SANDIA REPORT

SAND2003-1005
Unlimited Release
Printed April 2003

Laser Hazard Analysis for Ultra-Fast Sub-Nanosecond, Mode-Locked Near Infrared Lasers Operated with Pulse Repetition Frequencies Above the Critical Frequency

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National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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Laser Hazard Analysis For Ultra-Fast Sub-Nanosecond, Mode-Locked Near Infrared Lasers Operated with Pulse Repetition Frequencies Above the Critical Frequency

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Abstract

Ultra fast, sub-nanosecond (picosecond to femtosecond) duration, laser pulses present unique challenges when performing laser safety analysis involving mode-locked lasers, which operate at pulse repetition frequencies above the critical frequency in the near infrared wavelength bands. Two specific cases are presented, one such case that agrees and one that disagrees with the general rule on critical frequency. The results show that in all cases the appropriate maximum permissible exposure is always the smallest of the values calculated from ANSI rule 1, 2 and 3.

I. Introduction

Ultra fast, sub-nanosecond duration mode locked near infrared (NIR) lasers operated at pulse repetition frequencies (PRF) above the critical frequency (f_c) present some unique challenges when performing laser hazard analysis.

Central to any laser hazard analysis is the determination of the Maximum Permissible Exposure (MPE). The MPE is needed to determine the Allowable Exposure Limit (AEL) and the determination of the minimum optical density (OD_{min}) of the laser safety eyewear. All these values are strongly wavelength dependent.

MPE

The ANSI Standard (Z136.1-2000) presents three rules (section 8.2.3) to follow in the determination of the appropriate MPE for multiple pulsed lasers. For multiple pulse lasers in the wavelength range from 0.4 µm to 1.4 µm the appropriate MPE is **always the lowest** of the MPEs calculated using ANSI Rule 1 through Rule 3 [ANSI Std. Z136.1-2000 (8.2.3.2)].

Critical Frequency

In general the critical frequency is the boundary between ANSI Rule 3 and ANSI Rule 2 domination in the determination of the MPE for pulse duration greater than one nanosecond. For PRFs above this value the MPE determination in ANSI Rule 2-dominant whereas PRFs below this value is ANSI Rule 3-dominant.

Wavelength Range	**Critical Frequency**
$0.4\ \mu m \le \lambda < 1.05\ \mu m$	55 KHz
$1.05\ \mu m \le \lambda < 1.4\ \mu m$	20 KHz

In general for PRFs above the critical frequency (for pulse durations greater than a nanosecond) ANSI Rule 2 should be used to determine the appropriate MPE without the need for calculating the MPEs for ANSI Rule 1 and 3. As will be shown this rule may or may not apply to ultra fast or sub-nanosecond pulses.

Allowable Emission-Exposure Limit

The allowable emission limit (AEL) is the maximum output a laser may have and still remain in its particular hazard class.

The ANSI Standard (Z136.1-2000) presents the AEL as the product of the MPE and the area of the limiting aperture [section 3.2.3.4.1(2)].

From the prospective of the individual exposed to small-beam lasers ($d_o < d_{lim}$) this can be considered an *allowable exposure limit* (AEL). Henceforth the AEL will refer to both the allowable exposure limit as well as the allowable emission limit.

Minimum Optical Density (OD_{min})

Laser safety eyewear must present no greater than a laser hazard Class 1 (for use with invisible laser beams) to the wearer. The laser safety eyewear must possess, at a minimum, an optical density to maintain exposure within the Class 1 hazard regime, although laser safety eyewear may possess an optical density greater than this minimum.

The minimum optical density (OD_{min}) required can be determined either by the Irradiance-MPE method or the Radiance-AEL method.

$$OD_{min} = \log_{10} [E_o / MPE] = \log_{10} [Q_o / AEL]$$

Where;

E_o	Irradiance in J/cm^2.
MPE	Maximum Permissible Exposure in J/cm^2.
Q_o	Radiant Energy in J
AEL	Allowable Exposure Limit in J.

