Multiple Wavelength Laser Safety

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Info

Began working in the Laser and Radiation Safety field in 1987, after leaving the US Navy.

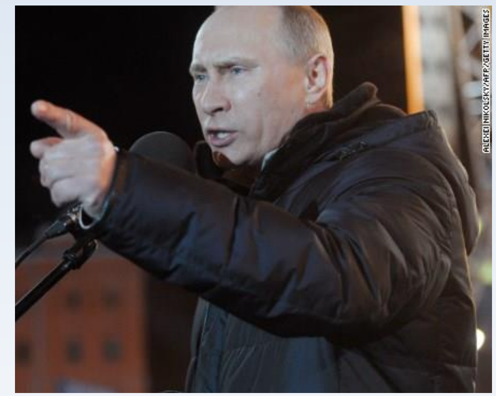
Past Experience:

- NASA-Ames Research Center
- UC Berkeley
- University of Cincinnati
- DOE
- Honeywell

Laser Safety Program Fails

Political Program

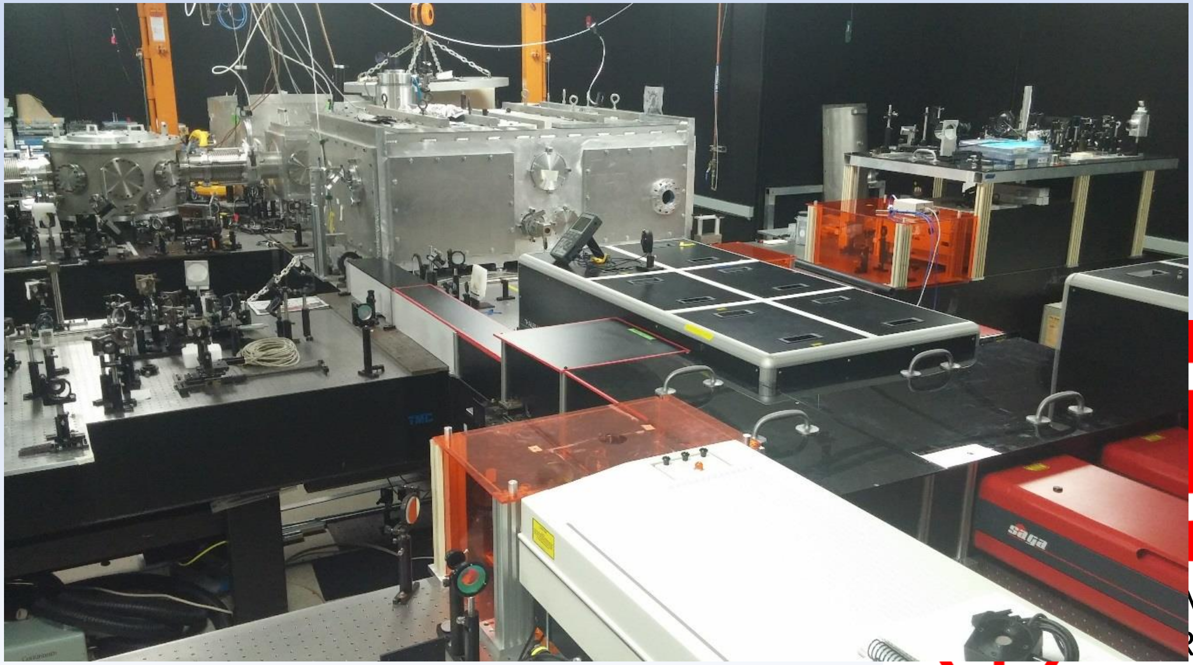
Do Nothing…

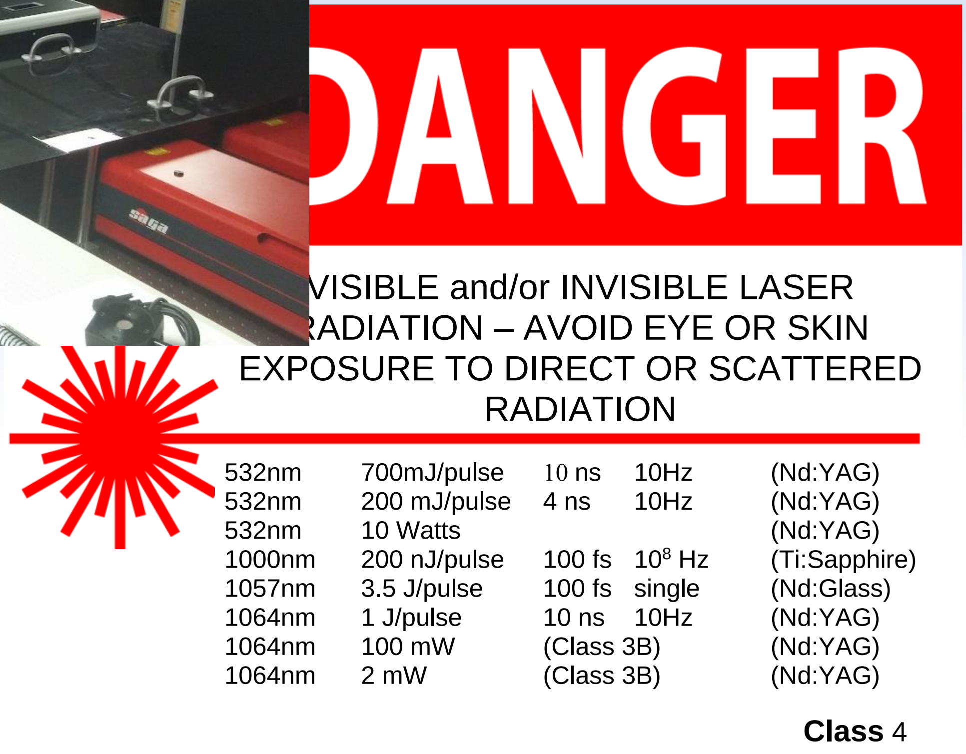


…blame everything

Multiple Wavelength Labs

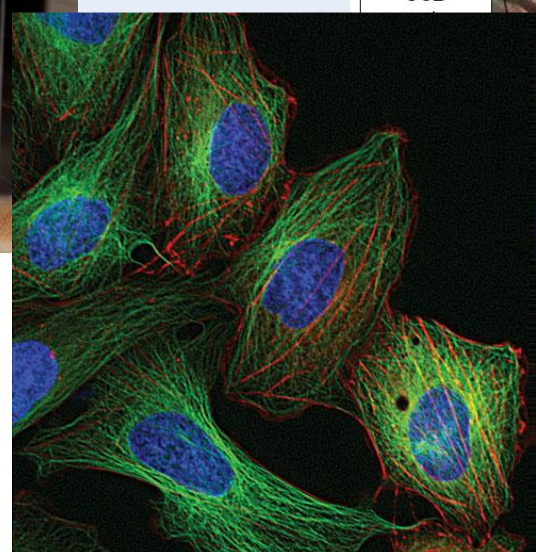
- Hi Power Physics Labs

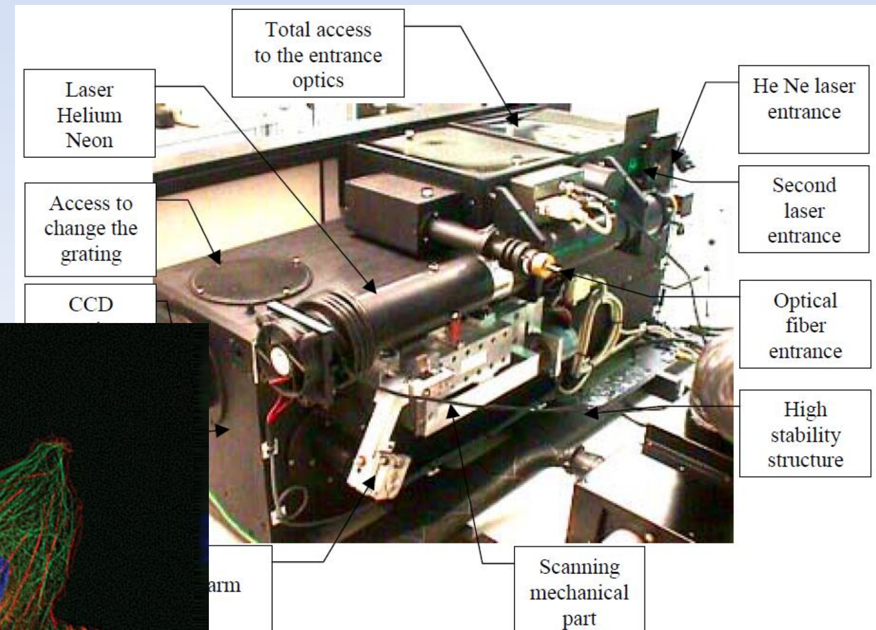




Multiple Wavelength Labs

- Biological Imaging, In Vivo interactions
  - Multiple lasers for bio-imaging microscopes
  - Lasers interacting with living cells, living animals





Topics to Consider

- Tissue Absorption
- Exposure Conditions
- Laser Beam Configurations
- Standards and Guidance
- MPE Calculation
- Laser Protective Eyewear

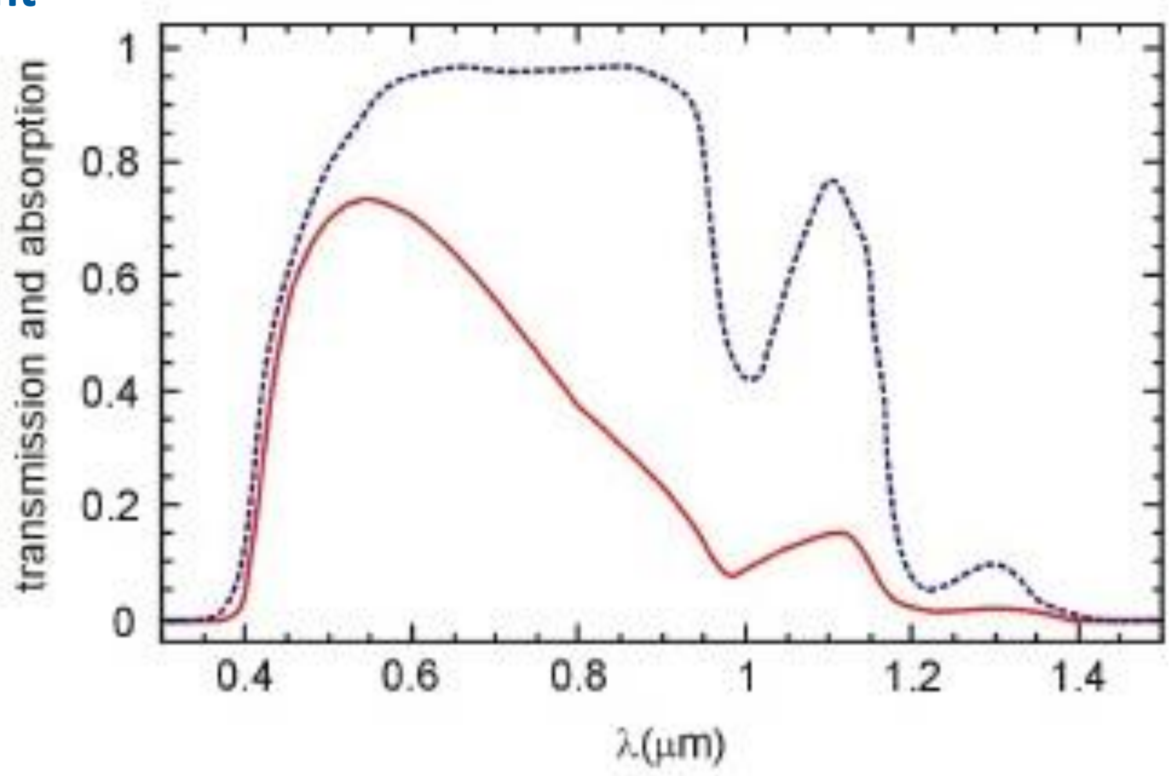
Guidance on Additive Wavelengths

- Additive on tissue sites- (T. Lyon, HP Journal, 1985)
