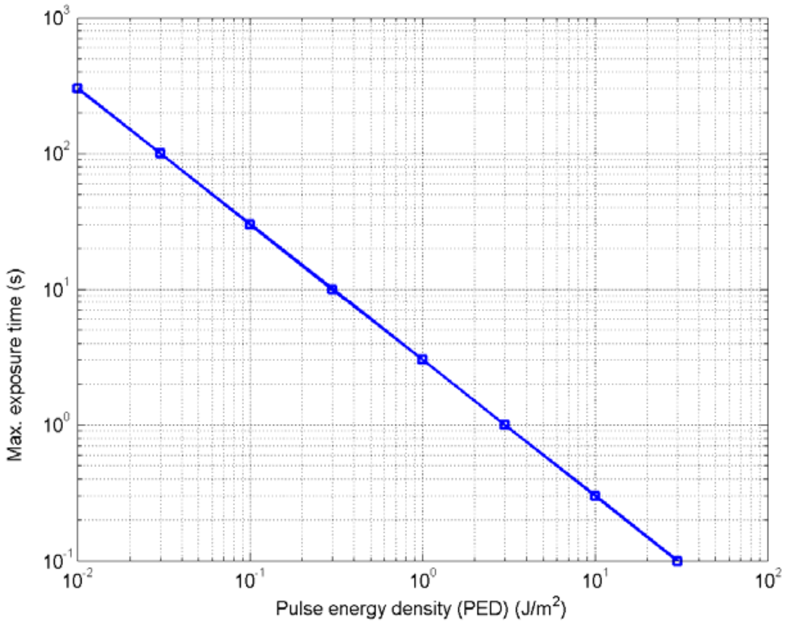

Figure 8 Relation between pulse energy density and maximum allowed exposure time for a 266-nm laser with 5-ns pulses and PRF 10 Hz. MPE for a pulse in the pulse train is 30 J/m^2; this is also the curve's right-most value.

The PTAED for different PEDs is shown in figure 9. Just like in the previous described mode, it is 30 J/m^2 for all selections of PED.

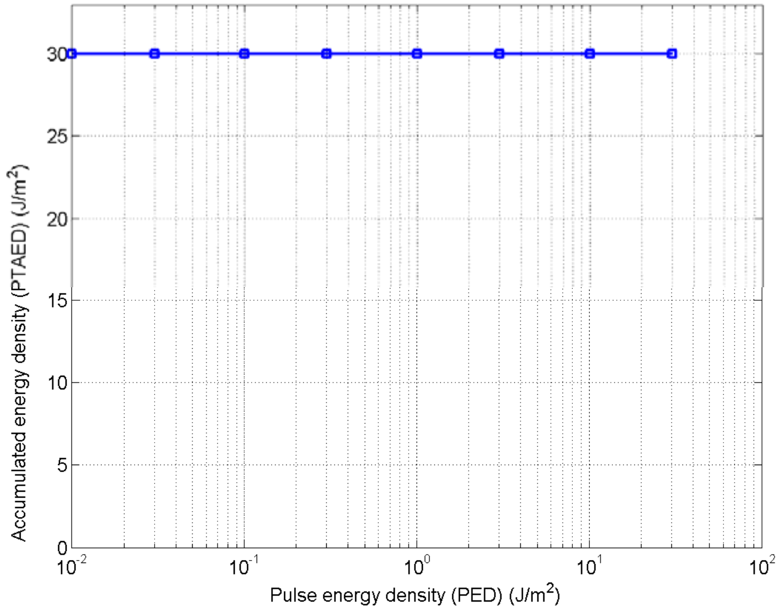

Figure 9 Accumulated energy density (PTAED) after maximum allowed exposure time for a 266-nm laser with 5-ns pulses and PRF 10 Hz. Following the curve to the right, the energy density of a pulse in the pulse train (PED) increases. The last value to the right is its MPE (30 J/m^2). Independently of high or low pulse energy densities, the PTAED is constant (30 J/m^2).

The PTAED as a function of exposure time (up to 100 s) for a number of different PEDs is shown in figure 10.

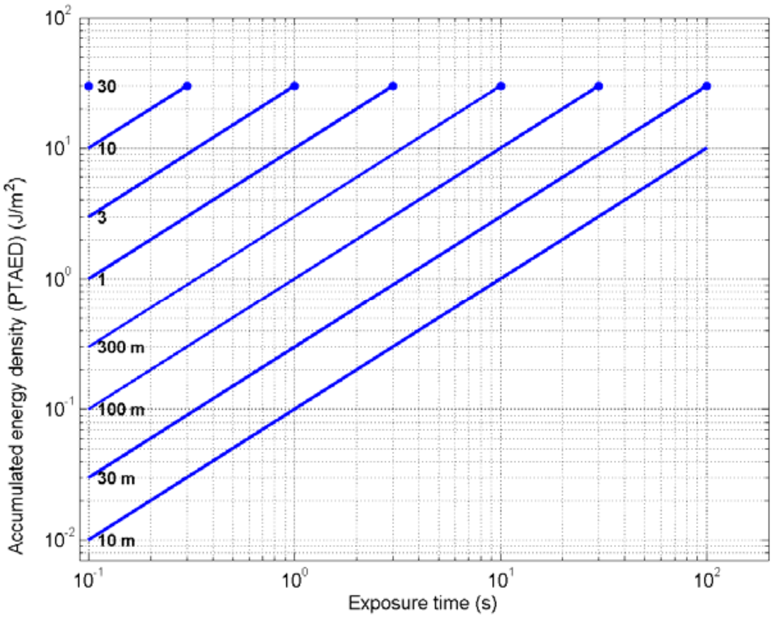

Figure 10 Accumulated energy density (PTAED) after exposure times up to 100 s for a 266-nm laser with 5-ns pulses and PRF 10 Hz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2 with SI prefix 'm' for milli.) Seven curves are discontinued earlier than 100 s, because MPE is reached; this is shown by a dot. Maximal allowed PED is 30 J/m^2. Therefore the upper-left curve, corresponding to this value, is just a point, because only one pulse is allowed.

3.4 OP 3: Wavelength 266 nm, pulse length 30 ps, PRF 10 kHz

This operational mode should be compared with the first mode. Here, though, the PRF is increased to 10 kHz. The maximum PED is once again 0.9 J/m^2, but the higher PRF increases the PTMI which restricts the corresponding exposure time to 3.3×10^{-3} s, corresponding to a pulse train of only 33 pulses. Figure 11 illustrates the relation between PED and maximum allowed exposure time. Just like in the foregoing modes, the PTAED (see figure 12) is limited to 30 J/m^2, independently on chosen PED. The value of PTAED after a certain exposure time, depending on chosen PED, is shown in figure 13.

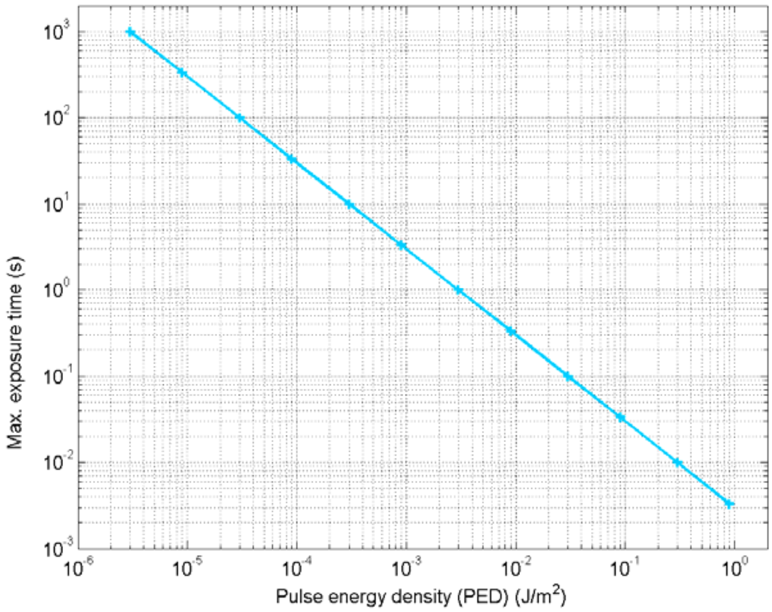

Figure 11 Relation between pulse energy density (PED) and maximum allowed exposure time for a 266-nm laser with 30-ps pulses and PRF 10 kHz. MPE for a pulse in the pulse train is 0.9 J/m^2; this is also the curve's right-most value.

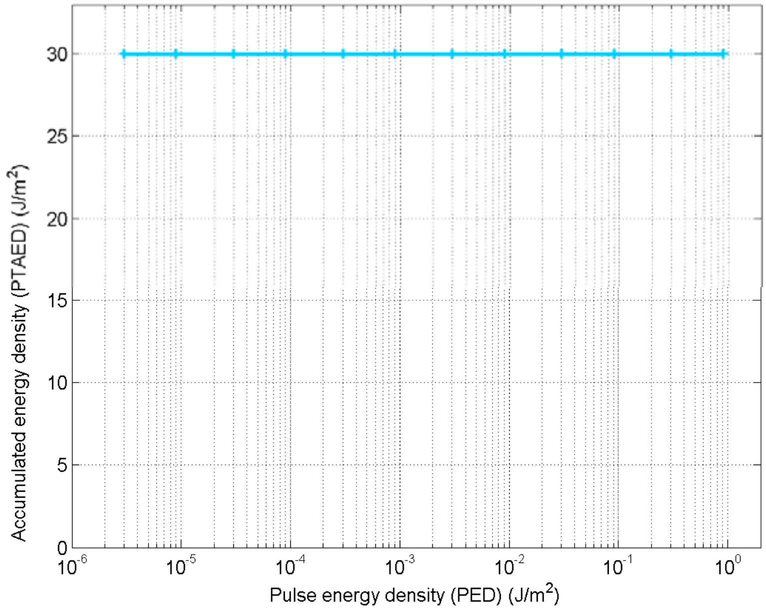

Figure 12 Accumulated energy density (PTAED) after maximum allowed exposure time for a 266-nm laser with 30-ps pulses and PRF 10 kHz. Following the curve to the right, the energy density of a pulse in the pulse train (PED) increases. The last value to the right is the MPE (0.9 J/m^2). Independently of high or low pulse energy densities, the PTAED is constant (30 J/m^2).

