LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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A Proposed Laser Incident Threshold Level

Peter King

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LIGO Science Collaboration

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of the LIGO Project.

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW22-295
185 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 159
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

1 Introduction

For Initial LIGO the laser incident threshold level for errant beams was set to be 100 μW. If a beam was found to be above this level, then a laser incident was deemed to have occurred. The laser would then be shutdown by the Laser Safety Officer and restoring the laser required LIGO Directorate approval.

With the advent of the 200 W Advanced LIGO Laser, it seems timely to revisit the 100 μW limit. 100 μW corresponds to the transmission of a 0.5 ppm mirror which is difficult, if not impossible, to obtain.

It should be noted that all stray beams and scattered light should be dumped or contained as a matter of good practice. It is proposed that the laser incident threshold level be set without regard to laser safety eyewear. This avoids a situation where a 200 W beam is deemed "safe" because people should be wearing laser safety eyewear. Most people would agree that a stray 200 W beam is hardly safe.

This document proposes that a new laser incident threshold be set. For the time being only one wavelength, 1064 nm, is being considered.

2 Properties of the Human Eye

2.1 Focal Length

The commonly accepted value for the focal length of a human eye is approximately 17 mm.

2.2 Pupil Diameter

Various measurements of the pupil diameter can be found in the literature. Whether under the influence of drugs, low light conditions or bright light conditions a good working number for the pupil diameter is 7.0 mm. This number is the one adopted by the ANSI Z136.1-2007 standard.

3 Calculation of Laser Parameters

In working out the Accessible Emission Limit (AEL) or the Maximum Permissible Exposure (MPE), the laser concerned must be categorised as either a small source or an extended source. By definition, a small source is one that subtends an angle, α, at the retina of less than the limiting angular subtense α_{min} (1.5 mrad).

3.1 Assumptions

For the purposes of this note, the distance used to determine the nature of the source is 100 mm. This happens to be the same distance used for the hazard classification of a laser. Although there are not enough 200 W Advanced LIGO Lasers in existence to get a good range for the output beam size of the laser, it is expected that the beam waist of the laser will range from 150 μm to 250 μm. Anecdotally this has been the case with the Initial LIGO 10 W lasers and the many NPRO lasers within the Project.

3.2 Beam Size at Evaluation Distance

For a Gaussian beam of wavelength λ, the beam radius w is given at any location z by the well-known formula

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

3.3 Full Angle Beam Divergence

The full angle beam divergence θ, is given by

$$\theta = \frac{2\lambda}{\pi w_0}$$

3.4 Angular Subtense

The angular subtense α, is given by

$$\alpha = \frac{D_L}{r}$$

For the calculations within this document, D_L is simply taken to be equal to $2w$. Figure 1 shows the relationship between the various quantities and the human eye.

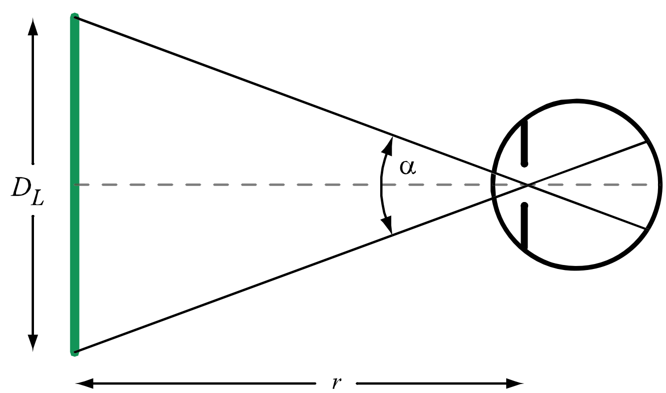

Figure 1. The relationship between the source size D_L, the distance to from the source to the eye r, the angular subtense α and the human eye.

3.5 Laser Parameters

Table 1 lists the assumed and derived laser parameters used in calculating the AEL and MPE values.

beam waist, w_0 (μm)	150	250
full angle beam divergence, θ (mrad)	4.516	2.709
beam diameter, $2w$ (μm)	542	568.7
angular subtense, α (mrad)	5.421	5.687
source type	extended	extended

Table 1. The laser parameters used in calculation of the AEL and MPE for an evaluation distance of 100 mm.

4 Eye Damage Threshold Level

Strictly speaking, eye damage in this context means retina damage. Finding references that state the eye damage threshold level has proven to be difficult. Most papers dealing with eye damage focus on the biological consequences and symptoms, not on exposure limits. It so happens that the ANSI-Z136.1 standard is a good reference, it being the result of a number of different experiments. This technical note bases its numbers on the 2007 ANSI standard and the references listed at the end of this note.

It should be noted that the ANSI exposure limits are a factor of 10 ***below*** any known damage threshold level.

4.1 Pre-retinal Absorption Correction Factor C_C

C_C is a correction factor related to the pre-retinal absorption for wavelengths between 1.150 μm and 1.400 μm. For 1064 nm, C_C is equal to 1.

