SAM SYSTEM DESIGN NOTE

SAM-AD-02-0004

Laser safety of SAM

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1 Introduction

The SAM LGS system contains a powerful (class IV) Q-switched UV laser. The parameters of the likely laser are listed in Table 1 and used below for the safety analysis. This table also gives the notations for main parameters.

Table 1: Characteristics of the Q301-HD laser from JDSU

Parameter	Value
Wavelength λ	355 nm
Average optical power W	10 W
Pulse duration t_p	34 ns
Pulse repetition frequency f_p	10 kHz
Pulse energy E_p	1 mJ

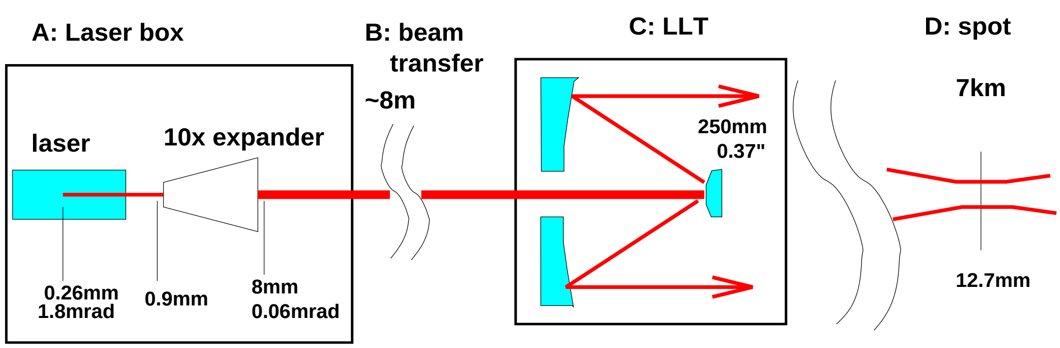

Figure 1: Beam path through the SAM LGS system. The double 1/e^2 beam waist diameter $2w$ and beam divergence 2θ are indicated.

A schematic of the SAM LGS system is given in Fig. 1. For the purpose of safety analysis, we consider 4 zones:

1. **Zone A - laser box.** The light- and air-tight box encloses the laser, beam expander and some other optics.
2. **Zone B - beam transfer** from the box to the laser launch telescope (LLT) located above the SOAR secondary mirror.
3. **Zone C** - beam exiting from the LLT.
4. **Zone D** - beam propagation in free air, including the beam waist at a distance of ∼7km.

2 Effects of the UV radiation and MPE

2.1 Biological effects of the UV laser radiation

The 355 nm wavelength of the SAM laser is outside the visible range. At 380 nm, the photoptic efficiency of human eye is already as low as $4 \cdot 10^{-5}$ relative to maximum sensitivity at 555 nm, so the SAM laser is totally invisible. Visual hazards and retinal damage are not produced by this laser.

The adverse biological effects of the UV laser are essentially of two types – thermal and photo-chemical. The maximum permissible exposure (MPE) for the eye and the skin is the same. In UV-A (315–400 nm), the absorbtance of the cornea is quite small and the lens is the predominant absorber. *Thermal damage* of the cornea and the lens is the main concern for pulsed lasers. The skin absorbs the UV radiation efficiently (it penetrates only by ∼0.01 mm), essentially by the pigments of the epithelium.

The *photo-chemical* effects can occur at irradiances that are not sufficient to cause thermal damage. At UV wavelengths, the photon energies are high enough to create toxic radicals in the cells or even to damage the DNA molecules, in remote analogy with sun-burns. However, in the UV-A range the thermal effects dominate and determine the MPE.

Very short (nanoseconds) and intense pules can provoke a *thermo-mechanical* injury caused by the thermal explosion of the tissue. This regime is not relevant for SAM (34 ns pulses).

The heat in the skin or cornea creates a sensation of pain and provokes the *aversion response.* The aversion response time is set conservatively at 10 s. This is why the thermal MPE is constant for longer exposures. On the other hand, the photo-chemical effect does not produce an aversion reaction and is cumulative up to 8 h (30 000 s). For longer exposures, the additivity of exposure time does not hold because the repair mechanisms set in.

2.2 MPEs

The Maximum Permissible Exposure (MPE) for exposure time t ranging from 1 ns to 10 s and $\lambda =$ 355 nm is defined by the ANSI standard [3] as C_1 [J/m^2], where $C_1 = 5600\, t^{0.25}$ (see also HS04, p. 125). For $t > 10$ s, the MPE is 10^4 J/m^2. [1] The MPEs for the skin and the eye are the same. However, in calculating the MPE, the incident radiation must be averaged over a circular *limiting aperture* which is 1 mm for the eye and 3.5 mm for the skin (HS04, p. 87).