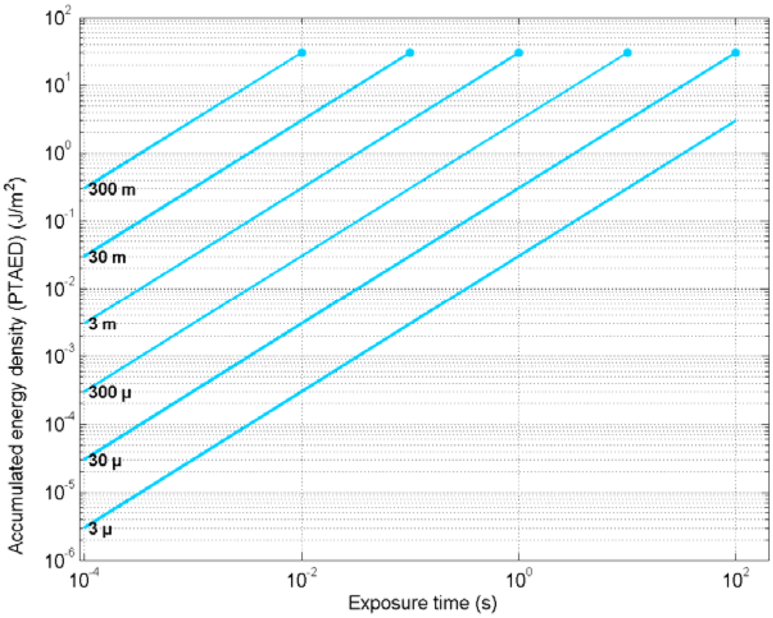

Figure 13 Accumulated energy density (PTAED) after exposure times up to 100 s for a 266-nm laser with 30-ps pulses and PRF 10 kHz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2 with SI prefix ‘m’ for milli and ‘µ’ for micro.) Five curves are discontinued earlier than 100 s, because MPE is reached; this is shown by a dot.

3.5 OP 4: Wavelength 266 nm, pulse length 5 ns, PRF 10 kHz

This mode is similar to the second mode, but with a higher PRF of 10 kHz. The maximal PED is 30 J/m^2. At this pulse energy density, maximal exposure time is 1×10^{-4} s, corresponding to only one pulse. The relation between PED and maximum allowed exposure time is shown in figure 14. As is the case with the foregoing modes with wavelength 266 nm, the PTAED is 30 J/m^2 for all PED values (figure 15). The PTAED as a function of time and various PEDs can be seen in figure 16.

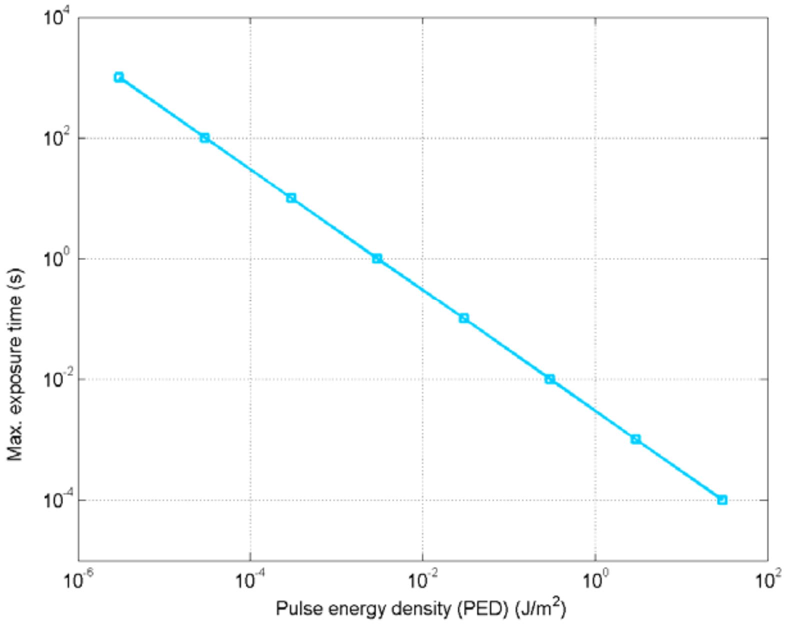

Figure 14 Relation between pulse energy density (PED) and maximum allowed exposure time for a 266-nm laser with 5-ns pulses and PRF 10 kHz. MPE for a pulse in the pulse train is 30 J/m^2; this is also the curve's right-most value.

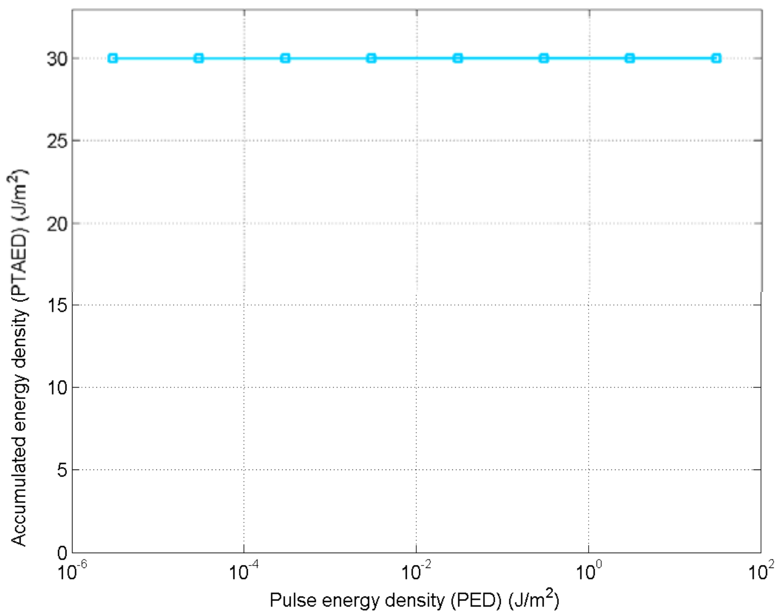

Figure 15 Accumulated energy density (PTAED) after maximum allowed exposure time for a 266-nm laser with 5-ns pulses and PRF 10 kHz. Following the curve to the right, the energy density of a pulse in the pulse train (PED) increases. The last value to the right is the MPE (30 J/m^2). Independently of high or low pulse energy densities, the PTAED is constant (30 J/m^2).

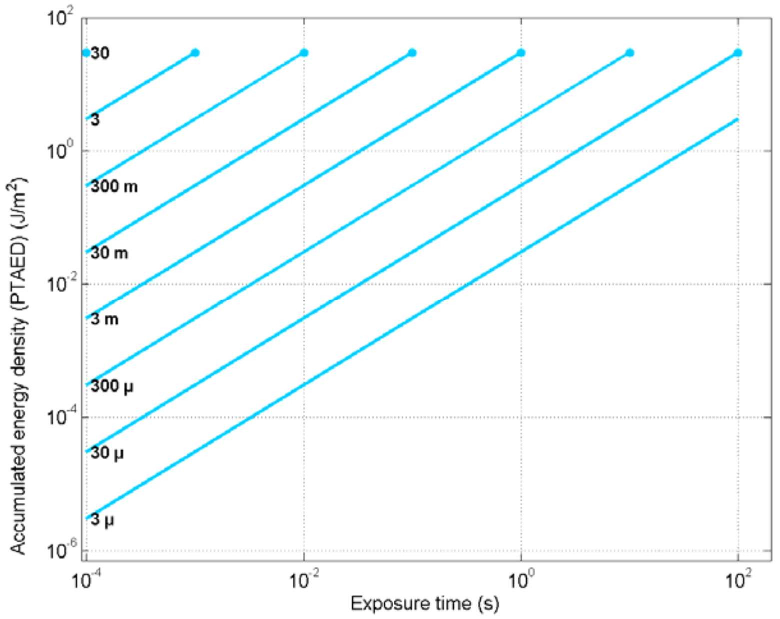

Figure 16 Accumulated energy density (PTAED) after exposure times up to 100 s for a 266-nm laser with 5-ns pulses and PRF 10 kHz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2 with SI prefix 'm' for milli and 'µ' for micro.) Six curves are discontinued earlier than 100 s, because MPE is reached; this is shown by a dot. Maximal allowed PED is 30 J/m^2. Therefore the upper-left curve, corresponding to this value, is just a point, because only one pulse is allowed.

3.6 OP 5: Wavelength 355 nm, pulse length 30 ps, PRF 10 Hz

This operational mode uses the wavelength 355 nm, which is less hazardous to tissue. The PED for an individual pulse is still limited to 0.9 J/m^2, but the MPE that limits the PTMI is very much higher. In this mode, PTMI is (PED) × (PRF) = (0.9 J/m^2) × (10 Hz) = 9 W. This should be compared with the MPE, which is 10 W. Obviously, MPE is never exceeded and the maximum allowed exposure time is set to 3×10^4 s, the highest value in the tables in the standard. This relation between PED and exposure time has been plotted in figure 17. In practice, this radiation can be regarded as harmless[12] and the allowed exposure time has no limits.

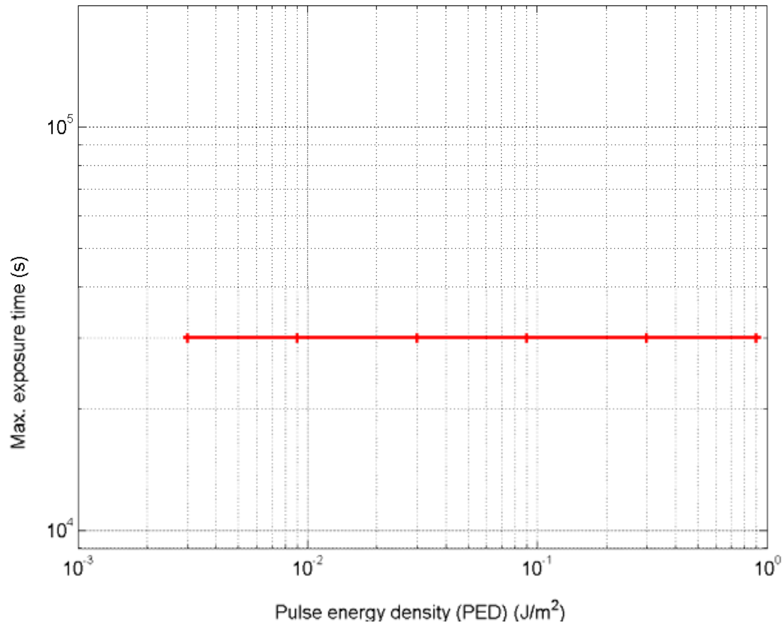

Figure 17 Relation between pulse energy density and maximum allowed exposure time for a 355-nm laser with 30-ps pulses and PRF 10 Hz. MPE for a pulse in the pulse train is 0.9 J/m^2; this is also the curve's right-most value. The allowed exposure time is in each instance 3×10^4 s, which in practice means without limit, because of low radiation levels.

The PTAED is shown in figure 18. The values are in the order 10–10,000 times higher compared to the previous modes with wavelength 266 nm. The reason for this is, of course, the allowed exposure time, which now is incomparably much longer. In practice the accumulated energy density could increase without bonds, but for this to happen a very long exposure time is needed.

[12] According to correspondence with Mr. Janez Marinko and Mr. Per Nylen at Arbetsmiljöverket, the authority that publishes the Swedish version of the ICNIRP standard.

