Laser Safety: Corporate Responsibility, Training and Hazard Analysis

Bill G. Janssen, CLSO
Product Manager, LASERVISION USA
ST. Paul, MN

Laser Safety

Lasers are increasingly being used in a variety of workplace settings and their unique properties, physical environments and numerous applications present both direct beam exposure and non-beam hazards. Understanding and controlling hazards associated with laser systems is the responsibility of the designated Laser Safety Officer (LSO) or safety engineer to minimize their potential for causing injury, promote workplace safety and be in compliance with local, state and federal requirements. This overview will acquaint safety engineers with laser operation, hazard evaluation, recommended training, regulatory requirements, workplace safety audits and serve as a resource for developing appropriate engineering, administrative and procedural control measures.

Laser Operation

Unlike conventional light sources lasers produce highly collimated, coherent and monochromatic beams of light by the process of light amplification by the stimulated emission of radiation (LASER). Lasers produce light (non-ionizing radiation) that is represented on the electromagnetic spectrum between ultraviolet at 180nm and far infrared at 10^3µm. Visible light is generally considered to be between 400-to-700nm wavelengths. Conditions necessary for stimulated emission of radiation to occur require that energy first be imparted to a suitable collection of atoms, ions or molecules known as an active medium. In typical gas laser systems for example this energy transfer usually results from direct currents passing through or RF signals across the laser tube whereas solid state and tunable liquid dye lasers are usually optically excited using flashlamps or light from other laser sources. Semiconductor lasers with their extremely high electrical efficiencies are essentially P-N junction diodes that emit light as a result of current passing through the device.

As a result of intense pulsed or continuous “pumping” or “excitation” absorbed energy raises the collective energy levels of the active medium well above their atomic ground state to upper level metastable states that have comparatively longer atomic lifetimes. Without the benefit of an outside influence or stimulus these charged atoms, ions or molecules will spontaneously decay and return to lower energy levels randomly emitting acquired energy in the form of photons and/or other radiationless transitions of energy during their downward transitions to atomic ground states.

Under very precise and controlled conditions within a laser cavity where the majority of atoms, ions or molecules within the active medium are charged to higher energy levels (i.e., population inversion) there is a higher probability that stimulated emission of radiation will prevail over spontaneous emission. During active pumping or excitation and while a population inversion exists, photons of emitted light become the stimulus for the premature release of potential energy stored in the highly charged active medium. This occurs when photons of light are emitted along and become trapped within the optical axis of a resonant cavity resulting in many successive passes through the charged active medium at the speed of light (3×10^8 meters/second). The stimulated photons are unique in that they are identical to the incident photons in wavelength, frequency and direction. Amplification of light occurs within the laser cavity or optical resonator via stimulated emission until the inherent optical gain of the system exceeds the combined inherent losses to produce a beam of light which emerges through a partially transmissive mirror or output coupler.

To increase the probability that stimulated emission of radiation occurs all lasers and laser systems must have the following major components:

- A suitable active medium (gas, liquid, solid or semiconductor) to produce the desired spectral or optical output characteristics
- An excitation mechanism with sufficient energy and efficiency to create and sustain a population inversion within the active medium
- An optical feedback mechanism which redirects laser energy through the active medium increasing the likelihood of additional collisions with other excited atoms, ions or molecules within the active medium. Comprised of two mirrors (three or more in many laser systems) that are parallel to each other and perpendicular to the optical axis they also sustain standing optical waves
- An output coupler (i.e., partially transmissive dielectric coated optical component) that allows energy to emerge from the laser as a collimated beam of light

By utilizing special intra cavity electro or acousto-optical components (Q-switches) and appropriate optical pulsing techniques it is possible to generate megawatt and terawatt pulses of light from some solid state lasers. Q-switches act as optical shutters that are closed during the initial few milli, micro or nanoseconds of the optical excitation pulse. In this condition the feedback mechanism of the laser (resonant cavity) is effectively blocked from the system. After a maximum population inversion is established within the active medium the Q-switch opens providing a feedback mechanism which reintroduces photons back into the charged active medium. Rapid depletion or de-excitation of the excited active medium results from stimulated emission to produce extremely short duration ($10^{-12} \sim 10^{-15}$ seconds possible) high peak power pulses of light potentially exceeding several Terawatts (10^{12} watts).

Another modification of some solid state lasers is the addition of an extra-cavity second harmonic generator (SHG). The Nd:YAG laser for example produces an invisible infrared output at 1064nm and has a corresponding frequency of 2.8×10^{14} Hz. During ‘quasi-continuous’ operation the Nd:YAG laser energy is made to pass through the second harmonic generator KTP crystal (potassium, titanyl, phosphate) or some other SHG component resulting in a portion of the energy being converted into a harmonic of the original 1064nm frequency. In the case of the frequency doubled Nd:YAG laser the result is a visible lime green laser beam (532nm) at half the original wavelength and at twice the original frequency.

While laser systems are usually named for their active medium or some other unique optical characteristic (i.e., CO_2, excimer, ND:YAG, KTP, argon$^+$, Q-switched, mode-locked, tunable dye, etc.) they all produce relatively coherent, collimated and monochromatic light. Coherent light refers to property of all the individual photon wavelengths being in-phase both spatially and temporally. The practical significance of coherence is that their amplitudes are additive and produce higher power or energy levels much like in-phase sine waves do when viewed on an oscilloscope. Collimated refers to the pencil thin, low divergence nature of laser light which allows for extremely precise focusing capabilities and higher power and energy densities. Monochromatic refers to the narrow spectral bandwidth or single wavelength nature of laser light. While useful in many practical applications these properties of laser light can also create hazardous situations at great distances from their source.

LASER AND NON-BEAM HAZARDS

Lasers are complex electro-mechanical-optical devices capable of producing UV, visible and invisible infrared light that have the potential to cause injury to various structures of the eye and skin as well as fire hazards. A laser hazard classification system has been devised based on accessible laser radiation with Class 1 lasers being least hazardous (exempt from any control measures) to Class 4 systems being capable of causing personal injury and/or fire hazards by either the direct or reflected beam or its diffuse reflections. A full description of the laser hazard and classification scheme can be found in the current American National Standards ANSI Z136.1-2000 for Safe Use of Lasers along with recommended and required engineering, administrative and procedural controls measures required being in place.