II. Sub-nanosecond Mode-locked YAG Laser Safety Analysis

A. Laser Parameters;

Manufacturer:	Time Bandwidth
Model:	GE-100-VAN-HP-ETL-CLX
<u>Parameters</u>	
Wavelength:	**1.064 μm**
Average Power:	550 mw
Average Pulse Energy:	7.33 nJ
Pulse Duration:	**320 ps** (320 x 10^{-12} seconds)
Pulse Repetition Frequency:	**75 MHz** (75 x 10^{6} sec^{-1})
Exit Beam Diameter:	2.65 mm
Beam Divergence:	1.52 mrad (V), 0.72 mrad (H)

B. MPE Determination

The PRF (75 MHz) of this laser exceeds the critical frequency (20 KHz), but has pulse durations less than one nanosecond. The general critical frequency rule (MPE determined by the application of ANSI Rule 2) may not apply.

The appropriate MPE is **always the smallest** of the MPE values calculated using ANSI rules 1 through ANSI Rule 3.

1. Rule 1: Single Pulse (t = 320 ps)

   No single pulse in a train of pulses shall exceed the single pulse MPE [ANSI Std. Z136.1-2000 (8.2.3 rule 1)].

   The single pulse MPE can be calculated by evaluating the formula presented in *Table 5a* of the ANSI Standard.

$$\mathbf{MPE_{s.p.} = 27\ C_c\ t^{0.75}\ J/cm^2} \qquad \text{for: } 1.05\ \mu m \le \lambda < 1.4\ \mu m,\quad 10^{-11}\ sec \le t < 10^{-9}\ sec$$

The value for IR (1.05 µm to 1.15 µm) wavelength correction factor (C_c) is given in ANSI *Table 6*.

C_c = 1.00 for: $1.05\ \mu m \leq \lambda < 1.15\ \mu m$

$$MPE_{s.p.} = 27\ C_c\ t^{0.75}\ J/cm^2$$

$$= 27\ (320 \times 10^{-12})^{0.75}\ J/cm^2$$

$$MPE_{s.p.} = 2.04\ \times 10^{-6}\ J/cm^2\ ^{*}$$

Rule 2: Average Power MPE (T = 10 seconds)

The exposure from any group of pulses delivered in time T shall not exceed the MPE for time T [ANSI Std. Z136.1-2000 (8.2.3 rule 2)].

$$MPE_{/pulse} = MPE_T / n$$

Where;

$MPE_{/pulse}$	Average per pulse MPE during exposure T.
MPE_T	MPE for duration T.
n	Number of pulses in duration T.

The standard exposure for this wavelength is given in ANSI *Table 4a* as 10 seconds. This is then the value for T_{max}.

$$T = T_{std} = T_{max} = 10\ \text{seconds}$$

The number of laser pulses delivered in this time is the product of the PRF and the exposure duration.

$$n = (PRF)\ (T_{max})$$

$$= (75 \times 10^6\ sec^{-1})\ (10\ sec)$$

$$\mathbf{n = 750 \times 10^6\ pulses}$$

* The results of all calculations are presented to three significant figures except where noted.

The appropriate MPE is calculated by the evaluation of the formulae present in ANSI *Table 5a* for the appropriate wavelength and exposure duration.