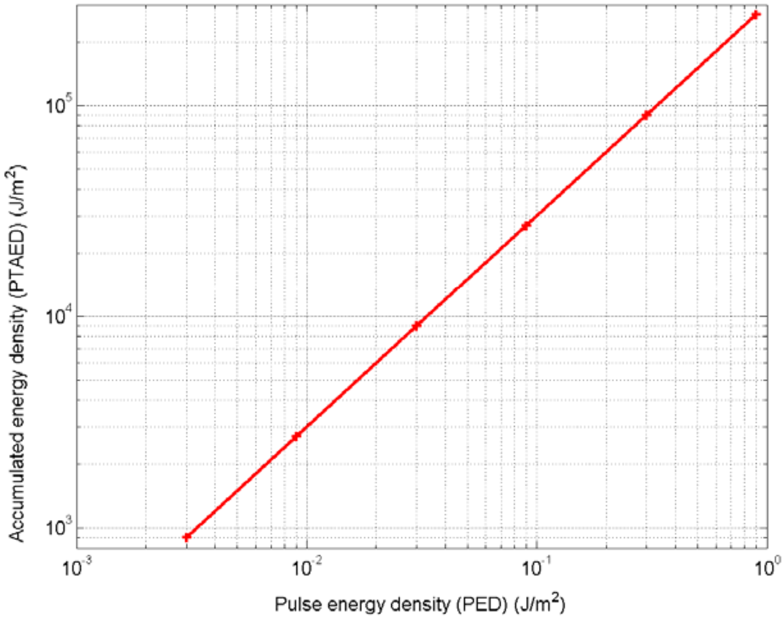

Figure 18 Accumulated energy density after maximum allowed exposure time for a 355-nm laser with 30-ps pulses and PRF 10 Hz. Following the curve to the right, the energy density of a pulse in the pulse train increases. The accumulated energy density is very high from start and increases, reflecting the fact that allowed exposure time is 3×10^4 s.

Perhaps is it of more practical value to know what PTAED could be achieved after a reasonably long exposure time of 100 s. This is shown in figure 19, for the maximum allowed PED 0.9 J/m^2 and a range of lower PEDs.

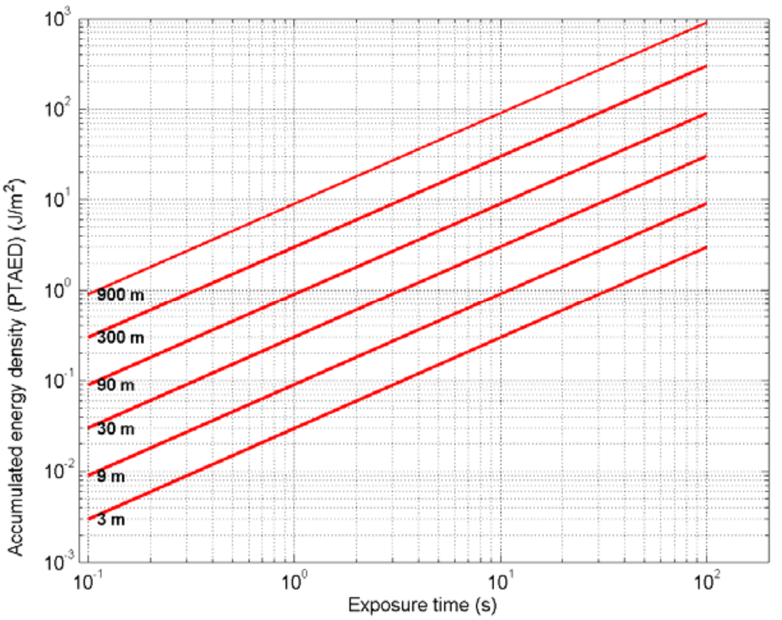

Figure 19 Accumulated energy density (PTAED) after exposure times up to 100 s for a 355-nm laser with 30-ps pulses and PRF 10 Hz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2 with SI prefix 'm' for milli.)

3.7 OP 6: Wavelength 355 nm, pulse length 5 ns, PRF 10 Hz

This mode is similar to the last one, but the pulse length is 5 ns. The MPE for such a pulse is $(5.6\times10^3) \times (\text{pulse length in seconds})^{0.25}$ J/m^2 = $(5.6\times10^3) \times (5\times10^{-9})^{0.25}$ J/m^2 = 47.09 J/m^2 (truncated value). The corresponding maximum exposure time is determined by the MPE 10^4 J/m^2 which gives (MPE) / (PTMI) = (MPE) / [(PED) × (PRF)] = (10^4 J/m^2) / [(47.09 J/m^2) × (10 Hz)] = 21.2 s (truncated value). However, as shown in figure 20, the maximum allowed exposure time will vary strongly if the PED is lowered. Low PEDs (below 1 J/m^2) are associated with harmless radiation and thus allow for very long exposure times (3×10^{-4} s or longer). High PEDs, on the other hand, limit the exposure time to lower values in the order 10–1000 s. These times are still considerably longer compared to the operational modes involving the shorter wavelength 266 nm.

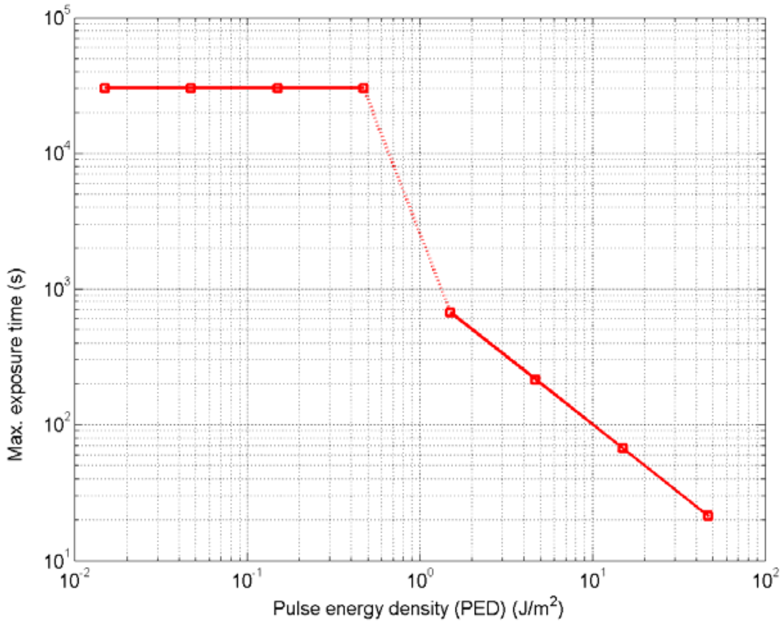

Figure 20 Relation between pulse energy density and maximum allowed exposure time for a 355-nm laser with 5-ns pulses and PRF 10 Hz. MPE for a pulse in the pulse train is 47.09 J/m^2; this is also the curve's right-most value. The allowed exposure time for pulse energy densities lower than 1 J/m^2 is 3×10^4 s, which in practice means without limit, because of low radiation levels.

Due to the large variation in exposure time with PED level, there will also be large variations in accumulated energy density. This is apparent in figure 21, where the curve's irregular behaviour is caused by shifting exposure times.

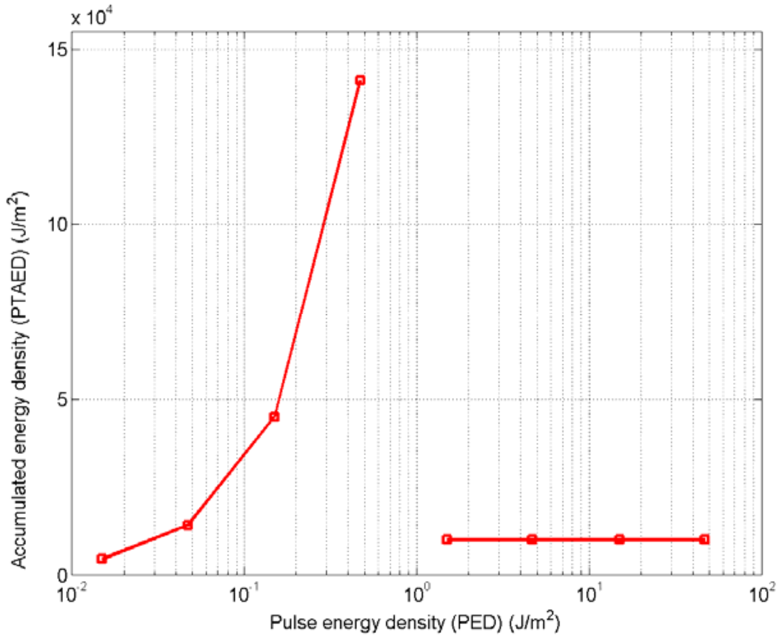

Figure 21 Accumulated energy density after maximum allowed exposure time for a 355-nm laser with 5-ns pulses and PRF 10 Hz. For pulse energy densities lower than 1 J/m^2 the allowed exposure time is 3×10^4 s, which in practice means without limit, because of low radiation levels. Therefore, in this region, the accumulated energy density could increase without bonds, but for this to happen a very long exposure time is needed. For all pulse energy densities higher than 1 J/m^2 the accumulated energy density is constant, 10^4 J/m^2. The last value to the right is the MPE (47.09 J/m^2).

The PTAED will increase to enormous 13×10^4 J/m^2 when the PED increases to 450 mJ/m^2. The reason is, however, the very long exposure times. In practice, the accumulated energy density could increase without bonds in this region, but for this to happen a very long exposure time is needed. For all PEDs higher than 1 J/m^2, the PTAED is constant, 10^4 J/m^2. This value also is relatively high, compared to operational modes with shorter wavelengths.

The PTAED achieved for more moderate exposure times, up to 100 s, is shown in figure 22. When using a PED of 47 J/m^2, MPE is reached after 21 s and no further exposure are allowed. Lowering the PED to 15 J/m^2 extends the exposure time to 66 s. Using still lower PED:s permits exposure times longer than 100 s, as shown in the figure.