  - "Often the output beam from such a laser system will contain multiple wavelengths which must be considered collectively from a hazard analysis standpoint."
  - "When multiple wavelengths act on the same tissue site of an organ, their combined effect should be considered."
  - "Independent action occurs when exposure to the multiple wavelengths are not, in fact, additive upon specific tissue sites."

- Synergistic – (Health Phys. 90(3):241–249; 2006 Roach, Thomas, et al.)
  - In general, for multi-wavelength exposure occurring simultaneously, the standard states that the effects of such exposures from pulsed- and continuous wave (CW)-laser radiation may act synergistically.

Ocular Hazard Regions

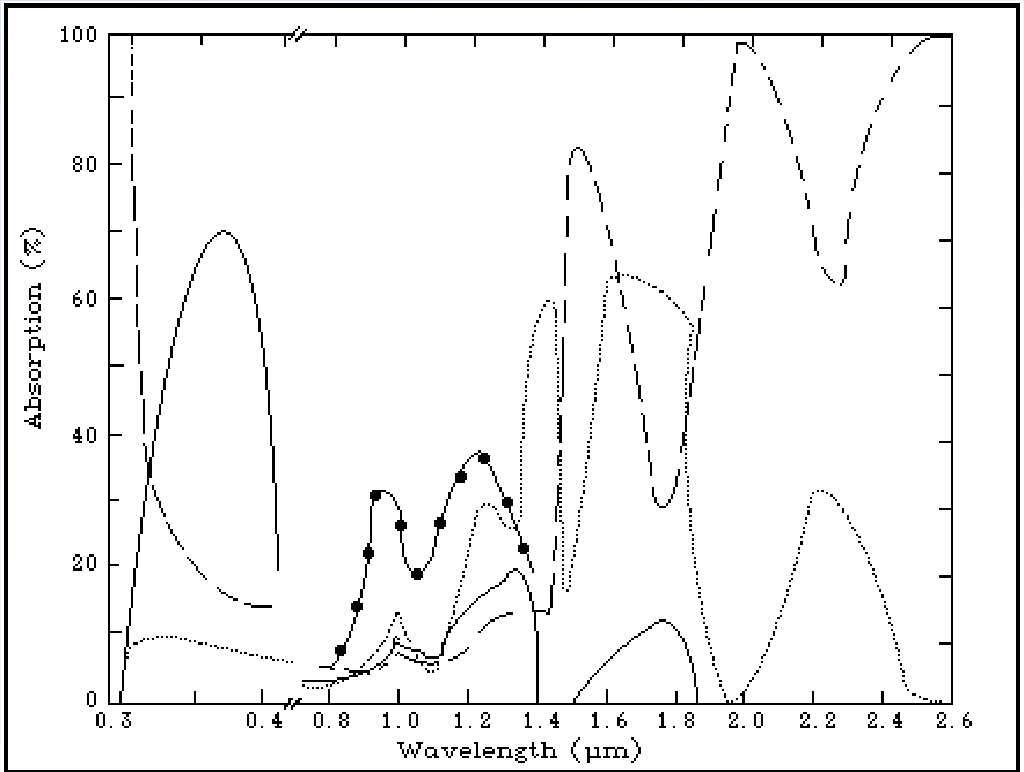
- **Pre-retinal components (transmission) ------**
  - **Cornea, Aqueous Humor, Lens, vitreous humor**
  - **UV and Far IR ranges**
- **Retinal Hazard Region (absorption) ——**
  - **Visible and Near IR spectrum**
  - **Absorption at focal point**
  - **Focal spot ~20 μm**
  - **High energy density**