4.2 Extended Source Correction Factor C_E

C_E is a correction factor used in calculating the MPE for the eye from the small source MPE. For extended sources with a wavelength between 0.400 μm and 1.400 μm and with an angular subtense between 1.5 mrad and 100 mrad, C_E is given by

$$C_E = \frac{\alpha}{\alpha_{\min}}$$

4.3 Constant Irradiance Injury Time T_2

T_2 is the exposure time beyond which extended source MPEs based on thermal injury are expressed as a constant irradiance. For extended sources with a wavelength between 0.400 μm and 1.400 μm and with an angular subtense between 1.5 mrad and 100 mrad, T_2 is given by

$$T_2 = 10 \times 10^{(\alpha - 1.5)/98.5}$$

Table 2 shows the calculated correction factors used in deriving the proposed laser incident threshold level.

w_0 (μm)	150	250
C_C	1.000	1.000
C_E	3.614	3.791
T_2 (s)	10.960	11.028

Table 2. Calculated correction factors.

5 Threshold Calculations

Table 3 lists the calculated MPEs for various exposure durations, as per Table 5a of ANSI Z136.1-2007 for small sources.

exposure duration, t (s)	MPE
10^{-13} to 10^{-11}	0.15E-6 J.cm^{-2}
10^{-11} to 10^{-9}	0.15E-6 J.cm^{-2}
10^{-9} to 50 x 10^{-6}	5.0E-6 J.cm^{-2}
50 x 10^{-6} to 10	5.4E-6 J.cm^{-2}
10 to 3 x 10^{4}	5.0E-3 W.cm^{-2}

Table 3. Calculated MPE for various exposure durations, in each case the lower bound of the time interval was used.

Converting the MPE values into AEL values simply involves multiplying by the area of the pupil (0.385 cm^{-2}). The lowest value small source AEL is therefore 1.9 mW.

Table 4 lists the calculated MPEs for various exposure durations, as per Table 5b of ANSI Z136.1-2007.

	150 (μm)	250 (μm)
exposure duration, *t* (s)		
10^{-13} to 10^{-11}	0.54E-6 J.cm^{-2}	0.59E-6 J.cm^{-2}
10^{-11} to 10^{-9}	0.55E-7 J.cm^{-2}	0.58E-6 J.cm^{-2}
10^{-9} to 50 x 10^{-6}	18.07E-6 J.cm^{-2}	18.96E-6 J.cm^{-2}
50 x 10^{-6} to T_2	19.34E-6 J.cm^{-2}	20.29E-6 J.cm^{-2}
T_2 to 3 x 10^4	17.9E-3 W.cm^{-2}	18.7E-3 W.cm^{-2}

Table 4. Calculated MPE for various exposure durations, in each case the lower bound of the time interval was used. Note the change in units for the last line of the table.

To the author's knowledge, there are no pulsed lasers within the LVEA with the exception of the thermal compensation system's CO_2 laser, which is run in a quasi-cw manner. Therefore only exposure durations of 50 x 10^{-6} s and higher are considered. With that consideration in mind, Figure 2 shows the calculated AEL versus exposure duration.

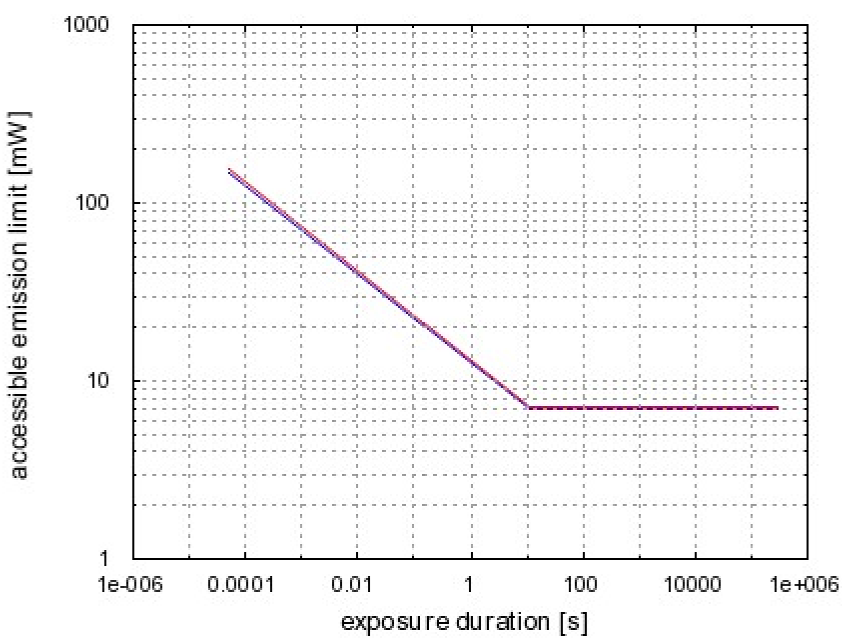

Figure 2. The extended source AEL plotted versus exposure time for the range of angular subtenses considered. The lowest value AEL is (7.0 ± 0.2) mW.