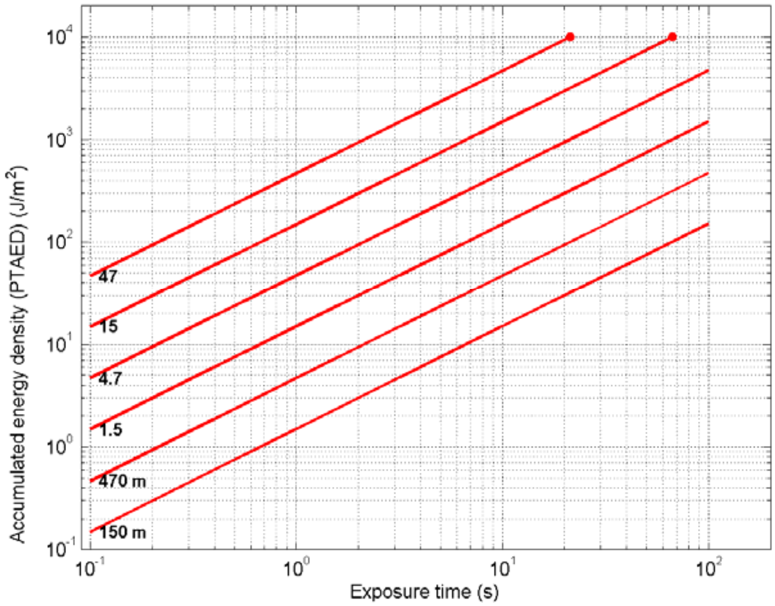

Figure 22 Accumulated energy density (PTAED) after exposure times up to 100 s for a 355-nm laser with 5-ns pulses and PRF 10 Hz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2 with SI prefix ‘m’ for milli.) Two curves are discontinued earlier than 100 s, because MPE is reached; this is shown by a dot.

3.8 OP 7: Wavelength 355 nm, pulse length 30 ps, PRF 10 kHz

This operational mode uses the high PRF 10 kHz. Together with the PED (maximum value 0.9 J/m^2) this increases the PTMI and despite the relatively harmless wavelength, the exposure time will now be bounded (for reasonable large fractions of maximum PED). Figure 23 shows the relation between PED and maximum allowed exposure time.

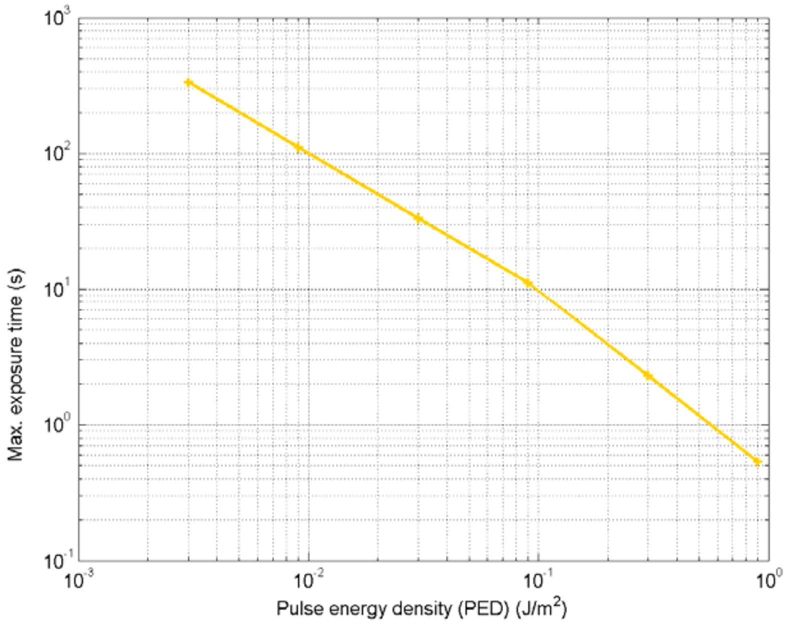

Figure 23 Relation between pulse energy density and maximum allowed exposure time for a 355-nm laser with 30-ps pulses and PRF 10 kHz. MPE for a pulse in the pulse train is 0.9 J/m^2; this is also the curve's right-most value.

To illustrate one type of calculation needed in this mode, consider a PED of 0.03 J/m^2. The PTMI is then (PED) × (PRF) and the PTAED is (PTMI) × (exposure time) = (PED) × (PRF) × (exposure time). The MPE is given by $5.6 \times 10^3 \times (\text{exposure time in seconds})^{0.25}$ J/m^2. Equating the two expressions for PTAED and MPE, and dropping the units of the expressions by assuming basic units everywhere, gives

$$(\text{PED}) \times (\text{PRF}) \times (\text{exposure time}) = 5.6 \times 10^3 \times (\text{exposure time})^{0.25}$$

$$\Leftrightarrow$$

$$(\text{exposure time}) / (\text{exposure time})^{0.25} = 5.6 \times 10^3 / [(\text{PED}) \times (\text{PRF})]$$

$$\Leftrightarrow$$

$$(\text{exposure time})^{0.75} = 5.6 \times 10^3 / [(\text{PED}) \times (\text{PRF})]$$

$$\Leftrightarrow$$

$$\text{exposure time} = \{5.6 \times 10^3 / [(\text{PED}) \times (\text{PRF})]\}^{1/0.75}$$

And so the exposure time for a PED of 0.03 J/m^2 is $\{5.6 \times 10^3 / [(0.3) \times (10 \times 10^3)]\}^{1/0.75} =$ 2.2 (truncated value) with seconds as units.

The PTAED after maximum allowed exposure time is shown in figure 24. Interestingly a lower PED implies a higher PTAED. The explanation is related to the fact that a lower PED means a longer exposure time.

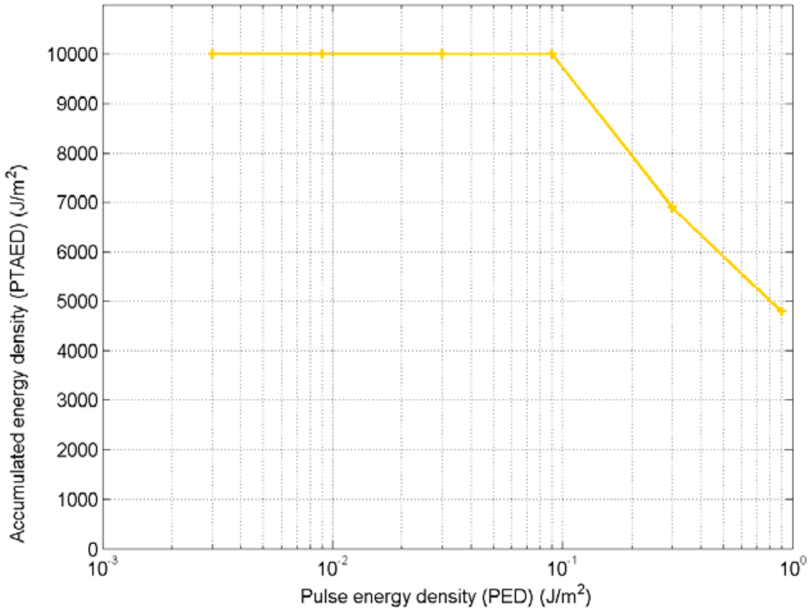

Figure 24 Accumulated energy density after maximum allowed exposure time for a 355-nm laser with 30-ps pulses and PRF 10 kHz. Following the curve to the right, the energy density of a pulse in the pulse train increases. The last value to the right is the MPE (0.9 J/m^2). The accumulated energy density is constant (1×10^4 J/m^2) for pulse energy densities up to 90 mJ/m^2 and then decreases.

The PTAED after exposure times up to 100 s is shown in figure 25. The PED must be decreased to 9 mJ/m^2 or lower, if an exposure time of 100 s should be used.

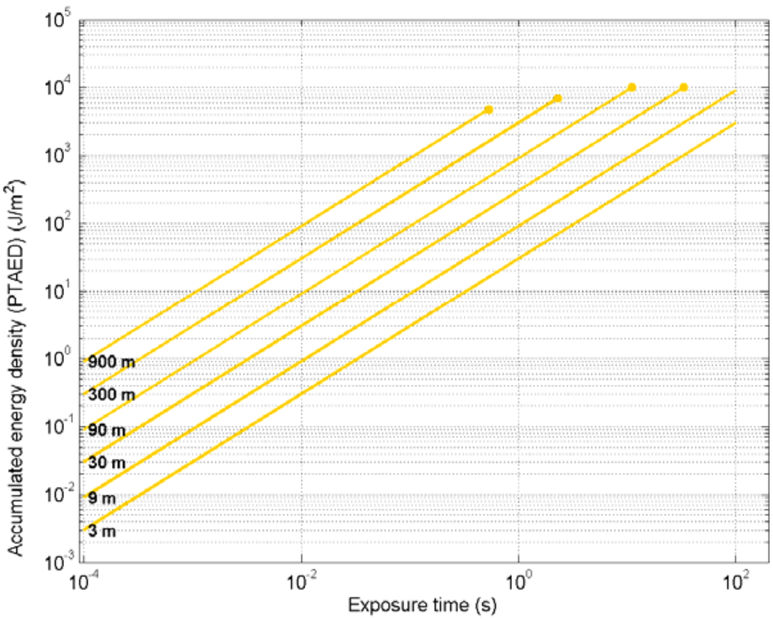

Figure 25 Accumulated energy density (PTAED) after exposure times up to 100 s for a 355-nm laser with 30-ps pulses and PRF 10 kHz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2 with SI prefix 'm' for milli.) Four curves are discontinued earlier than 100 s, because MPE is reached; this is shown by a dot.

3.9 OP 8: Wavelength 355 nm, pulse length 5 ns, PRF 10 kHz

This final operational mode is similar to the last one, only the pulse length is 5 ns. The relation between PED and maximum allowed exposure time (figure 26) is also similar to that mode, but here the PED has a higher MPE (47.09 J/m^2). Therefore the curve continues to higher PEDs and shorter exposure times. The PTAED for different PEDs is shown in figure 27 (for the maximum allowed exposure time) and figure 28 (for exposure times up to 100 s).

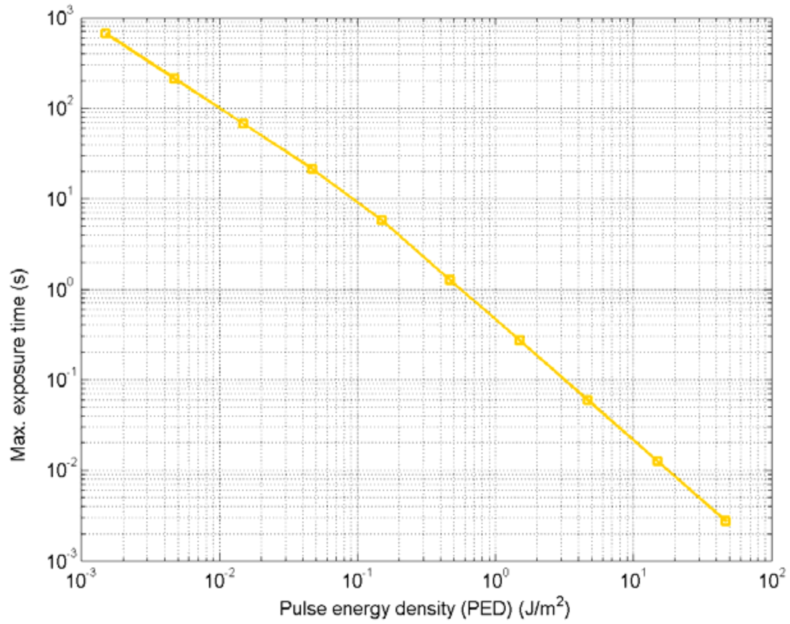

Figure 26 Relation between pulse energy density and maximum allowed exposure time for a 355-nm laser with 5-ns pulses and PRF 10 kHz. MPE for a pulse in the pulse train is 47.09 J/m^2; this is also the curve's right-most value.