Ocular Hazard Regions

- **Corneal Hazard Region**
  - 180nm, ends around 400nm
  - 1200nm – 1400nm

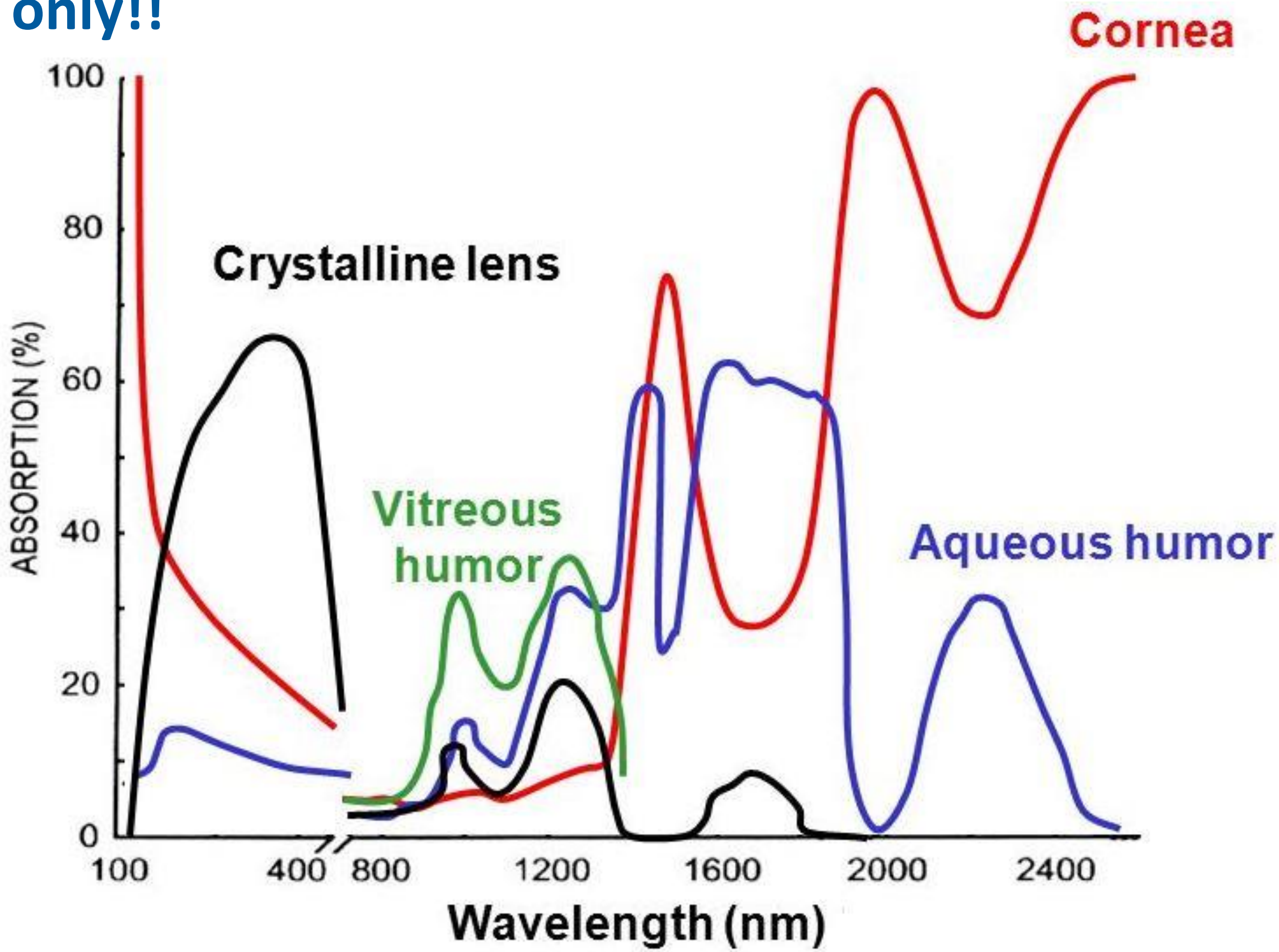
    (Dual exposure limits)
  - > 1400nm
- **Lens Hazard Region**
  - ~300nm to ~400nm
  - 700nm – 2.0µm
- **Retinal Hazard Region**
  - 400nm to 1400nm
  - Includes invisible NIR
- **Matches absorption curve**



The spectral absorption of the ocular media in the human eye. Each portion of the ocular media, the cornea (— —), the aqueous humor (. . .), the lens (___) and the vitreous humor (-•-), absorb different portions of the incident optical radiation at different wavelengths. Very little is absorbed in the visible region, hence, the break in the curves. Note the strong absorption of the lens in the near-ultraviolet region and the absorption of the vitreous in the 0.86-1.35 µm infrared region (From: Sliney & Wolbarsht, 1980).

Ocular Absorption

- **Absorption of different ocular media**
- **Complex absorption across wavelengths**
- **Conceptual uses only!!**



Standards

- **ANSI Z136.1 guidance**

8.2.1 Wavelength. The wavelength *A,* must be specified to establish which spectral region is applicable. The MPEs in Table 5a, Table 5b, Table 5c, Table 5d, Table 5e, and Table 5f are arranged in broad wavelength regions expressed in nanometers (nm). **For multiple wavelength laser emissions (e.g., where pump laser wavelengths are co-linearly produced with the emission wavelength in a frequency doubler), the MPE must first be determined for each wavelength separately.** **Exposures from several wavelengths are additive on a proportional basis of spectral effectiveness with due allowance for all correction factors.** In the ultraviolet region, special considerations may apply for multiple exposures (see 8.2.3.1).

- **Determine MPE for each wavelength separately**
- **MPEs for co-linear beams are additive on a proportional basis**

Application of Standards

- **Determine MPE for each wavelength separately**
- **MPEs for co-linear beams are additive on a proportional basis**

- **8.2.1 refers to a "Sum of fractions less than unity"**
- **Used in Health Physics for multi-isotope sources**
- **"Proportional" – Ratio of individual quantities to their limits**
- **The ratios represent a value for "Actual to Allowed"**
- **"Additive" – The sum of all the individual ratios**

$$\frac{H_1}{EL_1} + \frac{H_2}{EL_2} + \cdots + \frac{H_i}{EL_i} + \cdots \frac{H_n}{EL_n} > 1$$

T. Lyon, HP Journal, 1985

Search for Guides and Information

- **Some interesting results**

$$\sum \left[\frac{(\text{Power})}{\text{AEL}} \right] = \frac{0{,}16}{0{,}74} + \frac{0{,}16}{0{,}85} + \frac{4 \times 0{,}16}{15{,}6} = 0{,}45$$

Exposure to Laser Wavelengths

- **Exposure to a single wavelength**
  - **Exposure to one λ as a separate event**
- **Exposure to multiple wavelengths-Spatial alignment**
  - **All λ's exposures absorbed into same tissue**
- **Exposure to multiple wavelengths-Temporal alignment**
  - **Exposure to multiple λ's occurs at exact same point in time**

Multi-wavelength Exposures

- **Multiple wavelength Random exposure**
  - **Multiple λ's expose tissue as separate, random events**
  - **Energy deposited most likely not additive**
- **Multiple wavelength Simultaneous exposure**
  - **Multiple λ's absorbed in same tissue at same time**
  - **Temporal + Spatial alignment**
  - **Energy deposited is additive**

1 = 1

1 = 1

1 = 1

1 + 1 = 2

1 + 1 = 2

1 + 1 = 2

1 + 1 + 1 = 3

Standards

- IEC 60825 – MPE discussion (quote from older version – Not 2014)
- "Exposures from several wavelengths should be assumed to have an **additive effect on a proportional basis** of spectral effectiveness according to the MPEs of tables 6 and 8 provided that:
  - a) the pulse width or exposure duration are within one order of magnitude, and
  - b) the spectral regions are shown as additive by the symbols (o) for ocular and (s) for skin exposure in the matrix of table 5."

