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CONTROLS FOR MULTI-WAVELENGTH, TUNABLE AND CONTINUUM LASERS[1]

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Abstract

Many laser operations, especially in research applications, involve Class 3B and Class 4 beams of multiple wavelengths. Protective eyewear for the accessible laser beams can then pose a significant challenge, especially if these wavelengths span a significant portion of the 400-700 nm visible spectrum. The Laser Safety Officer must perform a good hazard evaluation to determine the best combination of engineering, administrative and PPE (personal protective equipment) controls to ensure there is an acceptable level of risk for the laser workers. This evaluation has to employ a hazard controls hierarchy, which gives highest priority to engineering controls.

Examples of multi-wavelength operations include: multiple laser sources; tunable OPAs, OPOs, and OPCPAs; and "white light" continuum lasers. Engineering, administrative and PPE controls for some examples of these are discussed. Full protection laser eyewear should be used for accessible laser beams, but considerations for alignment eyewear and remote operation are also needed.

Introduction

Determining laser hazard control requirements begins with a hazard evaluation of the laser sources that are to be used. What laser wavelengths are present? Which wavelengths are enclosed and which are accessible? For accessible wavelengths, what are the laser beam characteristics, laser classification and optical density (OD) requirements for the laser eyewear? Controls requirements depend on these factors as well as the environment of the area the laser is used in and the people who have access to that area.

The controls hierarchy needs to be employed. Engineering controls are used to mitigate as much of the laser hazard posed as practical. Administrative controls supplement the engineering controls and include Standard Operating Procedures (SOPs), warning signs and training. Lastly, laser eyewear protection (LEP) is needed if engineering and administrative controls are not adequate to ensure protection against a hazardous exposure. In general, LEP should be required for all accessible Class 3B and Class 4 laser beams.

Questions to consider when evaluating the laser hazards and which controls to implement include:

- What enclosures and barriers can be used?
- Can wavelength separators and filters be used to limit what wavelengths are accessible?
- Can remote controls and diagnostics be implemented to facilitate enclosing parts of the laser system or to permit remote operation?
- What combination of engineering and administrative controls are needed so that the LEP used can provide full protection?
- If alignment eyewear is needed, what additional controls are required? (Controls examples to consider for this include: ensuring no out-of-plane beams, perimeter and local barriers for the optics and beam paths, and reducing intensity during alignment.)

The ANSI laser safety standards, Z136.1-2014 [1] and Z136.8-2012 [2] do not have much direct discussion of broadly tuneable lasers or lasers operating at multiple wavelengths. However they provide a lot of general guidance that is applicable, including the following from Z136.1:

- 4.1 General considerations: a controls hierarchy should be followed with engineering controls employed first, followed by administrative controls and then the last line of defense is PPE.
- 4.4.4.2.1 Eye Protection: shall be required when not practical to only use engineering and administrative controls to reduce hazard to an acceptable level.
- 4.4.4.2.3.1 OD specifications for laser eyewear: eyewear may not have adequate OD over the tunable range of a laser, so may want to install cameras that permit remote or enclosed operation.
- 4.4.4.2.5 Alignment eyewear: for all routine laser operations and for most laser alignment procedures, the LEP used shall provide full protection against a possible direct beam. Alignment eyewear can be approved by the Laser Safety Officer (LSO), however, for specific procedures with visible beams when not practical to use full protection.

[1]Presented at 2019 International Laser Safety Conference, Kissimmee FL; www.lia.org/conferences/ilsc

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Multi-wavelength Lasers and Laser Systems

Consider a laser lab with Ti:Sapphire (Ti:Sa) and Nd:YAG laser systems with associated wavelength hazards shown in Table 1.

Depending on the experimental program, different combinations of wavelength hazards may be present. It is possible to choose LEP that blocks all the hazards listed in Table 1, but it would have a very low visible light transmission (VLT) of ~15% or less and so can be difficult to use.

A good approach for determining the controls to use is to first define the desired laser operation modes and what their accessible wavelengths are. An example is shown in Table 2, with the current mode highlighted. In this example, the laser facility operates at times with only one of the two laser systems but sometimes may operate with both. For each of the three possible laser modes it may operate with only the fundamental wavelength accessible (Normal mode), with the fundamental and harmonics wavelengths accessible (Normal with Harmonics), or with the fundamental and pump wavelengths accessible (Maintenance).