To fully analyze occupational hazards associated with lasers safety engineers and LSO's must understand the concepts of nominal hazard zones (NHZ) and maximum permissible exposure (MPE). The definition of NHZ is "*…the space within which the level of direct, reflected, or scattered radiation during normal operation exceeds the applicable MPE. Exposure levels beyond the boundary of the NHZ are below…*" The definition of MPE is "*…the level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin…*" (1). Tables used to define MPE's for skin and eye exposure are provided in the standards to aid in determining appropriate control measures and for preparing quantitative analysis or when reporting suspected laser exposures.

Optical density (OD) is term that describes the amount of light attenuation at a particular wavelength that an optical filter used in safety eyewear or windows provide. The definition of OD is the logarithm to the base ten of the reciprocal of the transmittance. (1) That is,
$D_\lambda = -\log_{10} \tau_\lambda$ Where τ_λ is transmittance
By knowing certain operating characteristics of a laser system, the MPE for that wavelength and using this equation safety engineers can determine the appropriate OD for protective eyewear within the NHZ for personnel to safely attenuate or reduce laser light to levels below allowable MPE's. For example: A 20watt 532nm laser beam entering a normally dilated 7mm eye would result in a calculated irradiance of 52watts/cm^2. The MPE for this wavelength is 2.55mw/cm^2. (2) The calculated exposure (irradiance) is 20,392 times higher than the allowed MPE (52watts/cm^2 ÷ 2.55mw/cm^2 = 20,392). The $\log_{10}$ of 20,392 = 4.31. Stated another way, installing protective windows or requiring laser safety eyewear be worn with an OD of >4.31 at 532nm would limit potential exposures to levels below the MPE (i.e., $1/10^{4.31}$ X 52watts/cm^2 = 2.55 mw cm^{-2}).

Familiarity with these and other calculations are also useful in preparing a quantitative analysis of reported or suspected accidental ocular exposure to supplement an ophthalmic exam (medical record) for legal liability purposes. A sample Laser Hazard Analysis Report has been included for evaluation and discussion purposes to acquaint safety engineers and LSO's with laser terminology, viewing conditions and preparing quantitative reports of potentially hazardous laser environments or viewing conditions.

While ocular laser hazards may receive the most attention in developing workplace safety programs electrical hazards are the leading causes of death in reported laser accidents. Regardless of their hazard classification most laser systems generate extremely high electrical currents and/or voltages in and around laser heads, flashlamps and storage capacitors that require appropriate and adequate safety control measures to be in place during normal operation or service procedures. Other non-beam hazards may include:

- Laser generated air contaminants
- Collateral and plasma radiation
- Fire
- Explosion
- Compressed gasses
- Laser dyes and solvents
- Mechanical hazards associated with robots
- Noise
- Waste disposal
- Limited work space
- Ergonomics

Laser Hazard Controls

As the use of lasers and laser systems in work place environments continues to expand it is imperative that occupational health and safety engineers be familiar and in compliance with the requirements of local, state and federal regulatory agencies that oversee and govern their safe use. The American National Standards Institute has approved the development process for the Safe Use of Lasers (ANSI Z136.1/2000) which is the parent document for an entire series of laser application environments that includes; LED's, telecommunications, health care facilities, educational institutions, measurements, instrumentation and outdoor use. The ANSI Z136 series for Safe Use of Lasers represent the standard of practice for laser safety in the United States and are published by the Laser Institute of America (LIA). An American National Standard implies a consensus of those substantially concerned with its scope and provisions and is intended as a guide to aid the manufacturer, the consumer and the general public and is also subject to periodic review. Therefore, the ANSI Z136 standards for safe use of lasers represent nationally recognized standards of practice in the US and by US courts and are often referenced by local, state and federal organizations.

The ANSI standards provide guidance for the safe operation and use of lasers and laser systems by defining control measures for each of four laser classifications. The basis of the laser classification scheme is the ability of the primary or reflected beam to cause biological damage to the eye or skin during its intended use. Many lasers used in manufacturing, R & D, telecommunication, material processing, health care and entertainment are designated Class 4 laser systems and may by definition present a skin, ocular or fire hazard by their direct or reflected laser radiation. The ANSI standards provide guidelines for developing appropriate control measures which minimize these potential hazards. Employees and personnel who routinely work in laser environments and/or who may enter within the nominal hazard zones of Class 3b or Class 4 laser systems meet the definition of laser personnel. As such the management (employer) has the fundamental responsibility for the assurance of the safe use of lasers owned and/or operated by the employer. The following laser hazard classification scheme is from current ANSI Z136.1/2000 for Safe Use of Lasers:

Class	Control Measures	Medical Surveillance
Class 1	Not applicable	Not applicable
Class 2	Applicable	Not applicable
Class 3a	Applicable	Not applicable
Class 3b	Applicable	Applicable
Class 4	Applicable	Applicable

In addition to the ANSI standards health and safety engineers or the appointed LSO's should also have an understanding of the role and requirements of other national and international regulatory agencies concerned with the safe use of lasers which may include:

- Center for Devices and Radiological Health
- Federal Laser Product Performance Standard
- International Electrotechnical Commission
- Occupational Safety & Health Administration
- State & local regulations may also apply

The Food and Drug Administration's Center for Devices and Radiological Health (CDRH) establishes Federal Laser Product Performance Standards (FLPPS) for light-emitting products under 21 CFR (Code of Federal Regulations) Part 1040.10 Laser Products & 21 CFR Part 1040.11 Specific Purpose Laser Products. Laser products manufactured, bought, sold or imported into the United States must be in compliance with the requirements of these standards. There is currently an effort under way on the part of the FDA/CDRH (Laser Notice No. 50) to amend its standards for laser products to harmonize many of its requirements with those of the IEC (International Electrotechnical Commission) 60825-1 and 60601-2-22 standards. CDRH has acknowledged the advantages of one set of criteria and requirements worldwide although the process will undoubtedly take several years to fully integrate.

While the ANSI standards represent the standard of practice in the United States the IEC 60825-1 (Safety of laser products Part 1: Equipment classification, requirements and user's guide), EN207 and EN208 are the definitive guides for laser safety in Europe and in other parts of the world. Both ANSI and the CDRH are attempting to amend their standards for laser products and laser safety as closely as possible to harmonize with those of IEC 60825-1 and 60601-2-22.