Let E be the intensity of the laser beam (in W/m^2) at some location and t – the exposure time to the laser radiation. The ANSI MPE translates to the requirement that

$$Et < 5600\, t^{0.25} \quad \text{or} \quad t < (5600/E)^{4/3}. \tag{1}$$

[1] The European stranded gives a more relaxed limit of 10 W/m^2 for exposure durations above 1000 s

The photo-chemical MPE limit increases with the wavelength. A strong (by more than 2 orders of magnitude) increase occurs between 300 nm and 320 nm (HS04, Fig. 3.18). The official photo-chemical MPE of 10^4 J/m^2 is conservative at 355 nm, by as much as an order of magnitude. At 355 nm, the thermal MPE is always more restrictive than the photo-chemical MPE.[2]

Exposure to multiple laser pulses in the UV is evaluated according to special criteria.

1. First, each single pulse must be below the MPE, calculated for the pulse duration.

2. Second, the irradiance averaged over some duration t must be below the MPE. All averaging times between the pulse duration and the maximum exposure time have to be considered (HS04, p. 127). In the case of SAM (constant pulse repetition rate), the maximum exposure time gives the more restrictive limit. It should be normally set to the thermal aversion time of 10 s.

3. The ANSI laser safety standard also requires that the radiant exposure for each laser pulse be less than the MPE reduced by $N^{-1/4}$, where N is the total number of pulses within anticipated exposure duration. This condition applies for SAM (thermal damage in the UV). It sets more strict limit for exposure durations that satisfy the condition $t^2 f_p^3 t_{pulse} < 1$, or, in case of SAM, $t < 5$ ms. Hence, the standard MPE without pulse correction is more restrictive for exposure durations above 5 ms.

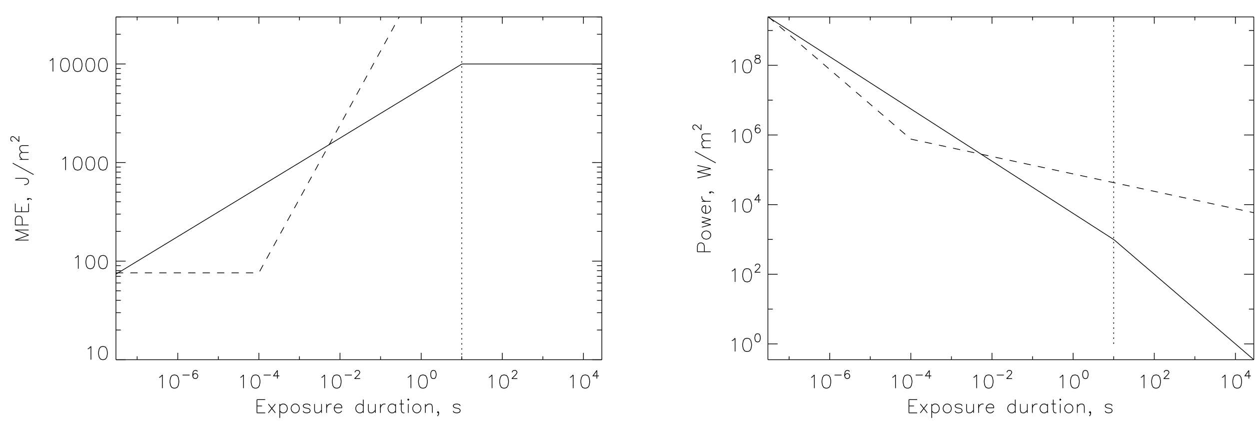

Figure 2: Maximum permissible exposure (left) and corresponding intensity (right) for skin and cornea exposure at the 355 nm wavelength. The dashed line includes the additional $N^{-1/4}$ correction for the number of pulses ($f_p = 10$ kHz). The vertical dotted line marks the maximum exposure time $t = 10$ s limited by aversion.

Figure 2 shows the MPE levels for skin and cornea exposure in function of the exposure duration. For the anticipated maximum exposure duration of 10 s (limited by aversion), the MPE is 10 000 J/m^2, with the corresponding power of 1000 W/m^2 or 0.1 W/cm^2.

[2] The exposure time longer than T_1 where the photo-chemical limit becomes more restrictive than the thermal limit is defined by the standard as $T_1 = 10^{0.8(\lambda-295)-15} = 10^{33}$ s for $\lambda = 355$ nm, i.e. longer than the age of the Universe.