Determination of MPE for exposures of 10 seconds to 30,000 second [$MPE_{(10\ sec)}$] from ANSI *Table 5a*:

$\mathbf{MPE_{cw} = 5.0\ C_c \times 10^{-3}\ w/cm^2}$ for: $10\ sec \leq t \leq 3 \times 10^4\ sec$

$$= (5.0)\ (1.0) \times 10^{-3}\ w/cm^2$$

$$MPE_{cw} = 5 \times 10^{-3}\ w/cm^2$$

The $MPE_{(10\ sec)}$ is simply the product of the MPE_{cw} and the T_{max}.

$$MPE_{(10\ sec)} = (MPE_{cw})\ (T_{max})$$

$$= (5 \times 10^{-3}\ w/cm^2)\ (10\ sec)$$

$$MPE_{(10\ sec)} = 50 \times 10^{-3}\ J/cm^2$$

The appropriate per pulse MPE for the standard 10-second exposure.

$$MPE/pulse = MPE_{(10\ sec)} / n$$

$$= (50 \times 10^{-3}\ J/cm^2) / 750 \times 10^6$$

$$\mathbf{MPE/pulse = 66.7 \times 10^{-12}\ J/cm^2}$$

2. Rule 3: Multiple Pulse ($t_{min} = 50\ \mu sec$)

   Rule 3 protects against sub-threshold pulse cumulative thermal injury [ANSI Std. Z136.1-2000 (8.2.3 rule 3)]: "The exposure for any single pulse within a group of pulses (each separated by at least t_{min}) shall not exceed the single-pulse MPE for ($t > t_{min}$) multiplied by a multiple-pulse correction factor C_p."

$$MPE_{m.p.} = C_p \, MPE_{s.p.\text{-thermal}}$$

The multiple pulse correction-factor from ANSI *Table 6*:

$$C_p = n^{-0.25}$$

Rule 3 applies only to MPEs for **thermal injury**, where all laser pulses delivered in less than t_{min} are considered as a single pulse [ANSI Std. Z136.1-2000 (8.2.3 rule 3)].

"t_{min}" is the largest exposure time for which the single pulse MPE is equal to the MPE for a 1 nanosecond pulse. The value of t_{min} for a mode-locked YAG laser (λ = 1.064 µm) is 50 µsec [ANSI Std. 136.1-2000 (*Table 5a*)].

The pulse separation time (t_s) for a mode-locked YAG operating at a PRF of 75 MHz is as follows.

$$t_s = 1/\,75 \times 10^6 \text{ sec}^{-1}$$

$$t_s = 13.3 \times 10^{-9} \text{ sec}$$

In this case, the pulse separation is much less than t_{min} therefore all the laser pulses delivered in any "50-µsec-period" are to be considered as a single composite pulse of: 50-µsec duration.

The number of t_{min} composite pulses (N_{min}) that occur in the standard 10-second exposure (T_{max}) is as follows.

$$N_{min} = T_{max} \,/\, t_{min}$$

$$= 10 \text{ sec} \,/\, 50 \times 10^{-6} \text{ sec}$$

$$N_{min} = 200 \times 10^3 \text{ pulses}$$

The multiple pulse correction-factor for t_{min} exposure is:

$$C_{p(min)} = (N_{min})^{-0.25}$$

$$= (200 \times 10^3)^{-0.25}$$

$$C_{p(min)} = 0.0473$$

The formula for the MPE for a 1-nanosecond pulse (also valid for 50-microsecond as well) is presented in *Table 5a* of the ANSI Standard.

$\mathbf{MPE_{(1ns)} = 5.0\ C_c \times 10^{-6}\ J/cm^2}$ for: $1.05\ \mu m \leq \lambda < 1.4\ \mu m$
10^{-9} sec $\leq t < 50 \times 10^{-6}$ sec

The IR wavelength correction factor (C_c) from Table 6 of the ANSI Standard:

$\mathbf{C_c = 1.00}$ for $1.05\ \mu m \leq \lambda < 1.15\ \mu m$

$$MPE_{(1ns)} = 5 \times 10^{-6}\ J/cm^2$$

The "t_{min}" multiple-pulse MPE is calculated as follows.

$$MPE_{(tmin)} = Cp_{(min)}\ MPE_{(1ns)}$$

$$= (0.0473)\ (5 \times 10^{-6}\ J/cm^2)$$

$$MPE_{(tmin)} = 236 \times 10^{-9}\ J/cm^2$$

The $MPE_{(tmin)}$ is distributive over the number the pulses (n_{min}) delivered in t_{min}. The number of pulses delivered in t_{min} is the product of the PRF and t_{min}.