Table 5 – Additivity of effects on eye (o) and skin (s) of radiation of different spectral regions

Spectral region*	UV-C and UV-B 180 nm to 315 nm	UV-A 315 nm to 400 nm	Visible and IR-A 400 nm to 1 400 nm	IR-B and IR-C 1 400 nm to 10^6 nm
UV-C and UV-B 180 nm to 315 nm	o s			
UV-A 315 nm to 400 nm		o s	s	o s
Visible and IR-A 400 nm to 1 400 nm		s	o** s	s
IR-B and IR-C 1 400 nm to 10^6 nm		o s	s	o s

* For definitions of spectral regions, see table B1.

** Where AELs and ocular MPEs are being evaluated for time bases or exposure durations of 1 s or longer, then the additive photochemical effects (400 nm to 600 nm) and the additive thermal effects (400 nm to 1 400 nm) shall be assessed independently and the most restrictive value used.

Standards

- IEC 60825 – Additive exposure matrix
  - **General guidance for applying tissue absorption by wavelength**
  - **Do not need to apply additive MPEs if not directed by table**

Table 5 – Additivity of effects on eye (o) and skin (s) of radiation of different spectral regions (older version)

Spectral region*	UV-C and UV-B 180 nm to 315 nm	UV-A 315 nm to 400 nm	Visible and IR-A 400 nm to 1 400 nm	IR-B and IR-C 1 400 nm to 10^6 nm
UV-C and UV-B 180 nm to 315 nm	o s			
UV-A 315 nm to 400 nm		o s	s	o s
Visible and IR-A 400 nm to 1 400 nm		s	o** s	s
IR-B and IR-C 1 400 nm to 10^6 nm		o s	s	o s

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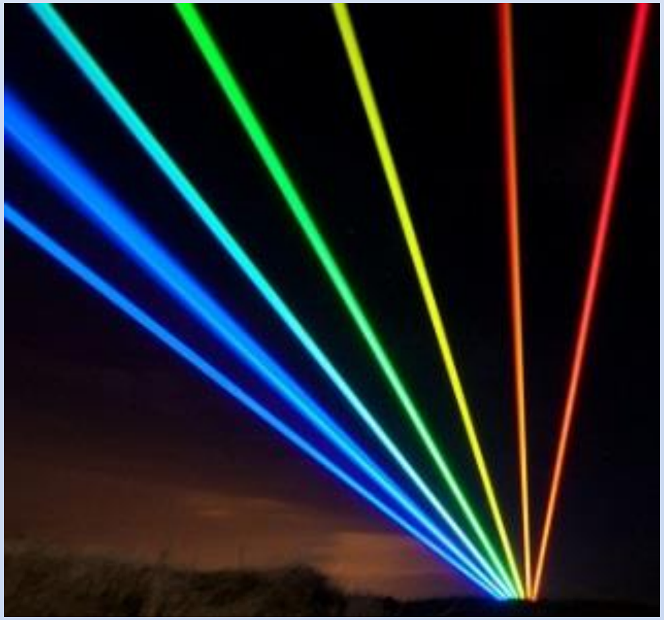
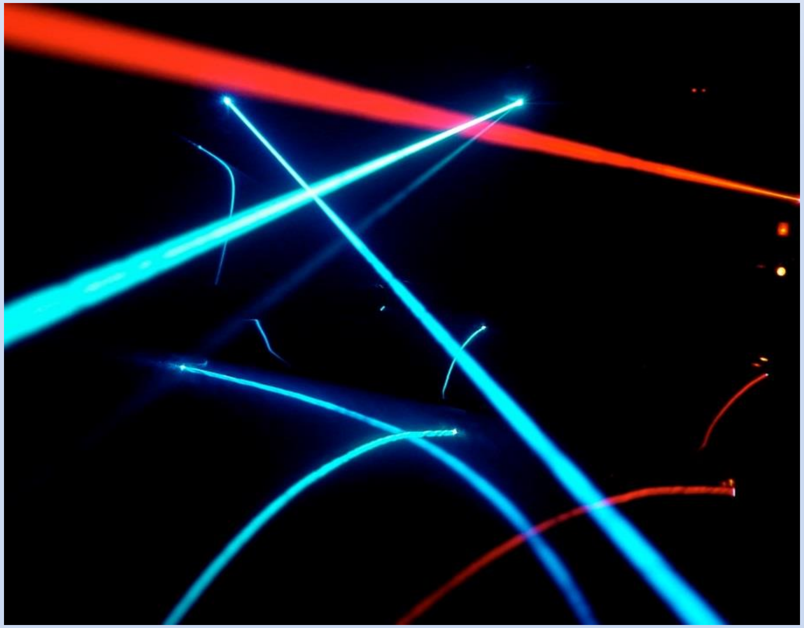
Multiple Wavelength Optical Setup