Employers also have responsibilities and accountabilities to the U.S. Department of Labor Occupational Safety & Health Administration (OSHA) under directives; STD 01-05-001 - PUB 8-1.7 - Guidelines for Laser Safety and Hazard Assessment and under the OSH Act of 1970 often referred to as the General Duty Clause to "*…furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees…*" To that end OSHA inspectors may reference the ANSI standards for informational purposes and have recently formed an alliance with the Laser Institute of America that focuses on providing access to training resources to help protect worker safety and health particularly by reducing and preventing exposure to laser beam and non-beam hazards in industrial and medical workplaces.

In order to meet workplace laser safety requirements employers shall appoint a laser safety officer who has the responsibility and authority to monitor and enforce the control of laser hazards and effect the knowledgeable evaluation and control of laser hazards. This shall include, but not be limited to, such actions as establishing an NHZ, approving SOPs, avoiding unnecessary or duplicate controls, selecting alternate controls, conducting periodic facility and equipment audits, and training. The following tables describe control measures for the various laser classes and may serve as a useful tool to document that appropriate and recommended control measures are in place. (3)

Table #1. Administrative & procedural control measures for all laser classifications*

Control Measures	**Classification**				
Administrative & Procedural Controls	**1**	**2**	**3a**	**3b**	**4**
Standard Operating Procedures (4.4.1)	Θ	Θ	Θ	●	X
Output Emission Limitations (4.4.2)	Θ	Θ	LSO Determination		
Education and Training (4.4.3)	Θ	●	●	X	X
Authorized Personnel (4.4.4)	Θ	Θ	Θ	X	X
Alignment Procedures (4.4.5)	Θ	X	X	X	X
Protective Equipment (4.6)	Θ	Θ	Θ	●	X
Spectator (4.4.6)	Θ	Θ	Θ	●	X
Service Personnel (4.4.7)	Δ MPE	Δ MPE	Δ MPE	X	X
Demonstration with General Public (4.5.1)	MPE[†]	X	X	X	X
Laser Optical Fiber Systems (4.5.2)	MPE	MPE	MPE	X	X
Laser Robotic Installations (4.5.3)	Θ	Θ	Θ	X NHZ	X NHZ
Eye Protection (4.6.2)	Θ	Θ	Θ	● MPE	X MPE
Protective Windows (4.6.3)	Θ	Θ	Θ	X NHZ	X NHZ
Protective Barriers and Curtains (4.6.4)	Θ	Θ	Θ	●	●
Skin Protection (4.6.6)	Θ	Θ	Θ	X MPE	X MPE
Other Protective Equipment (4.6.7)	Use May Be Required				
Warning Signs and Labels (4.7) (Design Requirements)	Θ	●	●	X NHZ	X NHZ
Service and Repairs (4.4.7)	LSO Determination				
Modifications and Laser Systems (4.1.2)	LSO Determination				

Table #2. Engineering control measures for all laser classifications*

Control Measures	**Classification**				
Engineering Controls	**1**	**2**	**3a**	**3b**	**4**
Protective Housing (4.3.1)	X	X	X	X	X
Without Protective Housing (4.3.1.1)	LSO shall establish Alternative Controls				
Interlocks on Protective Housing (4.3.2)	Δ	Δ	Δ	X	X
Service Access Panel (4.3.3)	Δ	Δ	Δ	X	X
Key Control (4.3.4)	Θ	Θ	Θ	●	X
Viewing Portals (4.3.5.1)	Θ	MPE	MPE	MPE	MPE
Collecting Optics (4.3.5.2)	MPE	MPE	MPE	MPE	MPE
Totally open Beam Path (4.3.6.1)	Θ	Θ	Θ	X NHZ	X NHZ
Limited Open Beam Path (4.3.6.2)	Θ	Θ	Θ	X NHZ	X NHZ
Enclosed Beam Path (4.3.6.3)	None is required if 4.3.1 & 4.3.2 is fulfilled				
Remote Interlock Connector (4.3.7)	Θ	Θ	Θ	●	X
Beam Stop or Attenuator (4.3.8)	Θ	Θ	Θ	●	X
Activation Warning Systems (4.3.9.4)	Θ	Θ	Θ	●	X
Emission Delay (4.3.9.1)	Θ	Θ	Θ	Θ	X
Indoor Laser Controlled Area (4.3.10)	Θ	Θ	Θ	X NHZ	X NHZ
Class 3b Indoor Laser Controlled Area (4.3.10.1)	Θ	Θ	Θ	X	Θ
Class 4 Laser Controlled Area (4.3.10.2)	Θ	Θ	Θ	Θ	X
Laser Outdoor Controls (4.3.11)	Θ	Θ	Θ	X NHZ	X NHZ
Lasers in Navigable Airspace (4.3.11.2)	Θ	Θ	●	●	●
Temporary Laser Controlled Area (4.3.12)	Δ MPE	Δ MPE	Δ MPE	Θ	Θ
Remote Firing and Monitoring (4.3.13)	Θ	Θ	Θ	Θ	●
Labels (4.3.17 & 4.7)	X	X	X	X	X
Area Posting (4.3.9)	Θ	Θ	●	X NHZ	X NHZ

Legend X ~ Shall
● ~ Should
Θ ~ No requirement
Δ ~ Shall if enclosed Class 3b or Class 4
MPE ~ Shall if MPE is exceeded
NHZ ~ Nominal Hazard Zone analysis required
† ~ Applicable only to UV and IR Lasers (4.5.1.2)

*Tables 1 & 2 were reproduced with permission from ANSI Z136.1-2000 for Safe Use of Lasers. Copyright 2000, Laser Institute of America, Orlando, Florida. The Laser Institute of America disclaims any responsibility or liability resulting from the placement and use in the described manner.