$$n_{min} = (PRF)\ (t_{min})$$

$$= (75 \times 10^6\ \text{pulses-sec}^{-1})\ (50 \times 10^{-6}\ \text{sec})$$

$$n_{min} = 3.75 \times 10^3\ \text{pulses}$$

The per pulse MPE ($MPE_{/pulse}$) can be expressed as:

$$MPE_{/pulse} = MPE_{(tmin)} / n_{min}$$

$$= (236 \times 10^{-9} \ J/cm^2) / (3.75 \times 10^3 \text{ pulses})$$

$$\mathbf{MPE_{/pulse} = 62.9 \times 10^{-12} \ J/cm^2}$$

The appropriate MPE is always the smallest of the MPEs calculated from ANSI Rule 1 through Rule 3. ANSI Rule-3 provides the smallest MPE in this case contrary to the general rule for PRFs operating above the critical frequency.

3. Summary Table

TABLE 1

Appropriate MPE for
Sub-nanosecond, 75 MHz Mode-locked YAG

ANSI Rule	MPE (J/cm^2)	Comment
1	2.04×10^{-6}	
2	66.7×10^{-12}	
3	$\mathbf{62.9 \times 10^{-12}}$	Smallest

Contrary to the general rule for lasers operating at PRF above the critical frequency **ANSI Rule 2 does not apply**. In this particular case ANSI **Rule 3** yields the appropriate per pulse MPE for this laser.

C. AEL Determination

The AEL is the product of the appropriate MPE and the area of the limiting aperture (A_{lim}).

$$AEL = (MPE)\ (A_{lim})$$

$$= (MPE)\ [\pi\ (d_{lim})^2 / 4]$$

The limiting aperture for this laser is given in ANSI *Table 8* as 7-mm.

$$AEL = \pi\ (62.9 \times 10^{-12}\ J/cm^2)\ (0.7\ cm)^2 / 4$$

$$AEL = 24.2 \times 10^{-12}\ J$$

D. OD_{min} Determination

The average radiant pulse output (Q_o) can be determined from the average radiant output power (Φ_o) and the PRF.

$$Q_o = \Phi_o / PRF$$

$$= 0.55\ watts / 75 \times 10^6\ sec^{-1}$$

$$Q_o = 7.33 \times 10^{-9}\ J$$

The minimum optical density for the laser safety eyewear can be determined from the radiant pulse energy output (Q_o) of a small beam laser ($d_o < d_{lim}$) and the AEL.

$$OD_{min} = \log_{10} [Q_o / AEL]$$

$$= \log_{10} [7.33 \times 10^{-9}\ J / 24.2 \times 10^{-12}\ J]$$

$$= \log_{10} [302]$$

$$\mathbf{OD_{min} = 2.48}$$

III. Sub-picosecond Mode-locked Ti-Sapphire Laser Safety Analysis

A. Laser Parameters

Manufacturer:	Coherent
Model:	MIRA 900
Parameters	
Wavelength:	**800 nm**
Average Power:	1 watt
Average Pulse Energy:	13.2 nJ
Pulse Duration:	**100 fs** (100 x 10^{-15} seconds)
Pulse Repetition Frequency:	**76 MHz** (76 x 10^{6} sec^{-1})
Exit Beam Diameter:	< 3 mm

B. MPE Determination

The appropriate MPE for a repetitively pulsed laser is always the smallest of the MPEs calculated using ANSI Rule 1 through ANSI Rule 3.

The general rule for lasers, which operate with PRFs above the critical frequency, indicates that ANSI Rule 2 should derive the appropriate MPE.