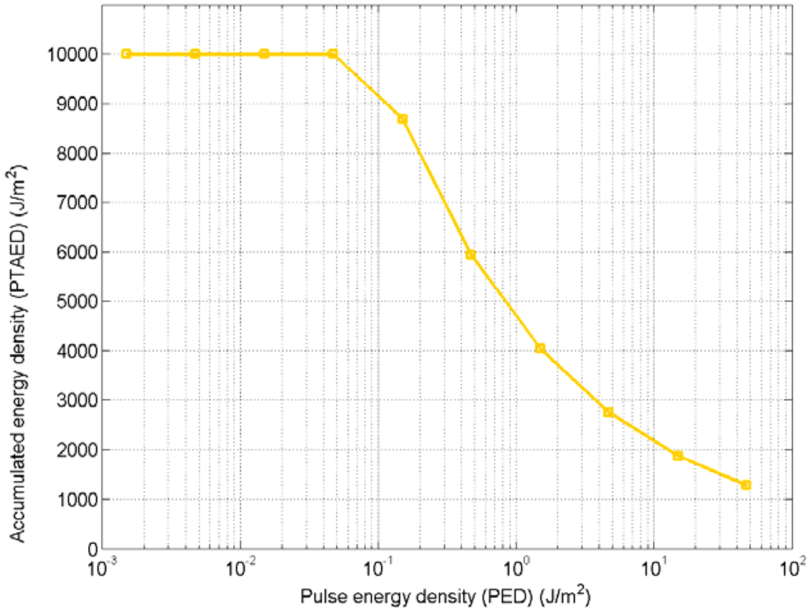

Figure 27 Accumulated energy density after maximum allowed exposure time for a 355-nm laser with 5-ns pulses and PRF 10 kHz. Following the curve to the right, the energy density of a pulse in the pulse train increases. The last value to the right is the MPE (47.09 J/m^2). The accumulated energy density decreases as the pulse energy density increases.

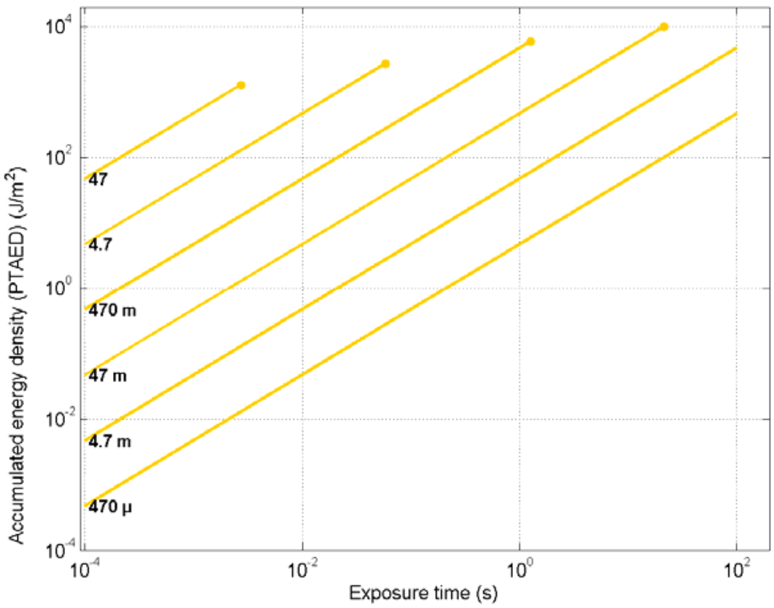

Figure 28 Accumulated energy density (PTAED) after exposure times up to 100 s for a 355-nm laser with 5-ns pulses and PRF 10 kHz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2 with SI prefix ‘m’ for milli and ‘µ’ for micro.) Four curves are discontinued earlier than 100 s, because MPE is reached; this is shown by a dot.

3.10 Maximising accumulated energy

For each operational mode in the last eight sections, we have presented diagrams, from which it is possible to calculate accumulated energy density (PTAED) for certain exposure times and pulse energy densities (PED). Specifically the PTAED after maximum allowed exposure time for different PEDs is presented and also the PTAED in the time interval 0–100 s for a number of different PEDs.

Here we will show what maximum PTAED that theoretically can be achieved in shortest possible time, without violating MPE. The results are shown in figure 29 for the eight operational modes. The horizontal axis shows exposure time from 10^{-4} to 10^2 s (a reasonably long time for an in-field examination). The vertical axis shows, for each operational mode, the accumulated energy density (PTAED) after a certain exposure time.

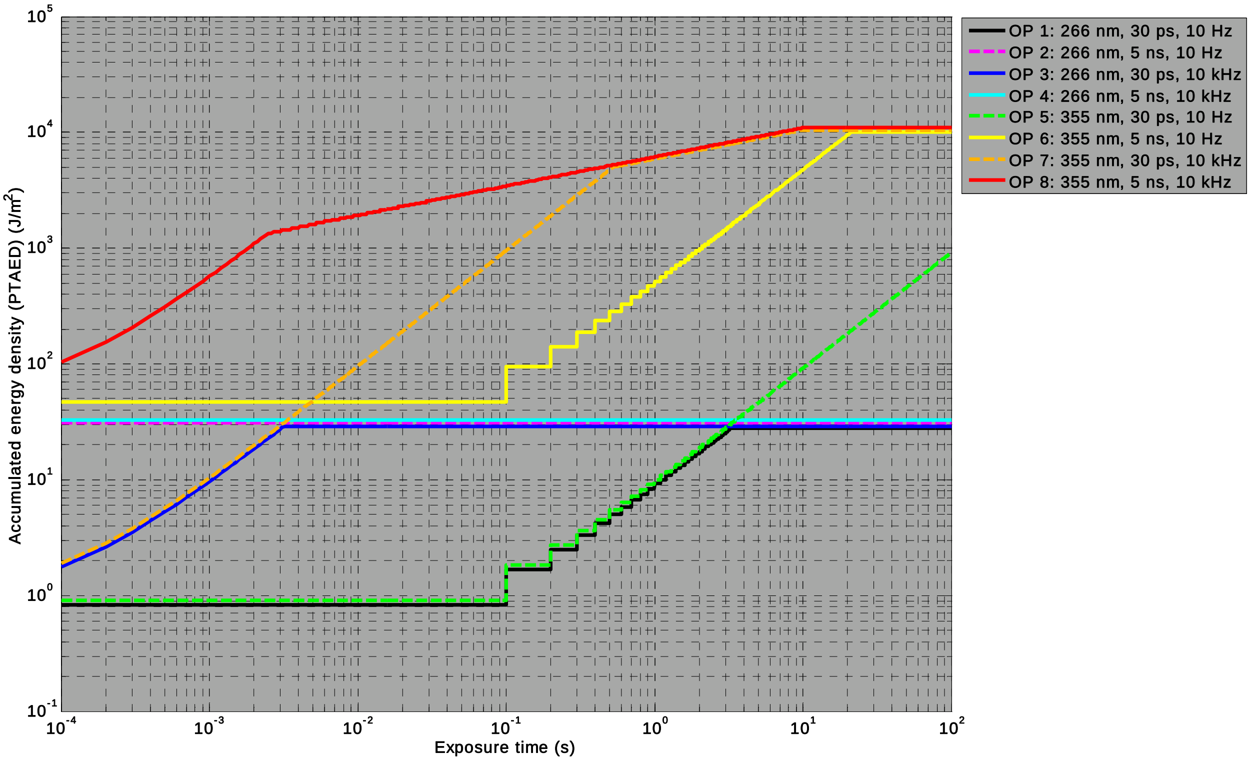

Figure 29 Maximal achievable accumulated energy density (PTAED) as a function of exposure time for each operational mode. This is a theoretical value which presupposes that PRF can be adjusted dynamically. Some of the curves have had their PTAED-values shifted up to 10 % from their true values to avoid cluttering and help the readability. This shift does not affect the figure's value as an orientational tool and the precise calculated values are available from the authors of this report.

Maximum allowed PED is assumed in each mode. Furter the PRFs have their nominal values initially. However, if the accumulated energy density is in danger of exceeding the MPE after some exposure time, individual pulses are 'blocked' and not counted. This lasts as long as needed. In some cases, the MPE increases with time and then new pulses are regarded. The PRF is, so to speak, dynamically adjusted to lower values when necessary. In the figure, this corresponds to the points where a curve bends *downward* from its original direction.

One notable thing in the figure are the curves that start to raise at the exposure time 10^{-1} s. This is because their PRF is 10 Hz and this is the point of time when the second pulse in the pulse train arrive. Another notable thing is the curves that are horizontal lines. These have attained their MPE and all remaining pulses are blocked; in effect they are switched off. For operational modes 2 and 4, this occurs already after the first pulse.

3.11 Example calculation for a specific laser beam

This chapter is closed with an example of the maximum pulse energy and power that could be permitted for a certain laser beam. Assume that the laser is of wavelength 355 nm, emitting 30-ps pulses at the rate 10 Hz. Further assume that 10 s should be used for exposure of the examined object and that the area of the object is 5 cm^2. Also let this be the location where the beam is at its smallest — MPE calculations should be done at the narrowest part of the beam, since the irradiance generally is highest there.

The settings for our example laser correspond to those in operational mode 5, which is described in section 3.6. The maximum allowed pulse energy density (PED) for a pulse in the pulse train is 0.9 J/m^2. This, however, does not set any limit on the exposure time for this operational mode, as described in mentioned section and illustrated by figure 17. Therefore the maximum allowed PED can be used in this case. The maximum allowed mean irradianse of the pulse train (PTMI) is thus (PED) × (PRF) = (0.9 J/m^2) × (10 Hz) = 9 W/m^2. After 10 s the accumulated energy density (PTAED) will be (PTMI) × (exposure time) = (9 W/m^2) × (10 s) = 90 J/m^2.

The smallest area of the actual beam is 5 cm^2 and this should be used for calculating pulse energy and power of the beam: The maximum allowed pulse energy is (PED) × (beam area) = (0.9 J/m^2) × (5 cm^2)= (0.9 J/m^2) × (5×10^{-4} m^2) = 450 μJ. The maximum allowed mean power of the beam is (PTMI) × (beam area) = (9 W/m^2) × (5 cm^2) = (9 W/m^2) × (5×10^{-4} m^2) = 4.5 mW. The maximum accumulated energy on the target will be (PED) × (PRF) × (exposure time) × (beam area) = (PTMI) × (exposure time) × (beam area) = (mean power) × (exposure time) = (4.5 mW) × (10 s) = 45 mJ.