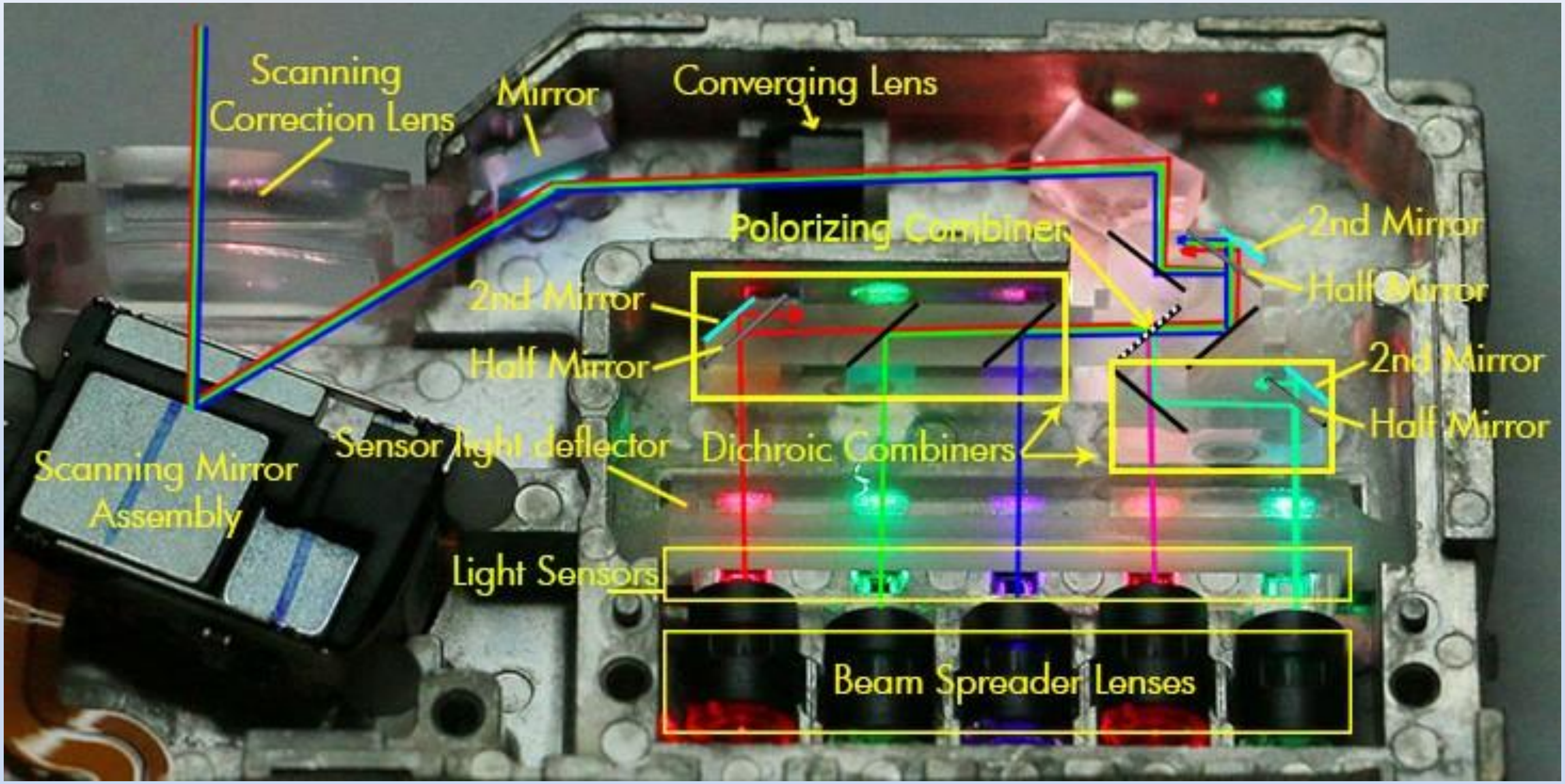
- **Non-convergent beams**
  - Beams not coaxial, and do not intersect
  - Beams may be on same table, or simply in same workspace
  - Highly unlikely to create simultaneous exposure condition
- **Off-axis beams**
  - Beams not coaxial, do not share beam path
  - Beams may intersect at some point, but do not become co-linear
  - Unlikely to create simultaneous exposure condition





Multiple Wavelength Optical Setup

- **Co-axial / Co-linear beams**
  - Beams are coaxial on optics table
  - Beams coexist in similar linear beam path
  - Create simultaneous exposure condition



MPE Calculations for Multiple Wavelengths

- **Determine MPE for each wavelength separately**

- **Calculate MPE for Each λ Separately**
- **Calculate irradiance (E) or radiant exposure (Q) for each λ**
- **Calculate ratio of irradiance to MPE for each λ**

  E_1/MPE_1 **E_2/MPE_2** **E_3/MPE_3**

- **Any ratio greater than 1 exceeds the MPE – not eye safe**
- **Even if all ratios are < 1, could still be hazardous**
- **3R laser pointers have ratio >1**
- **Most research and industrial lasers have ratios >1**
- **Co-linear visible with invisible—0.25 sec for additive**
- **Start with simplest worst case scenario—try easy first**

MPE Calculations for Multiple Wavelengths

- **MPEs for co-linear beams are additive on a proportional basis**

- **Determine the aggregate E/MPE ratio of the beams**

  (E_1/MPE_1 + E_2/MPE_2 + E_3/MPE_3)

  - **Can use Watts/AEL in place of irradiance and MPE**
- **If the sum of the ratios is < 1, eye safe condition**
  - **(Sum of Ratios <1 are unlikely for R&D, Industrial, etc)**
- **If the sum of the rations is > 1 – eye hazard condition**
- **Safety Analysis must address *both* MPE conditions:**
  - **Single λ MPE calculation – single ratio <1**
  - **Sum of MPE Ratios < 1**

Multi-wavelength MPE Example

- **Three wavelengths, CW, visible, retinal hazard**
  - **405nm, 488nm, 561nm---3mm coaxial beam ($1/e^2$)**
  - **Simultaneous exposure, 0.25 second exposure**
  - **MPE = 2.55×10^{-3} W/cm^2**
  - **Beam area (1/e) = $\pi r^2/2^{0.5} = \pi(0.15)^2 / 1.414 = 0.05$ cm^2**
  - **Beam area < limiting aperture – use 7mm pupil diameter- 0.385 cm^2**

Hinweis: Diese im Werk während der Systemintegration ermittelten Laserleistungen müssen während der Installation beim Kunden mindestens zu 90% erreicht werden.

Note: *The following laser powers measured in the factory during system integration. The value must be at least 90 % will be achieved when the system is installed on the customer's premises.*

Verwendetes Objektiv / *used objective*: → PA 63x1,4

Nominelle Laserleistung (Laser power) bei Messwellenlänge (Wave length) und Filtersatz (Filter set) : *Nominal laser power at measuring wavelength and filter set:*			Mit Photometer in der Objektebene gemessener Wert ... *With photometer measuered value in object plane ...*	
Wavelength	Laser power	Filter set	... während der Systemintegration im Werk CZ-Göttingen: *... during system integration at CZ Göttingen.*	... beim Kunden nach Installation *... at customer site after installation*
405 nm	50 mW		1,4 mW	mW
488 nm	20 mW		mW	mW
488 nm	100 mW		8,4 mW	mW
532 nm	75 mW		mW	mW
561 nm	20 mW		mW	mW
561 nm	40 mW		3,5 mW	mW
635 nm	30 mW		mW	mW

embedded

emission

Multi-wavelength MPE Example

- **Determine MPE for each wavelength separately**
  - **405nm – 1.4 mW*, E = W/a = 1.4mW/0.385 cm^2 = 3.64 mW/cm^2**
    - **3.64 mW/cm2 (E) / (MPE) 2.55 mW/cm^2 = 1.46 ratio > 1 !**
  - **488nm – 8.4 mW, E = W/a = 8.4 mW/0.385 cm^2 = 21.8 mW/cm^2**
    - **21.8 mW/cm2 (E) / 2.55 mW/cm^2 (MPE) = 8.54 ratio > 1 !**
  - **561nm – 3.5 mW*, E = W/a = 3.5 mW/0.385 cm^2 = 9.09 mW/cm^2**
    - **9.09 mW/cm2 (E) / 2.55 mW/cm^2 (MPE) = 3.56 ratio > 1 !**

    **** Class 3R laser emission***
- **MPEs for co-linear beams are additive on a proportional basis**
  - **SUM : 1.46 + 8.54 + 3.56 = 13.56 >>> 1 !!**
- **Every wavelength >MPE, and the Sum of ratios is >>> MPE**

Multi-wavelength MPE Example

- **Determine MPE for each wavelength separately---together!**
  - **Wavelengths in identical categories in table 5 – possible to sum**
  - **Must have identical MPE values and exposure characteristics**
  - **405nm – 1.4 mW**
  - **488nm – 8.4 mW**
  - **561nm – 3.5 mW**
  - **Total: 13.3 mW**

- **MPEs for co-linear beams are additive on a proportional basis**
  - **SUM – 13.3 mW*, E = W/a = 13.3 mW/0.385 cm^2 = 34.55 mW/cm^2**
    - **34.55 mW/cm2 (E) / 2.55 mW/cm^2 (MPE) = 13.55 ratio >>> 1 !**