1. Rule 1: Single Pulse (t = 100 fs)

   The single pulse MPE can be calculated by evaluating the formula presented in *Table 5a* of the ANSI Standard.

$$\mathbf{MPE_{s.p.} = 1.5\, C_A \times 10^{-8}\ J/cm^2}$$ for: $0.7\ \mu m \leq \lambda < 1.05\ \mu m$

$10^{-13}\ sec \leq t < 10^{-11}\ sec$

The NIR wavelength correction factor ($C_{A)}$ from ANSI *Table 6* can be evaluated as follows:

$$\mathbf{C_A = 10^{2\,(\lambda - 0.7)}} \qquad \text{for: } 0.7\ \mu m \le \lambda < 1.05\ \mu m$$

$$= 10^{2\,(0.8 - 0.7)}$$

$$= 10^{(0.2)}$$

$$\mathbf{C_A = 1.59}$$

Applied to the form presented above and evaluated yields:

$$MPE_{s.p.} = (1.5)\,(1.59) \times 10^{-8}\ J/cm^2$$

$$MPE_{s.p.} = 23.8 \times 10^{-9}\ J/cm^2$$

2. Rule 2: Average Power MPE (T = 10 seconds)

   The standard exposure (T_{std}) for NIR lasers is given in ANSI *Table 4a* as 10 seconds.

$$MPE_{/pulse} = MPE_T / n \qquad \text{ANSI Z136.1-2000 (8.2.3 rule 2)}$$

For:

$$T = T_{std} = 10 \text{ seconds}$$

The MPE for exposures of 10 seconds to 30,000 seconds can be determined from ANSI *Table 5a*.

$$MPE_{(cw)} = C_A \times 10^{-3} \text{ watts/ cm}^2 \qquad \text{for: } 10 \text{ sec} \le T \le 30{,}000 \text{ sec}$$

$$MPE_{(cw)} = 1.59 \times 10^{-3} \text{ watts/cm}^2$$

Evaluated for a 10-second exposure in J/cm^2.

$$MPE_{(10\ sec)} = MPE_{(cw)}\ T_{std}$$

$$= (1.59 \times 10^{-3}\ watts/\ cm^2)\ (10\ sec)$$

$$\mathbf{MPE_{(10\ sec)} = 15.9 \times 10^{-3}\ J/\ cm^2}$$

The number of laser pulses delivered in this standard exposure can be calculated as:

$$n = (PRF)\ (T_{std})$$

$$= (76 \times 10^6\ pulses\text{-}sec^{-1})\ (10\ sec)$$

$$\mathbf{n = 760 \times 10^6\ pulses}$$

The per pulse MPE for rule 2 is:

$$MPE_{/pulse} = MPE_{(10\ sec)}\ /\ n$$

$$= [15.9 \times 10^{-3}\ J/\ cm^2\ ]\ /\ [760 \times 10^6\ pulses]$$

$$\mathbf{MPE_{/pulse} = 20.9 \times 10^{-12}\ J/\ cm^2}$$

3. Rule 3: Multiple Pulse (18 μsec)

   Rule 3 protects against sub-threshold pulse cumulative thermal injury [ANSI Std. Z136.1-2000 (8.2.3 rule 3)]: "The exposure for any single pulse within a group of pulses (each separated by at least t_{min}) shall not exceed the single-pulse MPE for ($t > t_{min}$) multiplied by a multiple-pulse correction factor C_p."

$$\mathbf{MPE_{m.p.} = C_p\ MPE_{s.p.thermal}}$$

The multiple pulse correction-factor from ANSI *Table 6*:

$$\mathbf{C_p = n^{-0.25}}$$

ANSI Rule 3 applies only to MPEs for **thermal injury**, where all laser pulses delivered in less than t_{min} are considered as a single pulse [ANSI Std. Z136.1-2000 (8.2.3 rule 3)]. The radiant energy of a t_{min}-pulse is the sum of the radiant energy in each of the individual pulses delivered in t_{min}.