4 Practical aspects of handling the UV laser

4.1 Repeated exposure

The MPEs that are presented in the preceding chapter relate to the exposure of radiation during an 8-hour's working day, according to the standards[13]. The standards further state, that if the exposure is close to the MPE, then further exposure should be avoided for the next 16 hours. Obeying these rules will minimise the risk for acute lesions to eyes or skin. The limits, however, do not guarantee absence from long-term lesions, like skin cancer. Therefore the exposure should always be kept as low as possible.

4.2 Laser beam shaping and irradiation method

As explained earlier, the MPE, PI, PED, PTMI and PTAED are all measures of power or energy per area. Therefore, the geometry of the laser beam and the pulse energy could be varied within wide limits, as long as the relevant MPE is not exceeded.

It might be a good idea to assign such a shape and pulse energy for the laser beam that the MPE is not exceeded at the output of the laser, nor in the propagating laser beam. For example, the beam could be sufficiently wide at the output and then diverging, which minimises the risks. There could be situations where a focused laser beam is used. In this case it is important to consider the beam's focus and the possibility of humans crossing the beam between the laser and the examined object. It is further important to consider the reflection of the beam off an surface or part of the beam not hitting the target and passing on. Even with a diverging beam, reflections in particular should be considered—reflection at a concave surface, a metal surface on a vehicle for instance, could turn the diverging beam into a converging one.

Beside beam shape and pulse energy, the exposure time is of importance. For short times, a higher level could be tolerated, whereas for long times it must be lower. Personnel operating the laser might be exposed to lower values, for instance from scattering and reflections, but during a long time. People in close vicinity to the examined object could be exposed to relatively high values, but for a correspondingly shorter time.

There are both advantages and disadvantages of running the laser at the maximum permitted pulse energy density. For many of the operational modes, the total energy deposited to the examined object will be the same indepentently of pulse energy density after sufficiently long time. Therefore it might be preferable to run the laser at a high energy to shorten the examination time. This will also result in a stronger signal from the object. On the other hand, using a lower energy and averaging the signal by repeating the measurement a number of times might improve the noise reduction, also when the resulting accumulated energy density in the object is the same.

[13] AFS 2009:7, "Artificiell optisk strålning", Arbetsmiljöverket, Stockholm, Sweden, 2009.

5 Conclusions

The three main parameters for the laser system in this project – wavelength, pulse length and pulse repetition frequency (PRF) – all are of importance when determining the maximum pulse energy density (PED) that can be used without exceeding maximum permissible exposure (MPE) and also the accumulated energy density (PTAED) after some exposure time. An overview of these results are presented in table 2. The maximum allowed PED ranges from 0.9 J/m^2 for 30-ps pulses to 47 J/m^2 for some 5-ns pulses. The PTAED that can be achieved after an exposure time of 100 s (typical value for a field measurement) is much higher with the longer wavelength (355 nm) than with the shorter (266 nm); in fact it changes from 30 J/m^2 to 10,000 J/m^2. A high PRF in many cases signifies that MPE is quickly attained and so it is necessary to use a PED much lower than the maximal allowed if the measurement is to be performed with constant PED and PRF during a longer time (typical a few seconds).

Table 2 Laser system performance for the three main parameters wavelength, pulse length and pulse repetition frequency (PRF). Shown is the maximum allowed pulse energy density (PED) and the corresponding maximum allowed exposure time. Also tabulated is the maximum allowed PED if the exposure time should be extended to 100 s and the accumulated energy density (PTAED) after this time.

OP	Wave-length	Pulse length	PRF	Max. allowed PED	Max. allowed exp. time at max. allowed PED	Max. allowed PED for cont. exp. during 100 s	Max. PTAED after exp. time 100 s
1	266 nm	30 ps	10 Hz	0.9 J/m^2	3.3 s	30 mJ/m^2	30 J/m^2
2	266 nm	5 ns	10 Hz	30 J/m^2	0.1 s (one pulse)	30 mJ/m^2	30 J/m^2
3	266 nm	30 ps	10 kHz	0.9 J/m^2	3.3 ms (33 pulses)	30 µJ/m^2	30 J/m^2
4	266 nm	5 ns	10 kHz	30 J/m^2	0.1 ms (one pulse)	30 µJ/m^2	30 J/m^2
5	355 nm	30 ps	10 Hz	0.9 J/m^2	30 ks (without limit)	0.9 J/m^2	900 J/m^2
6	355 nm	5 ns	10 Hz	47 J/m^2	21.2 s	10 J/m^2	10,000 J/m^2
7	355 nm	30 ps	10 kHz	0.9 J/m^2	0.53 s	0.01 J/m^2	10,000 J/m^2
8	355 nm	5 ns	10 kHz	47 J/m^2	2.7 ms	0.01 J/m^2	10,000 J/m^2
9	266 nm	30 ps	1 kHz	0.9 J/m^2	33 ms	300 µJ/m^2	30 J/m^2
10	266 nm	5 ns	1 kHz	30 J/m^2	1 ms	300 µJ/m^2	30 J/m^2
11	355 nm	30 ps	1 kHz	0.9 J/m^2	11 s	0.1 J/m^2	10,000 J/m^2
12	355 nm	5 ns	1 kHz	47 J/m^2	58 ms	0.1 J/m^2	10,000 J/m^2

For short pules, less than 1 ns, the MPE is given as an irradiance (3×10^{10} W/m^2) and we have used this value to calculate the PED of such pulses. If pulses of extreme short duration (femotsecond, fs, or shorter) are to be used, we advice renewed consultation with expertise, since the medical effect of such short pulses are not well known today.

The limiting aperture that is used to calculate irradiance varies from 0.7 to 3.6 mm and we advice to use a beam that is everywhere wider than 3.6 mm to avoid effects that are not considered in this report.

In many cases a beam with even irradiance profile (cross-section) will be used, but it is important to pay attention to the case when the irradiance is varying over the profile. In that case, the part of the profile with highest irradiance will be the most hazardous to eye and skin and the MPE calculations should be based on this specific part of the beam and not the avarage irradiance of the whole beam.

This report is not specifying the power or the size of the cross-section of the laser. Instead maximum allowed power densities (irradiances) and energy densities have been presented and these should be used to balance laser beam area and power in the actual system.

Other important considerations when designing the shape of the laser beam and the beam path include whether the beam is diverging or converging (or collimated) and the risk that humans are irradiated by the beam on its way to the target, at the target or even at the far side of the target. Scattering and especially reflections must be considered – reflections could also change a diverging beam into a converging one. Besides from these considerations there might be others as well.

In addition to beam shape and laser power there are considerations to be made about tactical use and irradiation method. For instance, will the operating personnel be exposed from scattered or reflected radiation and for how long time? Can the examined object be irradiated without risk to other humans or will there be persons close to the object?

If the radiation level approaches MPE during a working day, further exposure should be avoided at least 16 hours. Following this recommendation, acute leisons to human tissue can be avoided. However, there might still be a risk for long-term lesions, and therefore the exposure should always be kept as low as possible.

6 Explanation of abbreviations

Table 3 Explanation of abbreviations used in this report.

ANSI	**American National Standards Institute**
EN	**European standard**
ICNIRP	**The International Commission on Non-Ionizing Radiation Protection**
IEC	**The International Electrochemical Commission**
IED	**improvised explosive device**
MPE	**maximum permissible exposure**; maximum radiation level that could be considered harmless to humans; depends on wavelength and exposure time; presented as an irradiance (W/m^2) or energy density (J/m^2)
OP	**operational mode**; each of the eight studied typical settings of the laser equipment with various wavelength (266 or 355 nm), pulse length (30 ps or 5 ns) and pulse repetition frequency (1 Hz or 1 kHz).
PED	**pulse energy density**; the pulse energy density (energy per area) transmitted by a separate pulse in a pulse train independently of the pulse length
PI	**pulse irradiance**; the irradiance (power per area) of a separate pulse in a pulse train
PRF	**pulse repetition frequency**; the rate at which a pulsed laser emitts laser pulses
PTAED	**pulse train's accumulated energy density**; the summed energy density (energy per area) from a pulse train after a certain exposure time
PTMI	**pulse train mean irradiance**; the time averaged irradiance (power per area) of a pulse train
UV	**ultraviolet;** refering to wavelengths in the interval 10–400 nm, which are not visible to the naked eye and more energetic than visible light.
UV-A	ultraviolett radiation in the wavelength interval 315–400 nm
UV-B	ultraviolett radiation in the wavelength interval 280–315 nm
UV-C	ultraviolett radiation in the wavelength interval 100–280 nm

7 Supplement—Operational modes with PRF 1 kHz

In addition to the operational modes that have been analysed in this report, we have also paid some attention to the case when the pulse repetition frequeny (PRF) is 1 kHz. This value is in between the boundary values 10 Hz and 10 Hz and it is also representative for some real laser systems. In this supplement we therefore presents the results, in the form of diagrams, from calculations with varying wavelengths (266 nm and 355 nm) and pulse lengths (30 ps and 5 ns) but a constant PRF of 1 kHz. The diagrams are of the same type as those that have been shown for the previous evaluated operational modes.

7.1 OP 9: Wavelength 266 nm, pulse length 30 ps, PRF 1 kHz

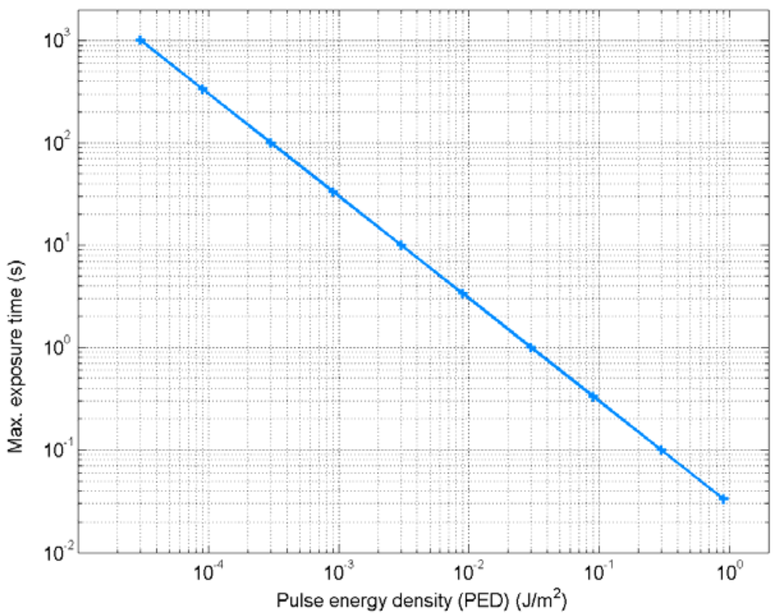

Figure S-1 Relation between pulse energy density and maximum allowed exposure time for a 266-nm laser with 30-ps pulses and PRF 1 kHz. MPE for a pulse in the pulse train is 0.9 J/m^2; this is also the curve's right-most value.