Table #3. Laser hazard analysis report (example) for evaluation and discussion

Laser Operational Parameters and Performance Specifications for Evaluation

1) Mode:	**Continuous Wave**	13) Pulse Time Envelope:	**Seconds**
2) Shape:	**Circular**	14) Lens Focal Length:	**1.25E+02mm**
3) Major Axis Dimension:	**2mm**	15) Beam Size at Lens:	**5.00E+00mm**
4) Major Axis Divergence:	**1.2mrad**	16) Beam Size on diffuser:	**1.00E+00mm**
5) Minor Axis Dimension:	**mm**	17) Diffuser-Observer Distance:	**5.00E-01 Meters**
6) Minor Axis Divergence:	**mrad**		
7) Gaussian Criteria:	**e^{-1}**	18) Viewing Angle off Normal:	**45.00 Degrees**
8) Average Power:	**2.00 E+01**	19) Reflection Coefficient:	**100.00 Percent**
9) Exposure Time:	**2.5E-01 Sec**	20) Fiber Optics Mode:	**Multi**
10) Pulse Energy:	**Joules**	21) Min. Beam waist:	**µm**
11) Pulse Length:	**Seconds**	22) Numerical Aperture:	**4.00E-01**
12) Pulse Rate:	**Hertz**	23) Small Source Range:	**5.00E+00 Meters**

Laser Hazard Analysis

24) **Maximum Permissible Exposure (MPE)**		38) **Small Source Diffuse Viewing**	
25) Small Source MPE (Eye)	**2.55E-03 W/cm^2**	39) Average power	**2.00E+01 Watts**
26) Small Area MPE (Skin)	**3.11E+00 W/cm^2**	40) Energy per pulse	**N/A**
		41) Minimum range	**5.00E-01 Meters**
27) **Small Source Intrabeam Viewing**		42) Irradiance at 0.50 Meters	**1.80E-3 W/cm^2**
28) Average power	**2.00E+01 Watts**	43) Radiant exposure at eye	**N/A**
29) Energy per pulse	**N/A**	44) Power at eye	**6.93E-04Watts**
30) Pulse peak power	**N/A**	45) Energy at eye	**N/A**
31) Time	**2.50E-01 Seconds**	46) Minimum required optical density	**0.00**
32) Limiting aperture (Eye)	**7.00E+00mm**	47) Filter transmittance	**1.00E+00**
33) Limiting aperture (Skin)	**3.50E+00mm**		
34) Irradiance at the eye	**5.20E+01 W/cm^2**	48) **Small Source Multiple Pulse Factors**	
35) Radiant exposure at eye	**N/A**	49) Small source effective total pulses:	**N/A**
36) Minimum required optical density	**4.31**	50) Multiple Pulse Correction Factor :Cp	**N/A**
37) Filter transmittance	**4.90E-05**	51) MPE rule applied:	**N/A**
52) **Small Source Intrabeam Viewing at Known Range**		64) Actual viewing angle (alpha)	**1.41E+00 mrad**
53) Beam area at 5.00E+00 Meters	**3.85E1 cm^2**	65) Limiting viewing angle (alpha-min)	**1.50E+00 mrad**
54) Calculated exposure	**5.20E+01 W/cm^2**	66) Maximum large source range	**N/A**
55) Minimum required optical density	**4.31**	67) Calculated exposure	**1.80E-03 W/cm^2**
56) **Nominal Hazard Zones**			
57) Small source diffuse reflections	**4.21E-01 Meters**	68) **Calculated Correction Factors**	
58) Lens on laser condition	**2.50E+03 Meters**	69) Thermal/photochemical factor: T1	**N/A**
59) Intrabeam exposure condition	**8.33E+02 Meters**	70) Near-infrared correction factor: CA	**N/A**
		71) Visible wavelengths correction factor: CB	

60) Multi-mode fiber optics	**2.13E+00 Meters**		**43.65**
61) Single mode fiber optics	**N/A**	72) Special near-infrared correction factor: CC	**N/A**
62) **Ocular Exposure to Diffuse Laser Radiation**		73) Extended source correction factor: CE	**N/A**
63) Source type	**Small**	76) Multiple pulse correction factor: Cp (Extended)	**N/A**
		77) UV eye or skin exposure over 2 days	**N/A**

Table #3 represents a software generated laser hazard analysis report based on a frequency-doubled Nd:YAG laser emitting at 532nm and is included for discussion and evaluation purposes only. (4) This type of laser hazard analysis could potentially become part of a quantitative analysis involving a suspected or reported accidental laser exposure, be used to accurately define nominal hazard zones or help determine the appropriate level of safety eyewear protection needed for laser personnel. The same information can also be determined using a scientific calculator and formulas, examples, factors, coefficients, etc. described in the ANSI standards.

NOTE: The following laser hazard analysis evaluates a variety of hypothetical laser operating parameters and viewing conditions that would be common to a medical or surgical environment. While the emphasis of this laser hazard analysis is on medical laser systems the same terms, variables, coefficients, correction factors, viewing conditions, exposure levels and hazards also apply to manufacturing, industrial, military, educational, communication and research laser environments and personnel. A complete table of symbols used in the following calculations can be found in Appendix B (B2) of the ANSI standards and in most optical physics reference books.

Discussion

As part of an effective institutional laser safety program industrial safety engineers, LSO's, health care laser personnel, risk managers, biomedical engineers and physicians would work together in the development of policies and procedures that reduce the possibility of accidental exposure to hazards associated with the use of medical laser systems (i.e., laser safety committee). For example in the event of an accident or suspected laser exposure the involved patient or health care personnel should be directed by the LSO to have an ocular evaluation by an ophthalmologist. As part of a thorough and complete investigation a quantitative analysis of the accident should be prepared to supplement the ophthalmic findings to determine if the reported or suspected laser exposure exceeded MPE levels. A report of incident and along with the analysis should be reviewed by the committee to determine if adequate and appropriate control measures are in place and being adhered to, to protect laser personnel in the future.

The following analysis is intended to provide safety engineers, LSO's and laser personnel with additional insight and use of terms, definitions, variables and coefficients necessary for a better understanding of laser hazards and hazard analysis reporting. Some laser parameters listed in Table #3 use logarithm to the base ten (Log_{10}) terms and exponents to define calculated values (i.e., 2.55E-03 $\mathrm{W/cm^2}$ = 2.55$\mathrm{mw/cm^2}$). Terms used to define Gaussian Criteria/beam diameter use natural logarithm ln (i.e., logarithm having base e, where e = 2.718...). Footnotes/endnotes are provided for accuracy and to assist in similar evaluation and reporting efforts. For the purpose of this hazard analysis a 20watt KTP frequency doubled Nd:YAG surgical laser emitting at 0.532μm (visible green) is being evaluated. Some KTP lasers also emit at 1064nm (near infrared) and would require a separate hazard analysis.