Multi-wavelength MPE Example

- **For sake of example, assume neutral density filter eyewear with OD of 1.5 (VLT = 3.2%)**
- **Determine Post-OD Irradiance values and new ratios:**
  - **OD = log (1/τ) $\tau = 1/10^{OD}$ $\tau = 1/10^{1.5}$ = 1/31.62 = 0.0316**
  - **405nm – 1.4 mW*, E = W/a = 1.4mW/0.385 cm^2 = 3.64 mW/cm^2**
    - **3.64 mW/cm^2 x 0.0316 = 0.115 mW/cm^2**
    - **0.115 mW/cm2 (E) / (MPE) 2.55 mW/cm^2 = 0.045 ratio < 1**
  - **488nm – 8.4 mW, E = W/a = 8.4 mW/0.385 cm^2 = 21.8 mW/cm^2**
    - **21.8 mW/cm^2 x 0.0316 = 0.689 mW/cm^2**
    - **0.689 mW/cm2 (E) / 2.55 mW/cm^2 (MPE) = 0.270 ratio < 1**
  - **561nm – 3.5 mW*, E = W/a = 3.5 mW/0.385 cm^2 = 9.09 mW/cm^2**
    - **9.09 mW/cm^2 x 0.0316 = 0.287 mW/cm^2**
    - **0.287 mW/cm2 (E) / 2.55 mW/cm^2 (MPE) = 0.113 ratio < 1**
- **MPEs for co-linear beams are additive on a proportional basis**
  - **SUM : 0.045 + 0.270 + 0.113 = 0.428 < 1**

Standards vs. Exposure Data

- **532nm + 860nm Rhesus Monkey exposures, Health Physics Journal 90(3):241–249; 2006**
- **Margin of safety maintained for additive exposures**

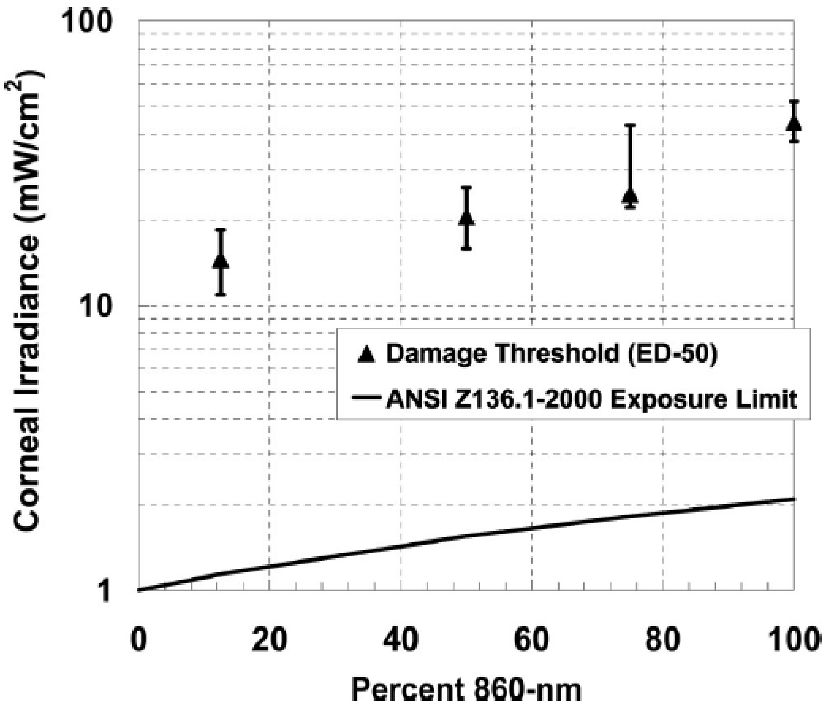
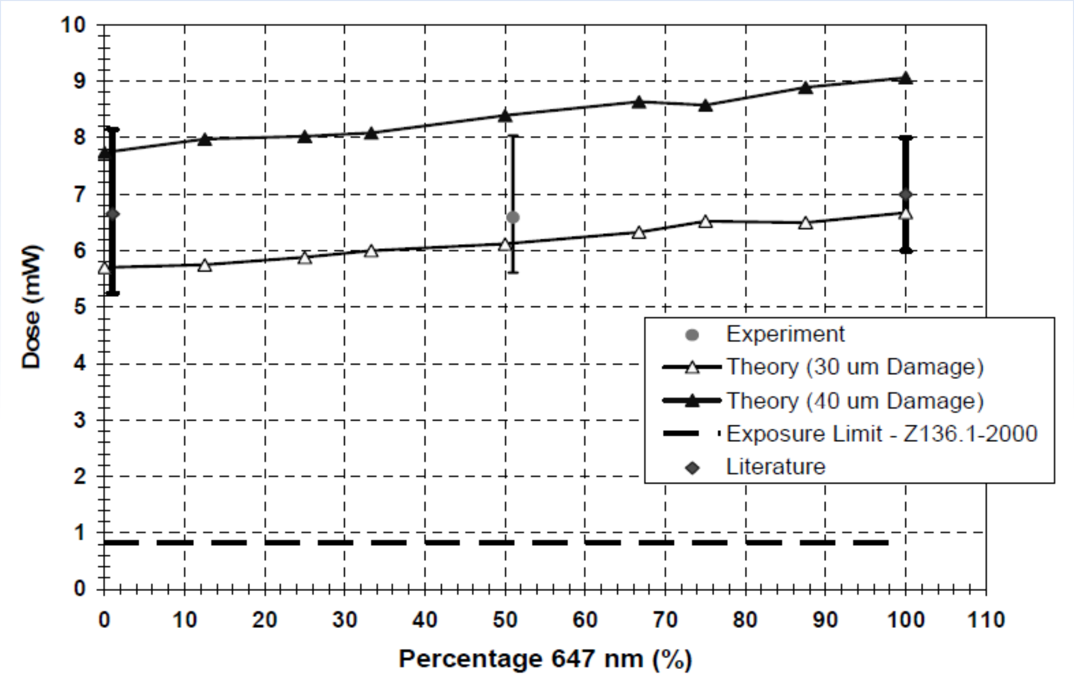


Fig. 5. Combined 532/860-nm MPEs and MVL-ED_{50}s (24 h post exposure) as percent of 860 nm.