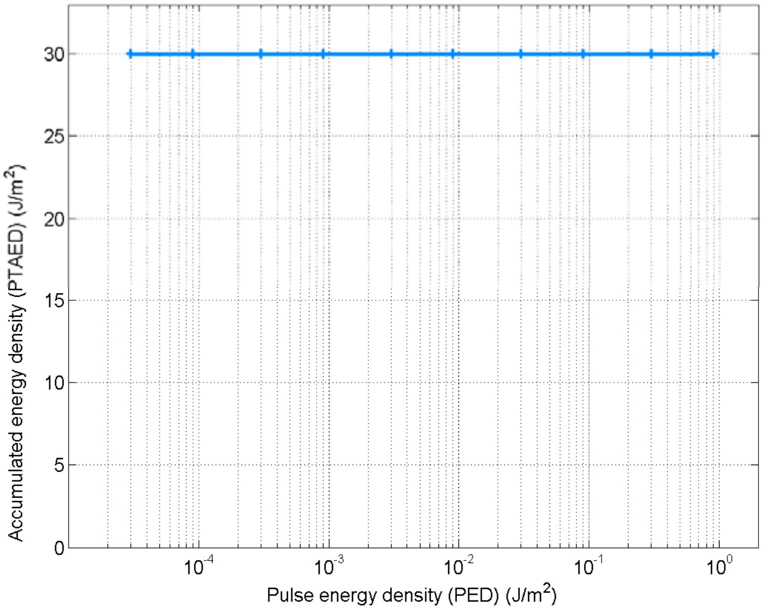

Figure S-2 Accumulated energy density (PTAED) after maximum allowed exposure time for a 266-nm laser with 30-ps pulses and PRF 1 kHz. Following the curve to the right, the energy density of a pulse in the pulse train (PED) increases. The last value to the right is its MPE (0.9 J/m^2). Independently of high or low pulse energy densities, the PTAED is constant (30 J/m^2).

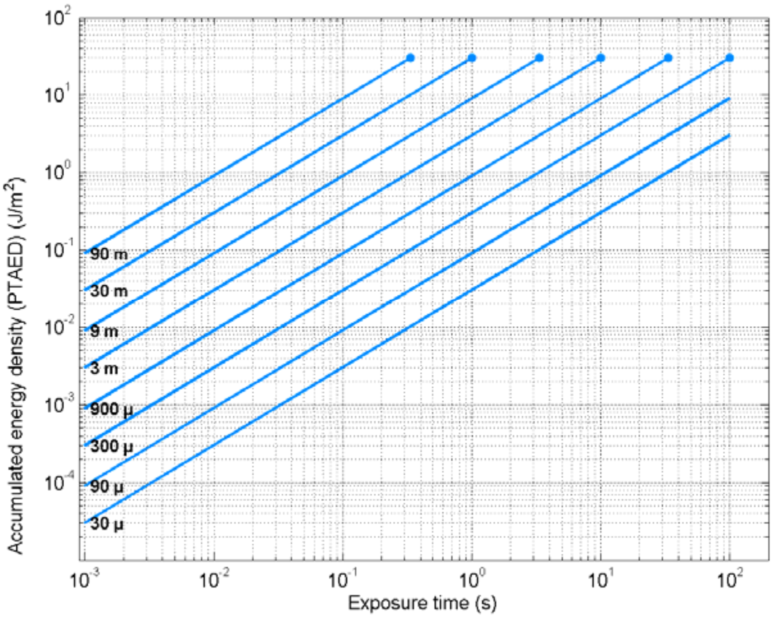

Figure S-3 Accumulated energy density (PTAED) after exposure times up to 100 s for a 266-nm laser with 30-ps pulses and PRF 1 kHz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2 with SI prefix ‘m’ for milli and ‘µ’ for micro.) Six curves are discontinued earlier than 100 s, because MPE is reached; this is shown by a dot.

7.2 OP 10: Wavelength 266 nm, pulse length 5 ns, PRF 1 kHz

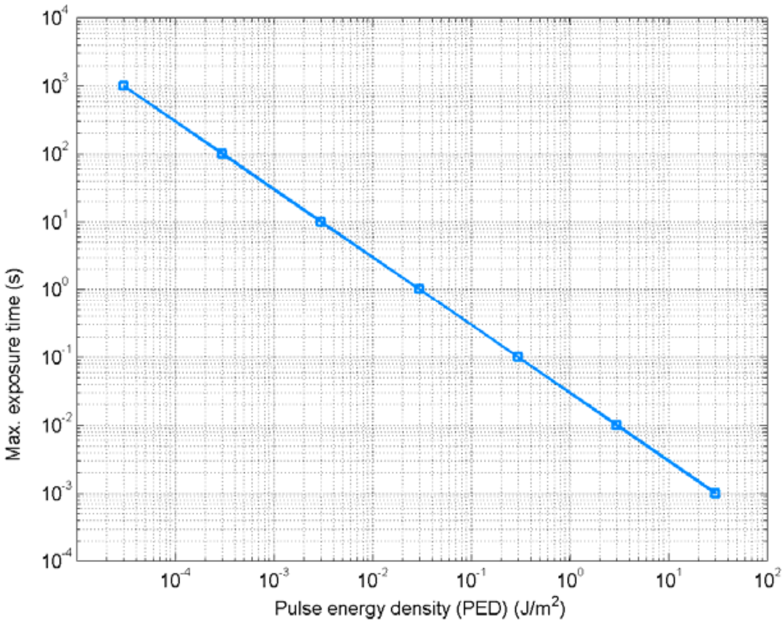

Figure S-4 Relation between pulse energy density and maximum allowed exposure time for a 266-nm laser with 5-ns pulses and PRF 1 kHz. MPE for a pulse in the pulse train is 30 J/m^2; this is also the curve's right-most value.

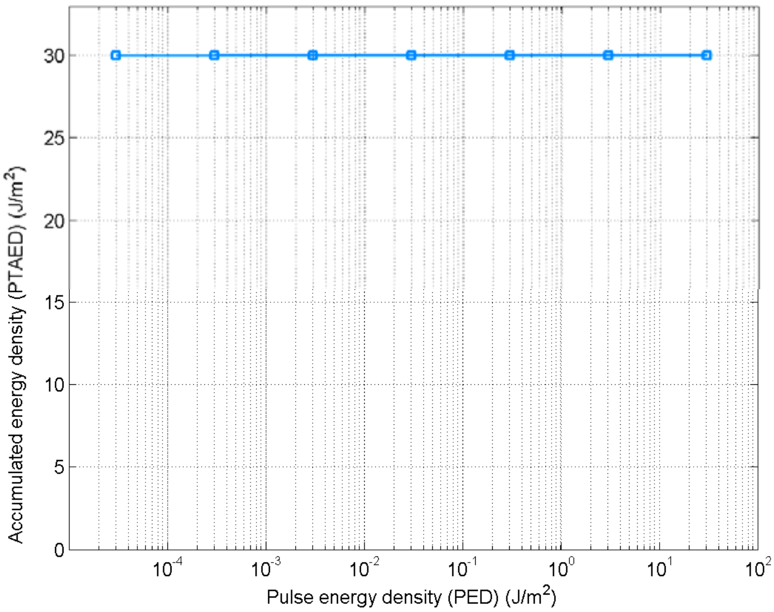

Figure S-5 Accumulated energy density (PTAED) after exposure times for a 266-nm laser with 5-ns pulses and PRF 1 kHz. Following the curve to the right, the energy density of a pulse in the pulse train (PED) increases. The last value to the right is its MPE (30 J/m^2). Independently of high or low pulse energy densities, the PTAED is constant (30 J/m^2).

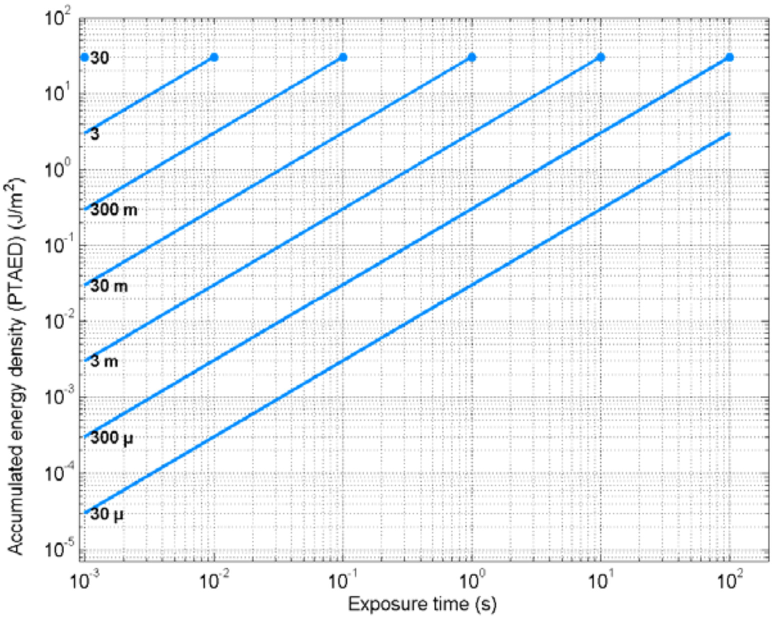

Figure S-6 Accumulated energy density (PTAED) after exposure times up to 100 s for a 266-nm laser with 5-ns pulses and PRF 1 kHz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2 with SI prefix 'm' for milli and 'µ' for micro.) Six curves are discontinued earlier than 100 s, because MPE is reached; this is shown by a dot. Maximal allowed PED is 30 J/m^2. Therefore the upper-left curve, corresponding to this value, is just a point, because only one pulse is allowed.

7.3 OP 11: Wavelength 355 nm, pulse length 30 ps, PRF 1 kHz

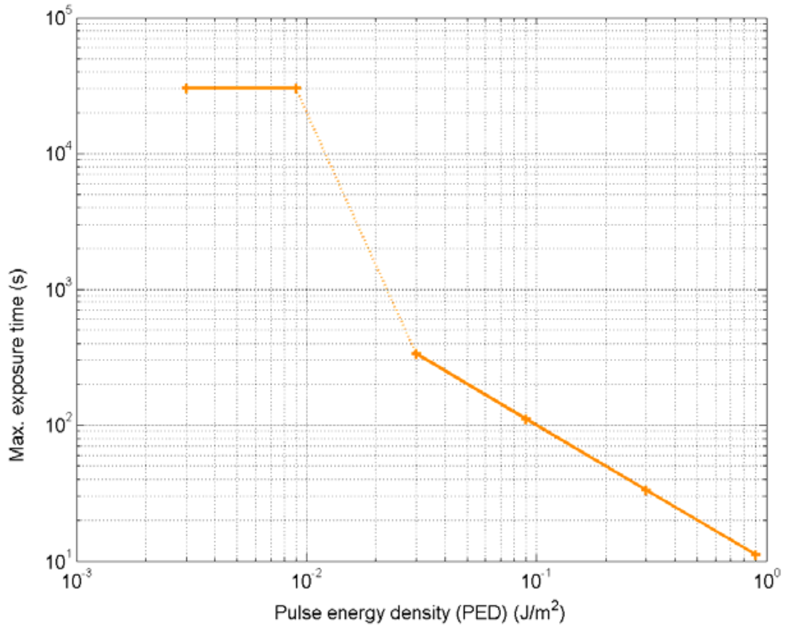

Figure S-7 Relation between pulse energy density and maximum allowed exposure time for a 355-nm laser with 30-ps pulses and PRF 1 kHz. MPE for a pulse in the pulse train is 0.9 J/m^2; this is also the curve's right-most value. The allowed exposure time for pulse energy densities lower than 0.01 J/m^2 is 3×10^4 s, which in practice means without limit, because of low radiation levels.