2.3 Other effects

Potential hazards of a powerful laser are not limited to the direct effects of its radiation. The laser beam can cause fire and/or smoke when interacting with flammable materials. The laser itself and its power supply can be dangerous becasue they contain high voltage (Q-switch).

3 Estimation of the exposure levels

The intensity in a Gaussian laser beam decreases form the center outwards following the law

$$E(r) = W \, \frac{2}{\pi w^2} \, e^{-2(r/w)^2}, \tag{2}$$

where W is the total beam power in Watts, $E(r)$ is the intensity in W/m^2, w is the 1/e^2 beam waist radius and r is the radial distance. For safety evaluation, we calculate the maximum intensity at the center, $E(0)$. This over-estimates the hazard in the narrow laser beam (compared to the 3.5 mm averaging aperture for skin), but this beam is highly dangerous anyway. We adopt conservatively $W = 10$ W, neglecting the light losses.

Table 2 lists the intensities in various zones of the SAM LGS system. The maximum exposure time t_{max} was evaluated from Eq. 1 for zones C and D. It makes no sense to define this time for the zone A because even exposure to a single laser pulse is not safe. For the zone B, we obtain $t = 3.4$ ms without N-pulse correction and 1.4 ms with this correction; the most restrictive of these two numbers is given in Table 2.

Table 2: Intensity in the SAM LGS system

Zone	w, mm	E, W/m^2	t_{max}
A	0.45	3.1 10^7	0
B	4.0	4.0 10^5	1.4 ms
C	124	415	32 s
D	6.3	1.6 10^5	11.4 ms

The conclusion from Table 2 is that the SAM laser beam is safe only in zone C, with a safety margin of 3.2. The exact parameters of the design might change, but this will not influence the conclusion on the safety because the MPEs in zones A, B, and D are exceeded by many times.

Let us now evaluate the safety of the scattered beam. The intensity of the diffusely scattered radiation at a distance z from the scatterer is governed by the Lambert's law

$$E = \frac{RW \cos\beta}{\pi z^2}, \tag{3}$$

where R is the reflection coefficient, β is the angle with normal to the surface. We assume conservatively $R = 1$, $\beta = 0$, $W = 10$ W. The size of the beam falling on the scatterer is not important.

Assuming the exposure time of 10 s, we find from Eq. 3 that the safe distance is $z_{safe} > 5.6$ cm. For an 8-h exposure, $z_{safe} > 3.1$ m. Thus, if the laser beam falls on the dome and is scattered diffusely inside, it is safe to work in the dome without protection.

4 Safety engineering

The SAM LGS system and the mode of its operation must be safe for the SOAR personnel and telescope users. The safety should be maintained in case of a single-mode failure.

4.1 Operational modes

Three distinct modes of the LGS are defined.

1. **Non-operational.** During all works not related to SAM, the laser must be switched off. Engineering protection against any accidental switching of the laser will be provided, e.g. by a special key.

2. **Observations.** The hazardous parts of the laser beam will be enclosed in the box or tubes. Inter-locks and alarm switches will be provided to turn off the radiation immediately in case of un-authorized access to the box or failure. All these measures ensure that the system will be safe for normal use. No special protective measures or training will be needed.

3. **SAM maintenance**. During beam alignment or some tests, an exposure to the laser beam is more likely. Safety inter-locks may be occasionally over-ridden. Maintenance is the most hazardous mode and should be done only by qualified personnel trained in laser safety. Protective clothing and eye-wear will be required.

4.2 Risk analysis during observations

The narrow beam emerging from the laser is intercepted by a small shutter mirror and directed to the beam dump located in the laser box. The shutter is removed from the beam by a solenoid only when the laser emission on the sky is required. The solenoid is controlled by a special circuit and connected through the inter-locks and emergency buttons. In case of the failure of this circuit or the loss of power, the shutter remains closed. Re-opening the shutter requires a special sequence of actions (the shutter will not be re-opened automatically when the failure condition disappears).

Some potential failures and their effects are listed below.

LGS beam falls on the dome because the telescope and dome lost the synchronization or the dome was closed. The beam will not cause the burning of the dome panels [TBC]. The scattered radiation is safe for the personnel in the dome for exposure duration over 8 h (distance $z > 6$ m). If needed, the scattered radiation can be detected by a photo-diode with a UV filter located somewhere in the dome, to activate the alarm signal and to close the laser shutter.

One of the optical elements in the beam train is severely mis-aligned. In most cases, the mis-aligned beam will be intercepted by the box walls or by the beam-protective tube. The energy density of the beam is high, hence it is necessary to use non-inflammable materials for the beam confinement. If part of the beam between the laser box and the LLT is not confined, it is necessary to evaluate the risk of the beam reaching the dome floor, where people might be present.