Recall "t_{min}" is largest exposure time for which the single pulse MPE is equal to the MPE for a 1-nanosecond pulse. The value of t_{min} for a mode-locked Ti-Sapphire laser (λ = 800 nm) is 18 µsec [ANSI Std. 136.1-2000 (*Table 5a*)].

The pulse separation time (t_s) for a mode-locked Ti-Sapphire laser operating at a PRF of 76 MHz is as follows.

$$t_s = 1/\ 76 \times 10^6 \text{ sec}^{-1}$$

$$t_s = 13.2 \times 10^{-9} \text{ sec}$$

In this case, the pulse separation is much less than t_{min} therefore all the laser pulses delivered in any 18-µsec-period are to be considered as a single composite pulse of 18-µsec-duration.

The number of t_{min} composite pulses (N_{min}) that occur in the standard 10-second exposure (T_{max}) is as follows.

$$N_{min} = T_{max} / t_{min}$$

$$= 10 \text{ sec} / 18 \times 10^{-6} \text{ sec}$$

$$N_{min} = 556 \times 10^3 \text{ pulses}$$

The multiple pulse correction-factor for t_{min} exposure is:

$$C_{p(min)} = (N_{min})^{-0.25}$$

$$= (556 \times 10^3)^{-0.25}$$

$$C_{p(min)} = 0.0366$$

The formula for the MPE for a 1-nanosecond pulse is presented in *Table 5a* of the ANSI Standard.

$$MPE_{(1ns)} = 5.0\ C_A \times 10^{-7}\ \text{J/cm}^2$$ for: $0.7\ \mu m \leq \lambda < 1.05\ \mu m$, $10^{-9}\ \text{sec} \leq t < 18 \times 10^{-6}\ \text{sec}$

The wavelength correction factor (C_A) from Table 6 of the ANSI Standard has been evaluated page 15 (shown to 3 significant figures):

$$C_A = 1.59$$

The MPE for t_{min}-pulse is as follows.

$$MPE_{tmin} = (C_{pmin})[(MPE_{(1\ ns)}]$$

$$= (0.0366)\ [(1.59)(5.0 \times 10^{-7}\ \text{J/cm}^2)]$$

$$MPE_{tmin} = 29.0 \times 10^{-9}\ \text{J/cm}^2$$

The MPE for a t_{min} period is distributed over the individual pulses in the t_{min} pulse group. The number of individual pulses in a t_{min} pulse group at a PRF of 76 MHz is as follows.

$$n_{min} = (PRF)\ (t_{min})$$

$$= (76 \times 10^6\ \text{pulses-sec}^{-1})(18 \times 10^{-6}\ \text{sec})$$

$$n_{min} = 1.37 \times 10^3\ \text{pulses}$$

The per pulse MPE for Rule 3 is as follows:

$$MPE_{/pulse} = MPE_{tmin} / n_{min}$$

$$= (29.0 \times 10^{-9}\ J/cm^2) / 1.37 \times 10^3 \text{ pulses}$$

$$\mathbf{MPE_{/pulse} = 21.2 \times 10^{-12}\ J/cm^2}$$

4. Summary Table

<u>TABLE 2</u>

Appropriate MPE for
Sub-picosecond, 76 MHz Mode-locked Ti-Sapphire Laser

ANSI Rule	**MPE (J/cm^2)**	**Comment**
1	23.8×10^{-9}	
2	$\mathbf{20.9 \times 10^{-12}}$	**Smallest**
3	21.2×10^{-12}	

In this case the general rule for lasers operating above the critical frequency does applies and ANSI Rule 2 does, in fact, yields the appropriate per pulse MPE for this laser.