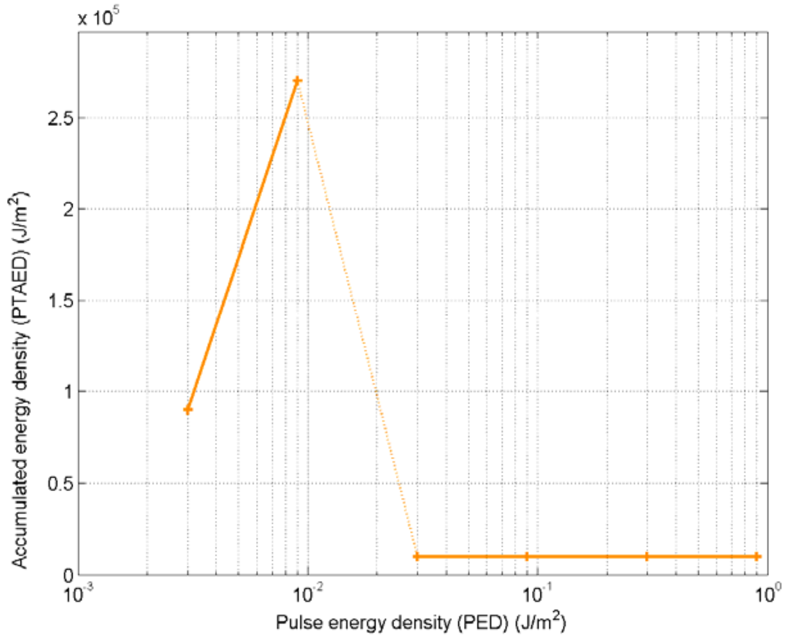

Figure S-8 Accumulated energy density (PTAED) after maximum allowed exposure time for a 355-nm laser with 30-ps pulses and PRF 1 kHz. For pulse energy densities lower than 0.01 J/m^2 the allowed exposure time is 3×10^4 s, which in practice means without limit, because of low radiation levels. Therefore, in this region, the accumulated energy density could increase without bonds, but for this to happen a very long exposure time is needed. For all pulse energy densities higher than 0.01 J/m^2 the accumulated energy density is constant, 10^4 J/m^2. The last value to the right is the MPE (0.9 J/m^2).

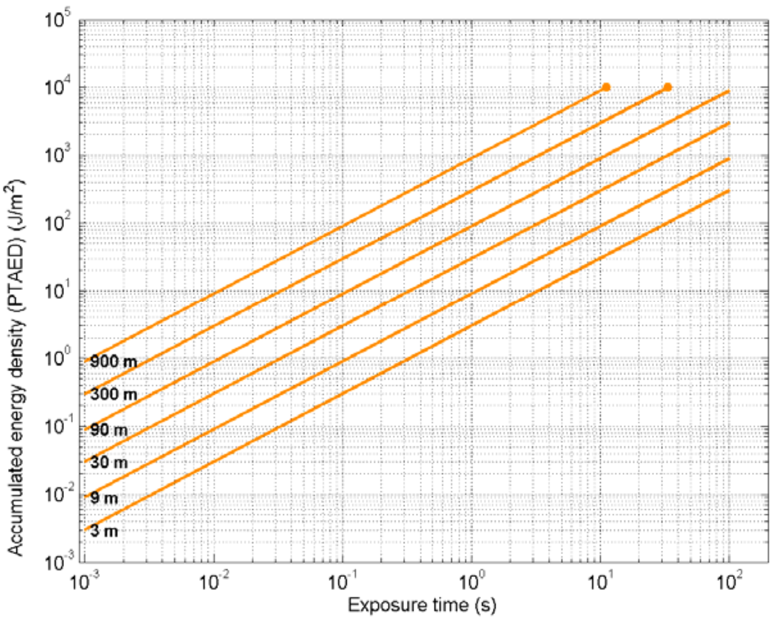

Figure S-9 Accumulated energy density (PTAED) after exposure times up to 100 s for a 355-nm laser with 30-ps pulses and PRF 1 kHz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2 with SI prefix 'm' for milli.) Two curves are discontinued earlier than 100 s, because MPE is reached; this is shown by a dot.

7.4 OP 12: Wavelength 355 nm, pulse length 5 ns, PRF 1 kHz

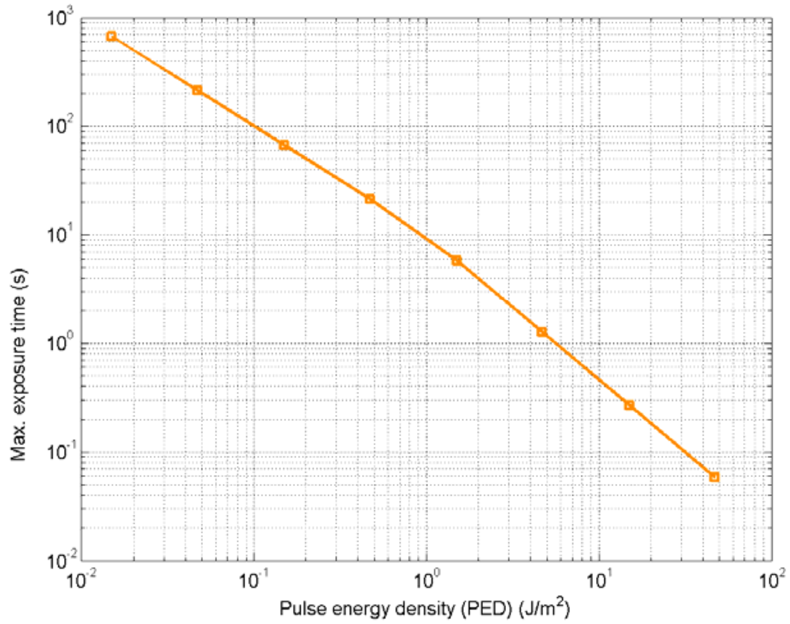

Figure S-10 Relation between pulse energy density and maximum allowed exposure time for a 355-nm laser with 5-ns pulses and PRF 1 kHz. MPE for a pulse in the pulse train is 47.09 J/m^2; this is also the curve's right-most value.

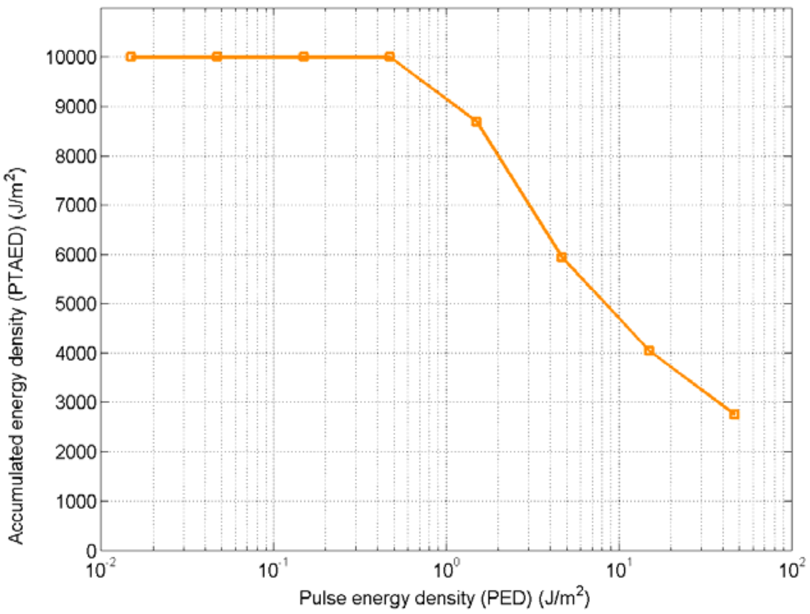

Figure S-11 Accumulated energy density after maximum allowed exposure time for a 355-nm laser with 5-ns pulses and PRF 1 kHz. Following the curve to the right, the energy density of a pulse in the pulse train increases. The last value to the right is the MPE (47.09 J/m^2). The accumulated energy density decreases as the pulse energy density increases.

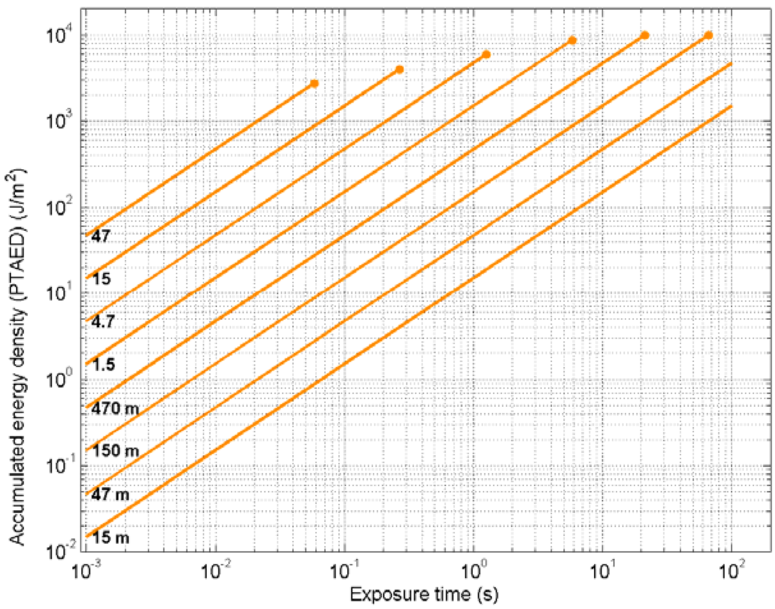

Figure S-12 Accumulated energy density (PTAED) after exposure times up to 100 s for a 355-nm laser with 5-ns pulses and PRF 1 kHz. Each curve represents a certain pulse energy density, as noted in the diagram. (The unit is J/m^2 with SI prefix ‘m’ for milli.) Six curves are discontinued earlier than 100 s, because MPE is reached; this is shown by a dot.