For small mis-alignment of the beam train, the beam (or part of it) may hit the entrance port of the LLT or miss part of the secondary and will be scattered into the dome. This situation is similar to the case of the dome illumination and does not present any identified hazards.

An insect gets into the beam and burns. The chance of burning is greatly reduced in the zones B and C (compared to the bare laser beam in zone A) because of the 10x expansion. Beam confinement is recommended to keep away insects and dust. No particular risks are identified.

4.3 Risk analysis during maintenance

Maintenance and alignment procedures will be defined in such way as to minimize the risks. Such measures may include the following:

1. use CCD detectors instead of eye whenever possible;
2. do most of the alignment with the visible low-power laser substituting the UV laser beam;
3. minimize the number of persons involved, define safe positions for each person during hazardous operations;
4. use protective eyewear and clothing.

Risk analysis during alignment and maintenance will be done for each procedure separately.

5 Aircraft and satellite safety

5.1 Aircraft safety

Visible laser beams present serious visual hazards for aircraft. The SAM laser is invisible, therefore visual hazards do not exist. We show below that the SAM laser is safe for any aircraft. We evaluate the risk of exposing bare, unprotected human skin and cornea while crossing the SAM beam in zone D, where the energy concentration reaches its maximum. Thus, according to the established practice, we take conservative approach and neglect additional factors that could increase the safety (such as absorption of the UV radiation in the air and by the window glass or plastic, direction of the laser beam, etc.). We further assume that if the beam is safe for human beings, there is no risk to the aircraft itself related to potential damage by the laser beam.

The beam waist diameter in the zone D is $d = 12.5\,\mathrm{mm}$, the energy density is $1.6\,10^5\,\mathrm{W/m^2}$ and the maximum permissible exposure time is $t = 11.4\,\mathrm{ms}$ (cf. Table 2). If the object crosses the beam fast enough, the crossing time will be less than 11.4 ms and the MPE level will not be exceeded. This happens if the object transverse velocity is larger than $V = d/t = 1.1\,\mathrm{m/s}$ or 3.9 km/h.

Commercial jet aircrafts fly at ∼10 km altitude with a typical speed of 900 km/h or 250 m/s. The transverse component of this velocity (perpendicular to the laser beam) will be smallest when the telescope is pointed at the lowest angle, 30° above the horizon, and the beam and aircraft speed have same azimuth. Even in this most unfavorable case, the transverse aircraft velocity is 125 m/s and the laser beam is safe with a safety margin of 113 times. The safety margin would be reached only for an aircraft moving with a speed of less than 9 km/h, which is impossible for airplanes.

The SAM laser beam is safe for any airplane and there is no need to use "spotters" to detect airplanes.

In principle, we can envision unlikely situation when a helicopter moves inside the SAM beam in a direction towards the telescope (i.e. downwards at an angle of more than 30° to horizon), "diving" into the laser beam. In this case, the thermal effect of the laser beam can exceed the MPE, putting the pilot at risk. To our knowledge, night-time helicopter flights are not permitted for reasons of visibility. If such flights do take place, an avoidance zone with a radius of 15 km around Cerro Pachón could be established to prevent potential risks, or a coordination with the laser launches would be required.

5.2 Satellite safety

According to ANSI,[3] scientific and research lasers require clearance by the U.S. Space Command (CMOC/J3) if beam divergence is below 10 μrad or if the peak irradiance at 18 km a.s.l. exceeds 1 mW/cm^2. The SAM laser beam emerges from the $D = 30$ cm aperture and is focused at a distance of $H = 7$ km, which gives a geometric divergence of $\epsilon = D/H = 43\,\mu$rad, or $8''$.

The irradiance at 18 km a.s.l. (15 km above telescope) in the worst case (zenith viewing) will be about 1/2 of the irradiance at the exit of the LLT (the beam is focused at 7 km and then diverges again, 1/2 is absorbed by the air), i.e. 110 W/cm^2 = 11 mW/cm^2. Such radiation is safe for exposure of > 10 seconds, hence it is safe for any moving space vehicle with a huge margin. Apparently, the low threshold established by the Space Command for the 18-km altitude is related to visual hazards for spacecraft entering the atmosphere and is irrelevant for SAM.

At a low orbit ($h = 200$ km), the 1/e^2 radius of the SAM beam is determined be its focusing at 7 km and is 200/7 times larger that at the LLT aperture, or 3.5 m. According to Eq. 1, the illumination is 0.5 W/m^2 and the irradiance created by one laser pulse will be 0.05 mJ/m^2. In fact about 1/2 of the energy will be absorbed by the air, but, on the other hand, a satellite can receive several pulses, hence the estimated irradiance level is conservative.