1. Mode: Continuous Wave. Lasers systems can operate or emit light in several output (temporal) characteristics; continuous, pulsed, single pulsed, repeat pulse, superpulse, Q-switched, mode-locked, etc. Commercially available medical KTP lasers operate in a 'quasi-continuous' output mode, however, due to the extremely high Q-switched rep rate (25kHz) their output is generally expressed and power measured as continuous.
2. Shape: Circular. This parameter relates to the polarization (orientation) of the electric component of the emergent electro-magnetic laser beam. Laser light can be linear, rectangular, circular, right or left hand, elliptical or un-polarized. (5)
3. Major Axis Dimension: 2.0mm. This beam diameter parameter was arbitrarily chosen and represents a 'typical' beam diameter which would be provided by the manufacturer in the specification section of a laser operator's manual.
4. Major Axis Divergence: 1.20mrad. Laser beam divergence is typically expressed in units of milli-radians (mrad) and would be listed in the specification section of the laser system's operators manual. A radian (approximately ~57.295°) is the angle at the center of a circle subtended by an arc equal in length to the radius, per System International d'Unites (SI). 2π radians = 360°. A 'typical' 1.20mrad beam divergence was arbitrarily selected for the purpose of evaluating this KTP doubled Nd:YAG laser emitting at 0.532µm.
5. Minor Axis Dimensions: mm. Some lasers (i.e., PN junction semi-conductor diodes) have two different divergences along the vertical and horizontal axis which may need to be considered separately. For the purpose of this hazard analysis these parameters are not factors for consideration.
6. Minor Axis Divergence: mrad. See #5 above.
7. Gaussian Criteria: e^{-1}. A 'Gaussian beam' refers to the ideal bell-shaped laser beam profile of a properly aligned laser system or TEM_{oo} mode (Transverse Electromagnetic Mode). Visual evidence of an optically aligned laser cavity emitting a Gaussian beam profile can be observed by making a burn on a wooden tongue depressor, UV illuminated IR screens, 'Zap-it' paper or beam analysis instrumentation. This criteria is applied to define the beam diameter (ω) of a Gaussian laser beam where the beam diameter is defined as the distance across the center of the beam for which the irradiance (E) equals 1/e of the maximum irradiance (1/2.718 = 0.368). The spot size of the beam is the radial distance (radius) from the point of maximum irradiance to the 1/e point. (6) Approximately 63.2% of the beam diameter is defined by applying this criterion. Another convention is to define spot size at the $1/e^2$ point ($1/2.7182 = 0.135\ E_{max}$).
8. Average Power: 2.00 E+01. Used for this example equals 20watts avg. ($2.00 \times 10^1 = 20$) and was chosen because it represents a 'typical' KTP medical laser output power.
9. Exposure Time: 2.5E-01 Sec. A 0.25sec exposure time was selected by default for evaluation as it represents the normal aversion response time (1) to light visible light between 400 – 700nm.
10. Pulse Energy. This parameter would only apply if the system being evaluated delivered light in a pulsed mode instead of a continuous output. Pulse energy would be expressed in radiometric terms as Joules. Joules = Power (watts) x Time (seconds). Examples of pulsed laser systems include; Q-switched Nd:YAG lasers used in ophthalmology (posterior capsulotomies) & dermatology (tattoo removal), flash lamp pulsed tunable dye lasers used for cutaneous treatment of vascular malformations or pigmented lesions and HO:YAG lasers for urology (urinary stone fragmentation), arthroscopy, etc.

11. Pulse Length. This parameter only applies to a pulsed laser not a continuous output system. When required to analyze pulse length can be found in the specification section of the system operator's manual and is usually expressed as T (sec) @ FWHM. Pulse length is usually expressed as the full width (time duration) at half maximum points (FWHM) of the pulse as captured by a fast photodiode and saved on a storage oscilloscope.

12. Pulse Rate. When applicable this term would be expressed as Hz or pulses per second.

13. Pulse Time Envelope. This expression would describe the duration of exposure of a train of pulses at a given pulse rate.

14. Lens Focal Length: 1.25E+02mm. For the purpose of this evaluation a 125mm focal length handpiece lens has been selected. Surgical handpieces used with KTP lasers do not generally have focusing capabilities. 125mm lenses are more common to CO_2 laser focusing handpieces, whereas 250mm, 300mm and 400mm focal lengths are common to operating microscopes. Rigid endoscopes (bronchoscopes, laryngoscopes, laparoscopes, etc.) may often have a variety of focal lengths to consider.

15. Beam Size at Lens: 5.00E+00mm. This value was arbitrarily selected for evaluation purposes only as KTP surgical laser handpieces don't usually have focusing capabilities. However, in the case of a CO_2 laser (for example) this information would be found in the operator's manual, measured or estimated. If this KTP laser being evaluated had a focusing handpiece it would not be unreasonable that the beam size at lens would be approximately 5mm.

16. Beam Size on diffuser: 1.00E+00mm. This value was arbitrarily selected for evaluation, however, would be stated in an operator's manual as 'spot size' at tissue.

17. Diffuser-Observer Distance: 5.00E-01Meters. This parameter was arbitrarily selected and assumes an average operating distance (i.e., arms length, ~50cm) from the focused laser energy on tissue to the operator's eye.

18. Viewing Angle off Normal: 45.00 Degrees. This parameter was arbitrarily selected and assumes the 'typical' operator viewing angle relative to normal incidence. Normal incidence: Light striking a surface at an angle perpendicular to the surface. (7)

19. Reflection Coefficient: 100 Percent. For a quantitative hazard analysis the actual reflection coefficient in a given situation may not be accurately known. Scientific tables are available that list reflection & absorption coefficients for various physical and biological substances as a function of wavelength. However, in the absence of certainty as to the exact reflection coefficient for this example a 'worst case' scenario of 100% reflection will be evaluated.