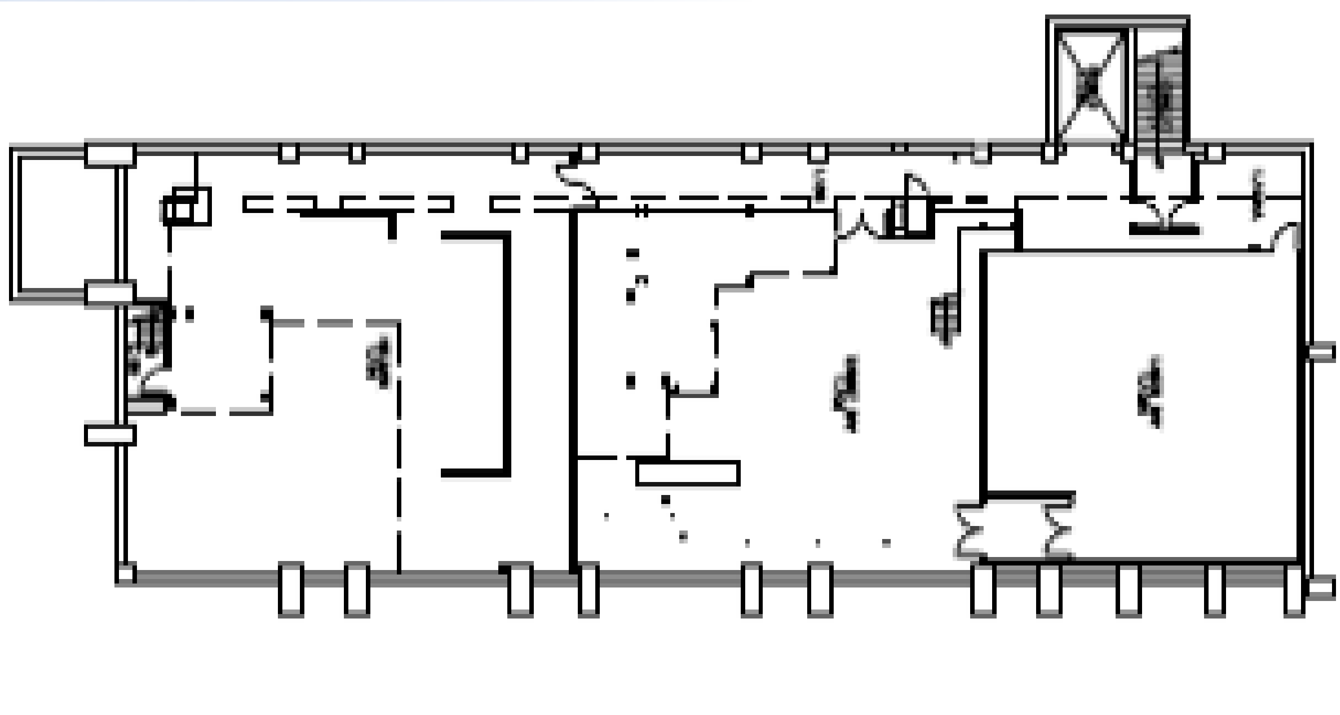
Standards vs. Exposure Data

- **532nm + 647nm Primate exposures, SPIE Proceedings,** Vol. 5695 (SPIE, Bellingham, WA, 2005—Stolarski, Cain, et al.)
- **Margin of safety maintained for additive exposures**



The Lab Setup

- Location of beam paths in the work space
- Co-axial vs non-convergent beam paths
- Useful / functional portion of the beam path
- Visible vs invisible beams
- Routine and Non-Routine processes with optics

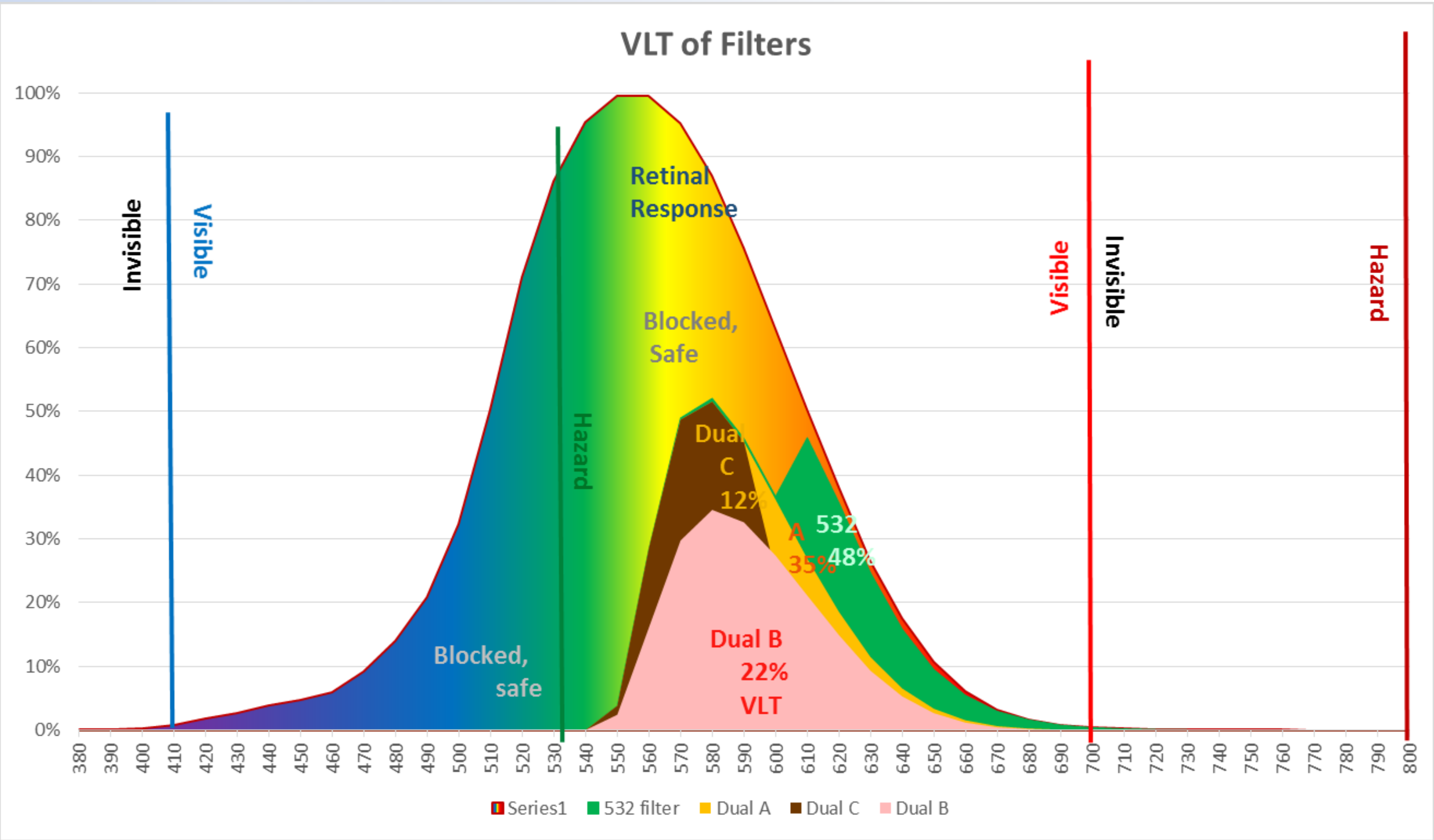


Removing Beam Hazards

- **Separate out one or more wavelengths**
  - **Segregate wavelengths in Lab Space Using Barriers/Curtains**
  - **Containment/Enclosure of portions of beam paths**
  - **Enclose pump lasers, boosters, amplifiers**
- **Adjust beam optics to eliminate wavelengths**
  - **Shutter, beam block, splitter, HR/AR coatings, filters, band pass, etc**
- **PI requires direct unfettered access to all optics at all times**
  - **Until you can demonstrate how it can be done to their advantage**
  - **$$$ Always talks**