Table 1: Laser hazard parameters

Laser system	λ (nm)	Max average power	Pulse width (FWHM)	Pulse Energy	Rep. rate	OD[1]
Ti:Sa oscillator	800	600 mW	15 fs	8.9 nJ	68 MHz	3.0
Ti:Sa regen	800	0.42 W	35 fs	3.5 mJ	120 Hz	5.4
Ti:Sa MPA	800	2.4 W	40 fs	20 mJ	120 Hz	6.1
Ti:Sa Oscillator pump	532	5.0 W	CW	CW	CW	3.7
Ti:Sa Regen, MPA pump	527	6 W	250 ns	50 mJ	120 Hz	5.8
Ti:Sa SHG	400	1.2 W	50 fs	10 mJ	120 Hz	5.7
Ti:Sa THG	267	0.6 W	50 fs	5 mJ	120 Hz	5.3[2]
Nd:YAG	1064	7 W	10 ns	700 mJ	10 Hz	6.0
Nd:YAG SHG	532	3 W	7 ns	300 mJ	10 Hz	6.6
Nd:YAG THG	355	1 W	5 ns	100 mJ	10 Hz	3.4

[1] Laser eyewear optical density (OD) requirements are for "effective ODs" that need to take into account the spectral bandwidth of ultra-short pulse laser beams (<~100 fs). They are determined with these considerations:

- ANSI Z136.1-2014 MPE values are used
- Exposure times are chosen to be 100s for UV (180-400 nm), 0.25s for Visible (400-700 nm) and 10s for IR (700 nm – 1 mm).
- Lasers with pulse widths shorter than ~100fs have a significant bandwidth. Hence, an effective OD [1] needs to be used which convolutes the laser spectrum with the "OD vs wavelength" curve supplied by the laser eyewear manufacturer. This table specifies the laser's central wavelength, but not its spectrum.

[2] For UV pulses shorter than 10 ps, a limited pulse width of 10 ps is used for the OD calculation since the single pulse MPEs are not given in Z136.1 for pulse widths shorter than 1ns and these shorter pulses have their MPEs scaled to keep the peak power the same as for ns pulses. Thus, for short UV pulses the single pulse MPEs are no more than 100 times the single pulse MPE for a ns pulse

Table 2: Laser Operation Summary

Laser Mode	Operation Mode	Accessible wavelengths (nm)
Ti:Sa	Normal	267, 355, 400, 527, 532, 800, 1064
Nd:YAG	Normal w/ Harmonics	
Ti:Sa + Nd:YAG	Maintenance	

Once the laser hazards and desired laser operation modes are determined, the appropriate controls can be developed with appropriate review and approval by the LSO. Example controls to consider are listed below.

<u>Multi-wavelength Engineering Controls</u>

- Safety shutters. These should be installed at the output of the Ti:Sa and Nd:YAG lasers. If practical, the safety interlock system (SIS) for the laser facility should only enable a shutter if the appropriate Laser mode is selected. Safety shutters

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could also be installed before harmonics crystals; and then, if practical, only enabled when a Harmonics mode is selected.

- Protective housings and cover interlocks. The Ti:Sa and Nd:YAG lasers should have protective housings with associated removable covers and cover interlocks. These interlocks would be active in a Normal operation mode, but could be bypassed or inactive in a Maintenance mode that allows the cover to be removed. With the protective housing cover installed, the pump laser wavelengths are fully enclosed.
- Laser operation modes. When practical, use the SIS to define these modes with associated electronic warning sign displays, cover interlocks, and permissives to enable safety shutters and laser power supplies.
- Laboratory lighting. This should provide capability for at least 500 lux throughout the laser lab, including on the optics tables. Higher illumination may be desired if the LEP has very low VLT. The lighting should also be easily adjustable so it can be dimmed to assist with some diagnostics such as fluorescent viewing cards.

Multi-wavelength Administrative Controls

- SOPs. These should define the laser operation modes and what wavelengths can be accessible for each. The associated requirements for each mode should be described, including: how to set the mode, which LEP to use, and what the configuration requirements are for safety shutters, enclosures and any other barriers.
- Warning signs and equipment labels. An electronic warning sign (or a posting/whiteboard indication) at the LCA (laser controlled area) entryway or eyewear storage location should indicate the laser operation mode, accessible wavelengths and LEP requirement. Equipment device labels may be needed for some covers, enclosures or barriers.
- Training. Laser workers require appropriate training specific to the lasers and laser wavelength hazards they will work with. A training syllabus should be developed and the training for each worker documented.

Multi-wavelength PPE Eyewear Controls

- LEP selection. For each laser operation mode, LEP needs to be identified that protects against the accessible wavelengths. An evaluation is needed to select an appropriate number of different eyewear types that balances the need for good VLT with the complexity and cost of having too many types.
- LEP labeling and storage. The frames of the LEP should have labels that identify the filter type or the laser operation mode the LEP is to be used for. A legend chart at the LEP storage location can be used to describe the characteristics for each type of LEP, the corresponding frame label and what modes or wavelengths they can be used for.