20. Fiber Optics Mode: Multi. The more common multi-mode medical fiber optic will be evaluated versus single-mode fibers used primarily in long-distance signal transmission (i.e., optical communication).

21. Min. Beam waist. Definition: That point in a Gaussian beam where the wavefront has a curvature of zero and the beam diameter is a minimum (7). While this variable may be necessary to know if the optical deck of a medical laser system is exposed (i.e., during service) it will not be considered for this example.

22. Numerical Aperture: 4.00E-01. The acceptance angle of a fiber optic is normally expressed as numerical aperture (NA) and for multimode fibers in air is approximately:

$NA = \sqrt{n_0^2 - n_1^2}$

Where: n_o = the core (fiber) index of refraction
n_1 = the cladding index of refraction

Example: For a multi-mode medical fiber with a core index of refraction of 1.457 (i.e., silica) and a cladding with a 1.401 index of refraction (silicone-based plastic cladding) the NA = 0.40. Geometrically the NA is the sine of the half angle of the acceptance, or 23.60 for a fiber with a NA of 0.40. For the purpose of this evaluation a numerical aperture of 0.40 was arbitrarily selected.

23. Small Source Range: 5.00E+00 Meters. A distance of 5.0 meters was arbitrarily selected for the purpose of hazard analysis as it represents a 'typical' working distance that a biomedical or service engineer might be away from a raw laser beam (intrabeam viewing condition) during normal preventative maintenance, service or calibration procedures. It is important to remember that the nominal ocular hazard distance (NOHD) of a raw laser beam can exceed several hundred meters and may require temporary or permanent physical barriers during routine maintenance procedures.

24. Maximum Permissible Exposure (MPE). The level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin. (1)

25. Small Source MPE (Eye): 2.55E-03 W/cm^2. Per table 5a (pg. 45) for wavelengths between 400nm & 700nm:

$$\begin{aligned}
\text{MPE: H (radiant exposure)} &= 1.8\ t^{0.75} \times 10^{-3} \\
&= 1.8\ (0.25^{0.75}) \times 10^{-3} \\
&= 1.8\ (0.354)\ \text{mj} \cdot \text{cm}^{-2} \\
&= 0.636\ \text{mj} \cdot \text{cm}^{-2} \\
2.55\ \text{mw cm}^{-2} &= \frac{0.636\ \text{mj} \cdot \text{cm}^{-2}}{0.25\ \text{sec}}
\end{aligned}$$

26. Small Area MPE (Skin): 3.11E+00 W/cm^2. Per table 7 (ANSI Z136.1 2000/pg. 48) for wavelengths between 400nm & 1400nm:

$$\begin{aligned}
\text{MPE for Skin Exposure to laser beam} &= 1.1\ \text{CA}\ t^{0.25} \\
&= 1.1\ (0.25^{0.25}) \\
&= 1.1\ (0.707) \\
3.11\text{W/cm}^2 &= \frac{0.778}{0.25\ \text{sec}}
\end{aligned}$$

27. Small Source Intrabeam Viewing. Analysis of intrabeam viewing conditions.

28. Average power: 2.00E+01 Watts (20watts). This value was arbitrarily selected as it is a common GYN or neuro treatment power setting when delivered laparoscopically or freehand. ENT procedures using a microscope and micro-manipulator (vocal cord pappilomas or lesions) generally use lower power settings.

29. Energy per pulse: N/A. Energy is not a factor to consider in this analysis as the laser output is continuous (CW).

30. Pulse peak power: N/A. Peak power is not a factor to consider in this analysis. NOTE: On laser systems that deliver pulsed laser energy peak power levels can be extremely high. For example, Q-switched ophthalmic ND:YAG lasers will typically deliver 10mj of energy in ~ 4x10^{-9} second pulses (i.e., LaserEx/Super Q). Using these values the peak power of a single pulse is calculated (energy ÷ time) to be ~ 2.5 Megawatts!

31. Time: 2.5E-01 Seconds. Because this system being evaluated produces visible light at 532nm the 0.25 second time duration was selected as it represents the normal 'aversion response' time. (1) It is important to remember that some KTP lasers also emit at 1064nm (invisible near infrared) either simultaneously or separately and that the 0.25 second aversion response criteria will not apply for those hazards analysis purposes.

32. Limiting aperture (Eye): 7.00E+00mm. The maximum diameter of a circle over which radiance and radiant exposure are averaged for the purpose of hazard evaluation and classification. (1 & 8) This value represents an 'average' ambient light condition human dilated eye and has a calculated area ($\pi D^2/4$) of 0.385cm^2.

33. Limiting aperture (Skin): 3.50E+00mm. This value was determined by ANSI for calculating MPE's for skin. (8)

34. Irradiance at the eye: 5.20E+01 W/cm^2. This value is calculated assuming a ‘raw’ laser beam (intrabeam exposure) fully enters an eye dilated to 7mm.

NOTE: Area = $\pi D^2/4 = \pi\,(0.7\text{cm}^2/4) = 0.385\text{cm}^2$

$$52\ \text{watts/cm}^2 = \frac{20\ \text{Watts}}{0.385\ \text{cm}^2}$$

35. Radiant exposure at eye: N/A. ‘Exposure’ assumes an energy calculation, whereas, this example treats this as ‘irradiance’ or power density.

36. Minimum required optical density: 4.31. The minimum optical density required for this Small Source Intrabeam Viewing condition is 4.31. Small source was formerly referred to in regulatory standards as ‘point source’ viewing conditions. This hazardous viewing situation could potentially be encountered by a biomedical or service engineer during routine preventative maintenance or system calibration when protective console covers are removed and the interlocks are defeated. Under this hazardous viewing condition laser personnel should wear protective eyewear having an optical density of >4.31 @ 532nm. Analysis: A 20watt beam entering a normally dilated 7mm eye results in a calculated irradiance of 52watts/cm^2 (example #34). The MPE for this wavelength is 2.55 mw cm^{-2} (example #25). The actual exposure (irradiance) is 20,392 times higher than the allowed MPE (52 watts/cm^2 ÷ 2.55 mw cm^{-2} = 20,392). Log_{10} 20,392 = 4.31. Stated another way, wearing safety eyewear having an OD of 4.31 would limit exposure to a level below MPE (i.e., $1/10^{4.31}$ X 52watts/cm^2 = 2.55 mw cm^{-2}).