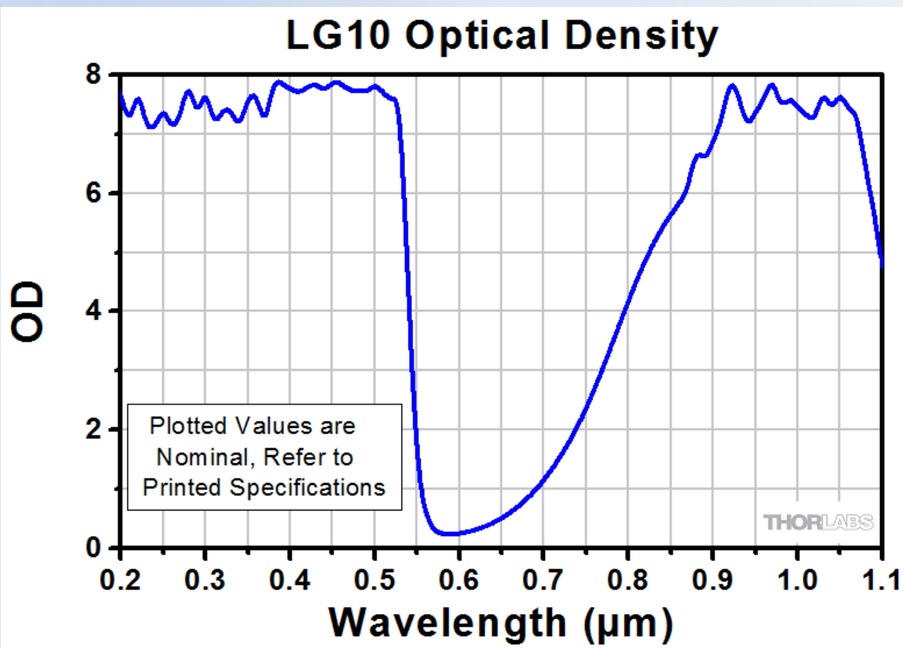
Eyewear Issues - VLT

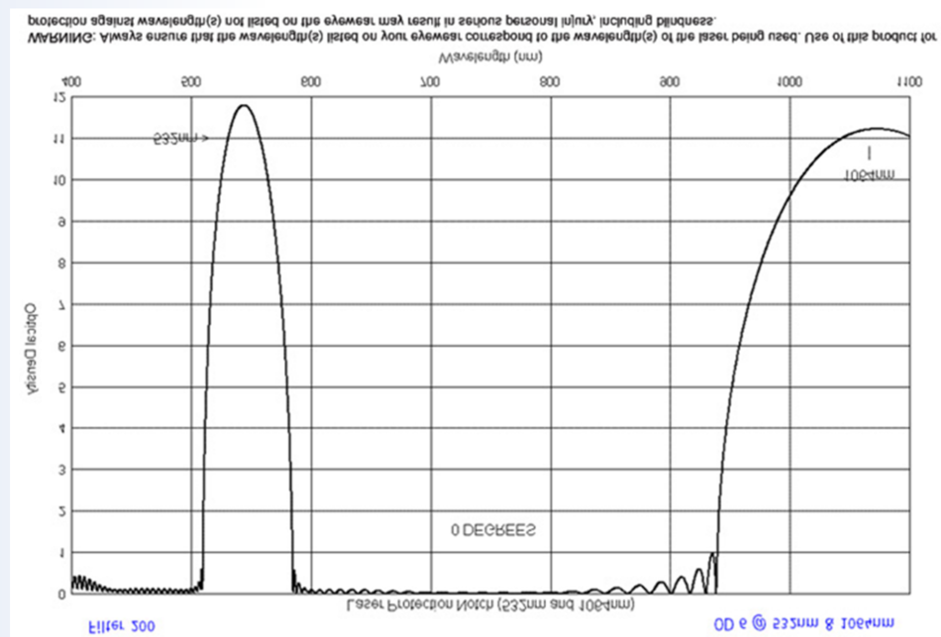
- **Carving out sections of visual portion of spectrum**
  - **Large portions of blocked visual spectrum from broadband absorption**
  - **Most of blocked spectrum does not have hazardous radiation**
  - **Example below, VLT for 532nm, and Dual 532nm + 800nm filtration**
  - **One type for all wavelengths—Cost, Convenience, Safety**



Eyewear Issues

- **OD considerations for Multiple wavelengths in lab space**
  - Eyewear to cover OD requirements for every wavelength
  - OD needs can be difficult even if MPEs not additive
  - Eyewear VLT becomes a real issue—Small ODs in visible region
  - Optical Coatings—Dielectric narrow band one option
  - Hi-output lab lighting to offset dark eyewear





(Flipped for comparison)

Eyewear Issues – VLT Calcs

- **Air Force created Algorithm and Code**
  - **Report AFRL-HE-BR-TR-2005-0137**
  - **Locates Max OD and Max VLT solution**
  - **Reduce iterations of MPE/OD calcs**

$$W_\lambda(D_\lambda) = 10^{-D_\lambda} \cdot \frac{Qf_\lambda}{AEL_\lambda \cdot V_\lambda}$$

Eyewear Issues – High Irradiance

- **Pulse and power limitations**
  - **High energy intensity of high power or short pulses**
  - **Use IEC 60825 specs for short pulses— M rating**
  - **Can be the limiting factor with multiple wavelengths**

Table 1 — Scale numbers (maximum spectral transmittance and resistance to laser radiation) of the filters and/or eye-protectors against laser radiations

Scale number	Maximum spectral transmittance at the laser wavelength $\tau(\lambda)$	Power (E) and energy (H) density for testing the protective effect and resistance to laser radiation in the wavelength range								
		180 nm to 315 nm			> 315 nm to 1 400 nm			> 1 400 nm to 1 000 µm		
		For test condition/pulse duration in seconds (s)								
		D $\geq 3\times10^{4}$	I, R 10^{-9} to 3×10^{4}	M $< 10^{-9}$	D $> 5\times10^{-4}$	I, R 10^{-9} to 5×10^{-4}	M $< 10^{-9}$	D $> 0,1$	I, R 10^{-9} to 0,1	M $< 10^{-9}$
		E_D W/m²	$H_{I,R}$ J/m²	E_M W/m²	E_D W/m²	$H_{I,R}$ J/m²	H_M J/m²	E_D W/m²	$H_{I,R}$ J/m²	E_M W/m²
LB1	10^{-1}	0,01	3×10^{2}	3×10^{11}	10^{2}	0,05	$1,5\times10^{-3}$	10^{4}	10^{3}	10^{12}
LB2	10^{-2}	0,1	3×10^{3}	3×10^{12}	10^{3}	0,5	$1,5\times10^{-2}$	10^{5}	10^{4}	10^{13}
LB3	10^{-3}	1	3×10^{4}	3×10^{13}	10^{4}	5	0,15	10^{6}	10^{5}	10^{14}
LB4	10^{-4}	10	3×10^{5}	3×10^{14}	10^{5}	50	1,5	10^{7}	10^{6}	10^{15}
LB5	10^{-5}	10^{2}	3×10^{6}	3×10^{15}	10^{6}	5×10^{2}	15	10^{8}	10^{7}	10^{16}
LB6	10^{-6}	10^{3}	3×10^{7}	3×10^{16}	10^{7}	5×10^{3}	$1,5\times10^{2}$	10^{9}	10^{8}	10^{17}
LB7	10^{-7}	10^{4}	3×10^{8}	3×10^{17}	10^{8}	5×10^{4}	$1,5\times10^{3}$	10^{10}	10^{9}	10^{18}
LB8	10^{-8}	10^{5}	3×10^{9}	3×10^{18}	10^{9}	5×10^{5}	$1,5\times10^{4}$	10^{11}	10^{10}	10^{19}
LB9	10^{-9}	10^{6}	3×10^{10}	3×10^{19}	10^{10}	5×10^{6}	$1,5\times10^{5}$	10^{12}	10^{11}	10^{20}
LB10	10^{-10}	10^{7}	3×10^{11}	3×10^{20}	10^{11}	5×10^{7}	$1,5\times10^{6}$	10^{13}	10^{12}	10^{21}

The symbols D, I, R and M relative to the test conditions are explained in Table 4.

Eyewear Issues – Max Power

- **$64,000 question…**

  “How much power can I put in the beam with these eyewear?”

  – **Use eyewear OD for each wavelength—solve for E_O**

$$OD = \log (E_O / MPE)$$

$$10^{OD} = E_O / MPE$$

$$E_O = 10^{OD} \times MPE$$

this will give you irradiance or radiant exposure W/cm2 or J/cm2

Questions?