Tuneable Lasers – OPAs, OPOs and OPCPAs

Optical parametric amplifiers (OPAs), optical parametric oscillators (OPOs) and optical parametric chirped pulse amplifiers (OPCPAs) use frequency mixing in non-linear crystals to generate secondary laser beams whose wavelengths are tuneable. As an example, let's consider an OPA that is pumped with a short-pulse 800 nm Ti:Sapphire laser. A small fraction of the 800 nm pump beam can be focused onto a crystal to generate white light continuum (WLC). The WLC is then combined with the main pump beam in another crystal to parametrically amplify the signal (S) component of the WLC whose wavelength is correctly phase-matched with the pump. The wavelength of the signal can be tuned by adjusting the angle of the crystal and the time delay between the pump and WLC. This parametric amplification process also generates an idler (I) beam whose frequency is the difference between the pump and the signal, $w_P = w_S + w_I$. Frequency mixing and harmonics conversion of the pump, signal, and idler beams in additional crystals (often done in a separate frequency mixing enclosure) enable other OPA beams in the range from 240-20,000 nm as summarized in Table 3 (SH is second harmonic; FH is fourth harmonic, SF is sum frequency with pump, and DFG is difference frequency generation between signal and idler).

Table 3: OPA beams and wavelengths

Pump and OPA Beams	Wavelength (nm)
Pump	800
Signal (S)	1100-1600
Idler (I)	1600-2400
SHS	550-800
SHI	800-1200
SFS	478-533
SFI	533-590
FHS	295-400
FHI	400-478
SHSFS	240-266
SHSFI	266-295
DFG	2400-20000

Which pump and OPA beams are accessible will depend on the configuration of the OPA, any subsequent frequency mixing, and the wavelength separators and beam dumps that may be used.

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In addition to the pump and OPA beams with associated wavelength hazards noted in Table 3, additional wavelength hazards can be present from the WLC and also from un-phase-matched beams from sum and difference frequency generation. The WLC and un-phase-matched beams are at much lower irradiance than the pump and main OPA beams, typically at or below the Class 3R accessible emission limit (AEL) or at the lower end of the Class 3B range. They can be fully enclosed with the proper use of OPA and frequency mixing stage enclosures and with a wavelength separator at the output.

OPA Engineering Controls

- Protective housing and cover interlocks. The OPA (and any additional frequency mixing stage) should have a protective housing whose cover is on for normal OPA operation. The cover can be interlocked to insert a safety shutter that blocks the pump beam if the cover is removed. The cover interlock can be defeated during tuning procedures.
- Safety Shutter and/or input beam block. In addition to the OPA manufacturer's safety shutter, it may be useful to have an additional safety shutter or input beam block in the pump beam path before the OPA. This additional safety device could be interfaced to the lab's SIS or used as part of a procedural control.
- Wavelength separator. To limit the accessible wavelengths, a wavelength separator can be installed at the OPA or frequency mixing stage output.
- Configuration controls. Ensure that configuration changes involving non-interlocked devices require a tool to move them.

OPA Administrative Controls

- SOPs, Warning signs and equipment labels, Training. Similar controls as those described above for multi-wavelength lasers should be used.
- Enclosure covers and wavelength separators. As much as practical, operate with enclosure covers on. Use wavelength separators as appropriate.
- Configuration changes. Block the pump beam when changing the configuration.
- Optimization with enclosure covers removed. Block the output beam or ensure it is terminated in appropriate diagnostics.
- Operating wavelength. If the LEP does not provide protection at the operational wavelength, perform the OPA optimization and beam alignment at a wavelength covered by the LEP. Then operate remotely/unattended at the desired operational wavelength.

OPA PPE Eyewear Controls

- LEP selection, labeling and storage. Similar controls as those described above for multi-wavelength lasers should be used.
- Alignment eyewear. The LSO can evaluate if alignment eyewear is needed and appropriate for use with visible OPA beams as well as for any WLC or un-phase-matched beam that may be present. To the extent practical, use full protection eyewear. Use remote operation for laser wavelengths the LEP does not provide protection.

Continuum Lasers

While tuneable lasers operate over a dynamic range of wavelengths one at a time, "white-light" continuum (WLC) lasers operate at multiple wavelengths simultaneously. A WLC laser can be produced by coupling an intense short-pulse monochromatic 1-micron pump laser into a dispersive non-linear fibre. Raman scattering, four-wave mixing and other non-linear processes create a very broadband laser output. An example spectrum from a WLC fibre laser is shown in Figure 1. If the pump laser intensity is reduced enough then the dominant spectral component is just the wavelength of the pump laser, which in many cases can be used for alignment and initial setup for the application.