Some consultation with the Laser Clearinghouse is needed related to potential hazard of the SAM LGS and the need to co-ordinate the target lists and observing moments with the Space Command.

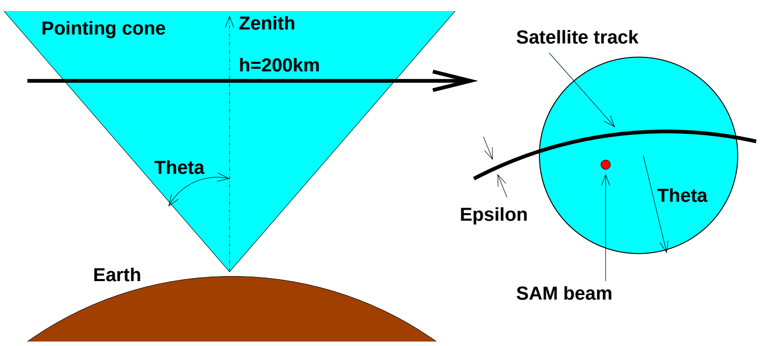

Figure 3: Calculation of the probability of illuminating a low-orbit satellite with the SAM beam. The geometric probability P_θ depends on the pointing cone half-angle θ and the spot angular diameter ϵ.

A rough estimate of the probability of hitting a satellite with the SAM laser beam shows that such event can happen. The calculation for low-orbit satellites is done as follows (Fig. 3). The SAM beam is assumed to have angular diameter of $\epsilon = D/H = 8'' = 43\,\mu$rad. It can be directed anywhere from the zenith to the zenith distance $\theta = 60°$. The solid angle of this *pointing cone* is $2\pi(1 - \cos\theta) = \pi$ steradians. The geometric probability P_θ that a satellite crosses the laser spot is the ratio of the satellite track surface, assumed $2\epsilon\theta$ (track near zenith) to the field solid angle,

$$P_\theta = \frac{2\epsilon\theta}{2\pi(1 - \cos\theta)} = (2/3)\,\epsilon = 2.9\,10^{-5}. \quad (4)$$

The speed of a low-orbit satellite is about 7 km/s, the height is assumed to be 200 km. The angular speed is hence $7200''$/s. During the 0.1 ms period between laser pulses the satellite will move on the sky by $0.72''$ – less than ϵ. This justifies the assumption that the "hit track" is continuous, rather than composed of individual pulses. The satellite will receive several ($\sim$12) laser pulses when crossing the SAM beam.

[3]ANSI Chapter 4.2.2

The satellite will cross the SAM pointing cone in $t_{cross} \sim 50\,\mathrm{s}$ every orbital period $P_{orb} \sim 1.5\,\mathrm{h}$. During an observing night of $T = 10\,\mathrm{h}$ duration, there may be as much as $N_{cross} = T/P_{orb} = 6.7$ crossings. Of course, the "pointing cone" rotates with the Earth, while the satellite's orbit does not. In 1.5 h, the Earth turns by 22.5°, hence a given orbit can still cross the 120° pointing cone ~ 5 times during the night. So we assume $N_{cross} = 5$ crossings per night.

We evaluate the probability of illuminating a satellite during a 5-year period with 100 nights of observing per year, or a total of $K_{night} = 500$ nights. For any given low-orbit satellite, the probability to be illuminated by the SAM beam is hence

$$P_1 = P_\theta N_{cross} K_{night} \approx 0.1. \tag{5}$$

Thus, 10% of low-orbit satellites could be illuminated during 5 yr SAM operation. This estimate is very approximate and may be revised. However, the conclusion that the probability of illuminating a satellite with the SAM laser beam is substantial is robust.

6 Conclusion

The SAM LGS system is safe for the personnel during its normal use (observations). In this respect, it matches the criteria for the class I (embedded) laser systems. However, the beam propagates in the free air. It is safe for airplanes, but some coordination with the Space Command may be required.

During maintenance, there are hazards related to the intense, invisible UV beam. All personnel doing maintenance must be trained in laser security and must wear protective clothing and goggles. Special alignment procedures minimizing the risk of exposure will be developed.

References

[1] J. Wilson & J.F.B. Hawkes. Lasers. Principles and Applications. Prentice Hall, NY, 1987

[2] Henderson, R. & Schulmeister, K. Laser Safety. Taylor & Francis, NY, 2004 (HS04)

[3] American National Standard for Safe Use of Lasers Outdoors ANSI Z136.6-2000