37. Filter transmittance: 4.90E-05. The ratio of the MPE to the irradiance at the limiting aperture (eye): 2.55mw/cm^2 ÷ 52watts/cm^2 = 4.90E-5.

38. Small Source Diffuse Viewing. A biomedical or service engineer could potentially be exposed to this hazardous viewing situation during optical deck power calibration of a KTP laser while using a matte-finish power head or some other form of beam stop. Analysis of a 20 watt KTP laser beam incident upon a 100% diffusely reflecting surface can produce a retinal image approximately 20-30μm in size (i.e., small source). NOTE: A distinction must be made between ‘small source’ and ‘extended source’ measurements: An extended source subtends an angle at the observer’s eye greater than the angular subtense, α_{min} (1.5 mrad), across the largest angular dimension of the source as viewed by the observer. (9)

39. Average power: 2.00E+01 Watts. 20 watts was arbitrarily selected for analysis as it represents a ‘typical’ treatment power level for a surgical KTP laser.

40. Energy per pulse: N/A. Energy is not a variable to consider for analysis as this example evaluates a continuous output.

41. Minimum range: 5.00E-01 Meters. An arbitrary arms-length viewing distance between the physician and that point where the laser impacts tissue if being used with a handpiece.

42. Irradiance at 0.50 Meters: 1.80E-3 W/cm^2. Viewing diffuse reflections from a matte surface can be hazardous (Class 4 lasers) when the viewer’s eye is located near the reflecting surface and the reflecting surface is near the laser exit port (10). Irradiance from diffuse reflective surfaces can be calculated by applying the following formula (ANSI Eg. B65):

$$E = \frac{\rho_\lambda \Phi \cos\theta_v}{\pi r_1^2}$$

$$= \frac{(20\text{w})\ (\cos 45^\circ)}{\pi\ (50\text{cm})^2}$$

$$= \frac{14.14}{7854}$$

$$= 1.8\text{E-}3\ \text{W/cm}^2$$

43. Radiant exposure: N/A. This parameter is not calculated as we are evaluating a continuous laser output. Radiant exposure is defined as surface density of the radiant energy received and is expressed in units of joules/cm^2.$^{(1)}$

44. Power at eye: 6.93E-04Watts. Power at the eye is determined by first calculating the area of a 'normal' dilated eye with a 7mm diameter. $A = \frac{\pi D^2}{4}$

$$= 0.385\text{cm}^2$$

Using the calculated irradiance in example #42 (1.8mw/cm^2) and multiplying the area (0.385cm^2) yields the power at the eye: 0.693mw = 1.8mw/cm^2 x 0.385cm^2

45. Energy at eye: N/A. This parameter is not calculated as we are evaluating a continuous laser output.

46. Minimum optical density: 0.00. Considering that the actual irradiance (example #42) is well below the MPE for this small source diffuse viewing condition no additional attenuation is required by means of protective eyewear having a certain optical density.

47. N/A (Since no attenuation [OD] is required)

48. Small Source Multiple Pulse Factors. These are not factors for analysis as this is an evaluation of a continuous laser power output condition.

49. N/A

50. N/A

51. N/A

52. Small Source Intrabeam Viewing at Known Range. This represents a 'worst case' scenario where a 'raw' collimated laser beam is inadvertently directed into an unprotected eye and would result in serious ocular (retinal) damage.

53. Beam area at 5.00E+00 Meters: 3.85E-01 cm^2. This answer is slightly different than when applying the formula for calculating beam area at known distance as presented in the ANSI standard (Eq. B40/pg. 102). The LAZAN program calculated this area (0.385 cm^2) based on a beam diameter of 0.7cm at 500cm (5.0 Meters) which translates into an area of 0.385cm^2 and a calculated exposure of 52watts/cm^2. Applying ANSI equation B40 yields the following results:

$$\begin{aligned} D_L &= a + r\Phi \\ &= 0.2\text{cm} + (500\text{cm} \times 1.2\text{mrad}) \\ &= 0.2\text{cm} + 0.6\text{cm} \\ D_L &= 0.8\text{cm} \end{aligned}$$

Therefore, the beam diameter at 5 meters (500cm) is 0.8cm which calculates to an area of:

$$A = \pi D^2/4$$
$$A = 0.503\text{cm}^2$$

54. Calculated exposure: 5.20E+01 W/cm^2. This LAZAN calculated exposure is arrived at by dividing output power by area: 20watts/0.385cm^2 = 52W/cm^2. Applying the area calculated using the ANSI formula (Eq. B40) yields the following answer:

$$20\text{watts}/0.503\text{cm}^2 = 39.8\text{w/cm}^2.$$

55. Minimum required optical density: 4.31. This LAZAN calculated Optical Density (OD) is correct if applied to: $\text{Log}_{10}\,(E/MPE) = OD$

$$\text{Log}_{10}\,(52\text{w/cm}^2 \div 2.55\text{mw/cm}^2)$$
$$\text{Log}_{10}\,20{,}392 = 4.31$$

The minimum required optical density is slightly different when applying the exposure calculated based on the ANSI formula:

$$\text{Log}_{10}\,(39.8\text{w/cm}^2 \div 2.55\text{mw/cm}^2)$$
$$\text{Log}_{10}\,15{,}608 = 4.19$$

56. Nominal Hazard Zones (NHZ). The space within which the level of the direct, reflected or scattered radiation during normal operation exceeds the applicable MPE. Exposure levels beyond the boundary of the NHZ are below the appropriate MPE level (1).