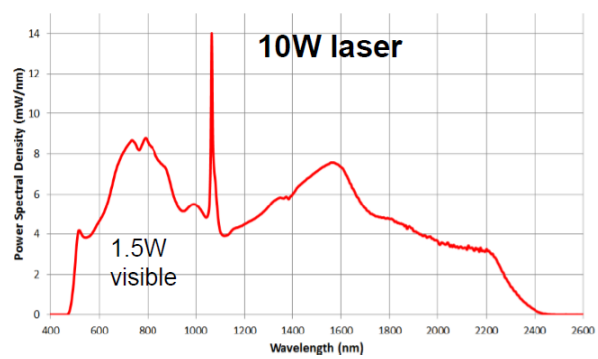

Figure 1: Example of the spectral power density from a WLC fibre laser.[4]

A variety of controls can be implemented to safely operate a WLC laser. These include enclosures, remote operation and use of wavelength separator filters to restrict which wavelengths are accessible.

An example of one application at SLAC is shown in Figure 2 for a Class 3B WLC laser. The enclosure has a movable beam block that does not permit simultaneous operation of the "Visible" and IR output beams. The 1064 nm pump beam is dumped inside the enclosure. For this application the "Visible" and IR beams are at about the Class 3R AEL and do not present

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a significant hazard. The enclosure has a padlocked cover and requires LEP for IR beams, including 1064 nm, for WLC laser operation with its cover removed. Additional controls would be needed for this configuration if operated at higher powers.

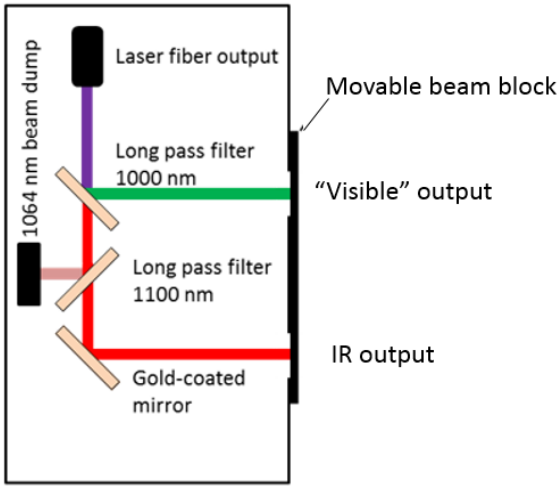

Figure 2: Enclosure, with locked cover, for a WLC laser with output apertures for "Visible" and IR beams.

Continuum Laser Engineering Controls

- Enclosure. Use a protective housing or enclosure with secured or interlocked covers for as much of the WLC laser system as practical.
- Safety shutter. Install a safety shutter at the WLC laser output. If practical, the SIS for the laser facility should only enable this shutter if an appropriate Laser mode is selected.
- Wavelength separator. To limit the accessible wavelengths, implement appropriate filters or wavelength separators.
- Configuration controls. Ensure that configuration changes involving non-interlocked devices require a tool to move them. Keep beam paths in the horizontal plane and install side panel perimeter barriers.
- Remote operation. Install controls and diagnostics to permit remote or unattended operation.

Continuum Laser Administrative Controls

- SOPs, Warning signs and equipment labels, Training. Similar controls as those described above for multi-wavelength lasers should be used.
- Enclosure covers and wavelength separators. As much as practical, operate with enclosure covers on. Use wavelength separators as appropriate.
- Alignment. Reduce the pump beam intensity to below threshold for generating WLC and perform as much alignment as practical with just the pump beam wavelength. Keep all beams in the horizontal plane. After pump alignment is complete, can raise intensity to generate WLC; an alignment eyewear procedure approved by the LSO may be required.
- Configuration changes. Block or disable the WLC laser output when changing the configuration.

Continuum Laser PPE Eyewear Controls

- LEP selection, labeling and storage. Similar controls as those described above for multi-wavelength lasers should be used.
- Alignment eyewear. The LSO can evaluate if alignment eyewear is needed and appropriate for use. To the extent practical, use full protection eyewear. When using alignment eyewear: perform frequent stray beam checks, ensure all beams are in the horizontal plane and confine laser beams to regions defined by perimeter barriers. Use remote operation for laser wavelengths the LEP does not provide protection.

References

[1] American National Standard *for Safe Use of Lasers*, ANSI Z136.1, (2014) published by Laser Institute of America, http://www.lia.org/.

[2] American National Standard *for Safe Use of Lasers in Research, Development or Testing*, ANSI Z136.8, (2012) published by Laser Institute of America, http://www.lia.org/.

[3] *Calculating laser eyewear effective OD and VLT using manufacturer OD curves*, Igor Makasyuk and Michael Woods, TP1002 presented at this conference.

[4] *Continuum "White Light" Generation*, T. Gerke, presentation at the 2013 DOE Laser Safety Officer Workshop.

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