C. AEL Determination

The AEL is the product of the appropriate MPE and the area of the limiting aperture (A_{lim}).

$$AEL = (MPE)\,(A_{lim})$$

$$= (MPE)\,[\pi\,(d_{lim})^2 / 4]$$

The limiting aperture for this laser is given in ANSI *Table 8* as 7-mm.

$$AEL = \pi\,(20.9 \times 10^{-12}\ J/cm^2)\,(0.7\ cm)^2 / 4$$

$$AEL = 8.04 \times 10^{-12}\ J$$

D. OD_{min} Determination

The average radiant pulse output (Q_o) can be determined from the average radiant output power (Φ_o) and the PRF.

$$Q_o = \Phi_o / PRF$$

$$= 1\ watt / 76 \times 10^6\ sec^{-1}$$

$$Q_o = 13.2 \times 10^{-9}\ J$$

The minimum optical density for the laser safety eyewear can be determined from the radiant pulse energy output (Q_o) and the AEL.

$$OD_{min} = \log_{10}\,[Q_o / AEL]$$

$$= \log_{10}\,[13.2 \times 10^{-9}\ J / 8.04 \times 10^{-12}\ J]$$

$$= \log_{10}\,[1.64 \times 10^3]$$

$$\mathbf{OD_{min} = 3.21}$$

IV. Conclusion

The general rule pertaining to lasers operating with PRFs above the critical frequency states that the appropriate MPE should be derived from ANSI rule 2 for pulse duration of one nanosecond or greater. For sub-nanosecond pulse widths this rule may or may not apply. The MPE should always be calculated for all three ANSI rules with the smallest value always to be the appropriate MPE.

V. References

ANSI Standard Z136.1-2000: for Safe Use of Lasers, Published by the Laser Institute of America.

VI. Symbols And Abbreviations

AEL	Allowable (emission or exposure) limit.
ANSI	American National Standards Institute.
C_c	Wavelength correction factor (ANSI *Table 6*).
cm	Centimeter (10^{-2} meters).
C_p	Multiple pulse correction factor.
$C_{p(min)}$	Multiple pulse correction factor for pulse groups of t_{min} duration.
cw	Continuous wave.
d_{lim}	Diameter of limiting aperture.
d_o	Exit diameter of laser.
f_c	Critical frequency.
IR	Infrared.
J	Joules (unit of energy).
KHz	Kilo-hertz (10^3 sec^{-1}).
MHz	Mega-hertz (10^6 sec^{-1}).
MPE	Maximum permissible exposure.
MPE_{cw}	The cw MPE.
$MPE_{m.p.}$	Multiple pulse MPE
$MPE_{s.p.}$	Single pulse MPE.
$MPE_{s.p.thermal}$	Single pulse MPE for the thermal limit.
MPE_T	MPE for duration T.
$MPE_{(tmin)}$	MPE for a t_{min} exposure.
$MPE_{/pulse}$	Per pulse MPE.
$MPE_{(1ns)}$	The MPE for a 1-nanosecond duration pulse.
$MPE_{(10sec)}$	MPE for a 10-second exposure.
$MPE_{(<10sec)}$	MPE for less than a 10-second exposure.
$MPE_{(>10sec)}$	MPE for greater than a 10-second exposure.
mw	Milliwatts (10^{-3} watts).
n	Number of pulses.

NIR	Near Infrared
nJ	Nano-joules (10^{-9} Joules)
N_{min}	The number of t_{min} duration groups in the exposure.
n_{min}	The number of pulses delivered in a t_{min} period.
ns	Nano-second (10^{-9} seconds)
OD_{min}	Minimum optical density of laser safety eyewear
PRF	Pulse repetition frequency
ps	Pico-second (10^{-12} seconds)
Q_o	Radiant energy output (pulse energy).
t	Pulse duration
T	Exposure period
T_{max}	Maximum exposure
t_{min}	Maximum duration for which the MPE is the same as for 1 ns
t_s	The time between pulses (pulse separation time).
T_{std}	Standard exposure listed in ANSI *Table 4a*.
YAG	Yttrium aluminum garnet crystal
λ	Wavelength
Φ_o	Radiant power output (average power).
μm	Micrometer (10^{-6} meters)

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