57. Small source diffuse reflections: 4.21E-01 Meters. This calculated value is the distance beyond which ocular exposure (irradiance) falls below the allowable MPE for this wavelength. The NHZ is determined by applying the following equation (11):

$$
\begin{aligned}
r_{NHZ} &= [(\rho\Phi\cos\theta) \div (\pi MPE)]^{0.5} \\
&= [(20\cos 45^{o}) \div (\pi 2.55 mw/cm^{2})]^{0.5} \\
&= [(14.14) \div (8.01 mw/cm^{2})]^{0.5} \\
42cm &= (1765.3)^{0.5}
\end{aligned}
$$

58. Lens on laser condition: 2.50E+01 Meters. This hazardous scenario could occur and would need to be evaluated in the event of a suspected exposure in or around the operative site during clinical use. The equation for calculation is (12):

$$
\begin{aligned}
r_{\ NOHD} &= (f_o/b_o)\ (4\Phi/\pi MPE)^{0.5} \\
&= (25)\ (100) \\
&= 2{,}500cm \text{ (or) } 25 \text{ meters}
\end{aligned}
$$

59. Intrabeam exposure condition: 8.33E+02 Meters. This hazardous scenario could be encountered during service or engineering procedures while the protective covers are off and interlocks defeated, thereby potentially exposing service personnel to raw/intrabeam viewing conditions. The equation for calculation is (12):

$$
\begin{aligned}
r_{\ NOHD} &= (1/\Phi)\ [(4\Phi/\pi MPE) - a^{2}]^{0.5} \\
&= (833.33)\ (99.93) \\
&= 83{,}275cm \text{ (or) } 832.7 \text{ Meters}
\end{aligned}
$$

60. Multi-mode fiber optics 2.13E+00 Meters. This hazardous scenario could occur and may need to be evaluated in the event of a suspected exposure in or around the operative site during clinical use or in the event of a fiber fracture during use. The equation for calculation is (12):

$$
\begin{aligned}
r_{\ NOHD} &= (1.7/NA)\ (\Phi/\pi MPE)^{0.5} \\
&= (4.25)\ (49.965) \\
&= 212.35cm \text{ (or) } 2.12 \text{ Meters}
\end{aligned}
$$

61. N/A

62. Ocular Exposure to Diffuse Laser Radiation

63. Source type: Small

64. Actual viewing angle (alpha): 1.41E+00mrad. The calculation used to determine the actual viewing angle is (ANSI Eq. B67): $\alpha = \dfrac{D_L \cos\theta_v}{r_1}$

$$
\begin{aligned}
&= \frac{0.1 \cdot \cos 45^{o}}{50} \\
1.41mrad &= \frac{0.0707}{50}
\end{aligned}
$$

65. Limiting viewing angle (alpha-min): 1.50E+00mrad. Limiting angular subtense (α_{min}): The apparent visual angle which divides small-source viewing from extended source viewing. α_{min} is defined as 1.5 mrad. (1)

66. Maximum large source range: N/A.

67. Calculated exposure: 1.80E-03 W/cm^2 (same as example #42). Viewing diffuse reflections from a matte surface can be hazardous when the viewer's eye is located near the reflecting surface and the reflecting surface is near the laser exit port. (10) Irradiance from diffuse reflective surfaces may be calculated by applying the following formula (ANSI Eq. B65):

$$E = \frac{\rho_\lambda \Phi \cos\theta_v}{\pi r_1^2}$$

$$= \frac{(20w)\ (\cos 45^o)}{\pi\ (50cm)^2}$$

$$1.8E\text{-}3\ W/cm^2 = \frac{14.14}{7854}$$

68. Calculated Correction Factors. Changes the applicable MPE's for various wavelengths and viewing conditions (see Table 6 to calculate).

69. Thermal/photochemical factor: T_1 N/A. The exposure duration (time) at which MPE's based upon thermal injury are replaced by MPE's based upon photochemical injury to the retina. (1)

70. Near-infrared correction factor: C_A N/A. Correction factor which increases the MPE values in the near infrared (IR-A) spectral band (700-1400nm) based upon reduced absorption properties of melanin pigment granules found in the skin and in the retinal pigmented epithelium. (1)

71. Visible wavelengths correction factor: C_B 43.65. Correction factor which greatly increases the MPE values in the red end of the visible spectrum (450-600nm), because of greatly reduced photochemical hazards. (1) Per Table 6;

$$C_B = 10^{\ 20(\lambda-0.450)}$$

$$= 10^{\ 20(0.532-0.450)}$$

$$= 10^{\ 1.64}$$

$$= 43.65$$

72. Special near-infrared correction factor: C_C N/A. Correction factor which increases the MPE values for ocular exposure because of pre-retinal absorption of radiant energy in the spectral region between 1150 and 1400nm. (1)

73. Extended source correction factor: C_E N/A. Correction factor used for calculating the extended-source MPE for the eye from the small-source MPE, when the laser source subtends a visual angle exceeding α_{min}. (1)

74. Total pulses: N/A.

75. Extended source effective total pulses: N/A.

76. Multiple pulse correction factor: C_P (Extended) N/A.

77. UV eye or skin exposure over 2 days: N/A.

Conclusion

Training and education are key components to safe use of laser energy. In order to properly address laser safety issues in a work environment an individual shall be designated the Laser Safety Officer (LSO) with the authority and responsibility to monitor and enforce the control of laser hazards and to effect the knowledgeable evaluation and control of laser hazards. This requires an understanding of all hazards, applicable regulations and guidelines and the implementation and documentation of appropriate training programs, control measures and medical surveillance for employees, laser personnel and service representatives. Laser safety is no accident!

Notes

1. ANSI Z136.1 2000/2.0 Definitions
2. ANSI Z136.1 2000/Table 5a, page 45
3. ANSI Z136.1 2000/Table 10, pgs. 51, 52

4. LAZANLITE software (version 3.6.8), Rockwell Laser Industries
5. Technical Educational Research Center (TERC)/Laser Optics/Module 5-8, Polarization
6. Technical Educational Research Center (TERC)/Fundamentals of Lasers & Measurements/Module 1-9, Spatial Characteristics of Lasers
7. The Photonics Dictionary/Book 4/2005/Photonics Spectra/51st International Edition
8. ANSI Z136.1 2000/Table 8, pg. 49
9. ANSI Z136.1 2000/9.2, Small-Source & Extended-Source Measurements, pg. 39
10. ANSI Z136.1 2000/B6.6.1, Diffuse Reflection Hazards, eq. B65, pg. 109
11. ANSI Z136.1 2000/Fig. B7, pg. 126
12. ANSI Z136.1 2000/Fig. B6, pg. 125

**Some of the mathematical symbols (Greek Alphabet) used in calculations presented in this report are not the exact & proper symbols due to limited options in Microsoft Word. A complete list of symbols is shown in Appendix B (pgs. 86-87) of the ANSI Z136.1/2000 standard.