By varying the angular subtense for the range of expected output beam waists, the AEL is calculated to be between 6.8 mW and 7.2 mW. This is higher than the small source AEL by a factor of approximately 3.5.

6 Proposed New Threshold Limit

Considering the worst-case scenarios for extended sources, the proposed laser incident threshold limit is 2.0 mW. This is slightly higher than the small source AEL of 1.9 mW but is an easier number to remember. 2 mW corresponds to the transmission of a 10 ppm mirror, which although is difficult to obtain, it is not impossible.

In short, for a particular wavelength the proposed laser incident threshold is the appropriate small source AEL for that wavelength. This is a worst-case scenario and factors in a safety factor of 10 included by the ANSI Z136.1-2007 standard.

7 Verification Measures

Obtaining accurate and reliable power measurements at the milliwatt level can often be quite difficult and tedious. For verification purposes, a reliable and relatively fast method for measuring the power of the stray beam or scattered light would be desirable. “Fast” meaning on the order of 10 s, since that is the time scale for which the retina is considered to be stationary.

7.1 Verification Eyeball

For measuring the power of the stray beam or stray scattered light, it is proposed that a collection system of a 7.0 mm diameter aperture be used with a 17 mm focal length lens[1]. The detector, placed at the focus of the lens, can be a large area photodetector that has been calibrated for low power levels.

7.2 Verification Location

For the purposes of verification, I would propose that the measurement be done at plane of the optical table edge where the stray beam or scattered light is located. For example, for the PSL this would be at the edge of the PSL table, where the table enclosure doors are located. This would coincide with the closest point a person would access a table without leaning over the edge or climbing onto the table and the point at which a person might sustain an eye injury. Figure 3 shows the geometry for the verification measurement for stray beams or scattered light.

[1] For example, a suitable lens might be the plano-convex lens PLCX-13.3-8.8-C from CVI Laser Corp. that has a focal length of 17.4 mm.

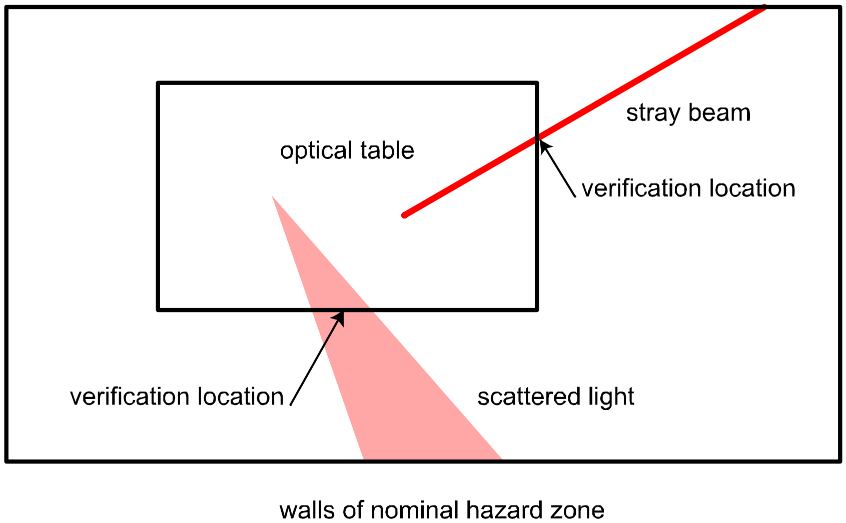

Figure 3. The proposed area where verification measurements of stray beams or scattered light would be performed.

8 References

François C. Delori, Robert H. Webb, David H. Sliney: Maximum permissible exposures for ocular safety (ANSI 2000), with emphasis on opthalmic devices
J. Opt. Soc. Am. A, Vol. 25, No. 5 (2007)

American National Standard for Safe Use of Lasers, ANSI Z136.1-2007

9 Appendix

9.1 Other Wavelengths In LIGO

The Pre-stabilized Laser is not the only laser used within LIGO. Other detector subsystems employ laser of a different wavelength to 1064 nm. Table 5 lists the other wavelengths, known at the time of writing this document, their respective small source MPEs and proposed laser incident threshold level.

detector subsystem/laser	**wavelength λ (nm)**	**MPE ($W.cm^{-2}$)**	**incident threshold (mW)**
Nd:YAG	532	1×10^{-3}	0.4
HeNe	632.8	1×10^{-3}	0.4
optical levers	635	1×10^{-3}	0.4
AOS	980	3.6×10^{-3}	1.4
photon calibrator	1047	5.0×10^{-3}	1.9
TCS	10.6 (μm)	0.1	9.6

Table 5. The proposed laser incident power threshold for other wavelengths encountered in LIGO. For all wavelengths listed, a 7.0 mm diameter aperture was used to calculate the incident threshold power level.