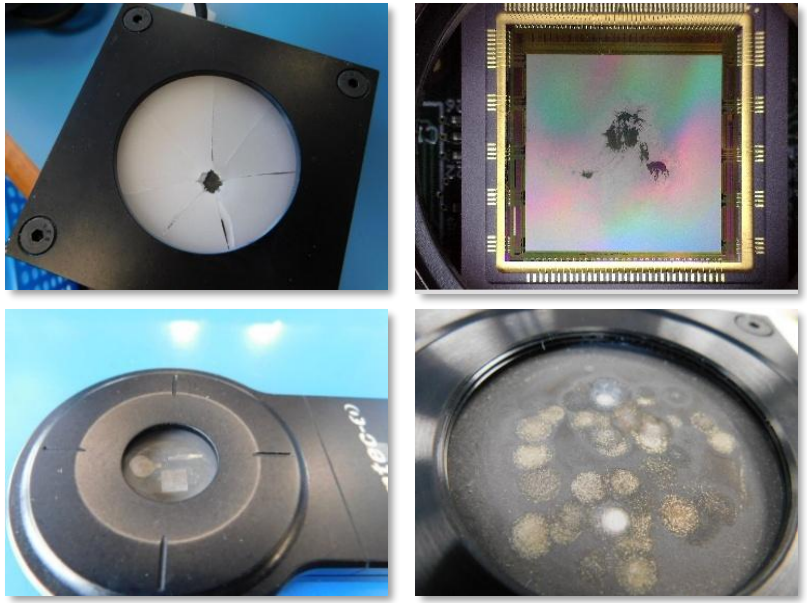
PROTECTING PEOPLE, SYSTEMS AND FACILITIES BY DOING SAFE LASER BEAM DIAGNOSTICS



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2026-05-19

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PARTNERS FOR ACCURACY

- Independent company since 1972
- Canada HQ, offices in U.S. and Japan
- Design and manufacture laser measurement solutions
- Offer best practices for accurate measurements

POWER & ENERGY METERS

BEAM PROFILING

TERAHERTZ MEASUREMENT

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SAFETY: NOT ONLY ABOUT HUMAN EXPOSURE

- Being safe around lasers = not only protecting people from direct hazards (eye/skin)
- Being efficient with lasers = not only improving seed, amplification, compression, delivery optics, heat extraction, etc
- Light-target interaction matters = where does the energy go?

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SAFETY: NOT ONLY ABOUT HUMAN EXPOSURE

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SAFETY: NOT ONLY ABOUT HUMAN EXPOSURE

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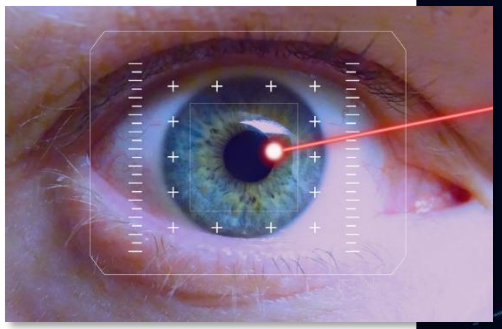
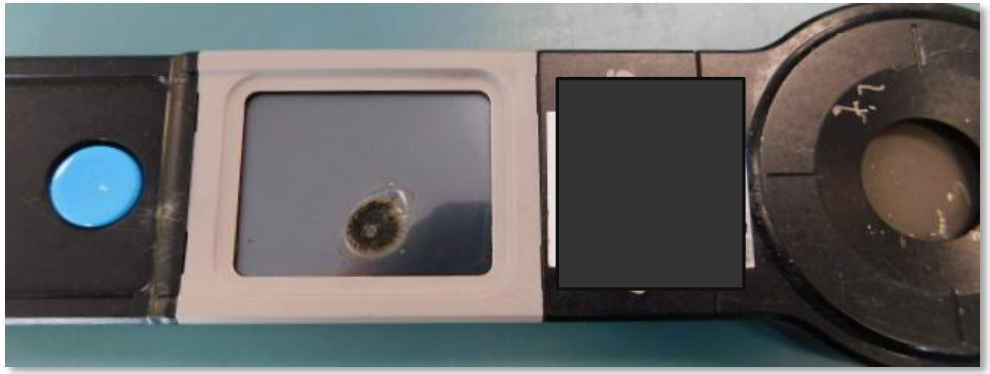
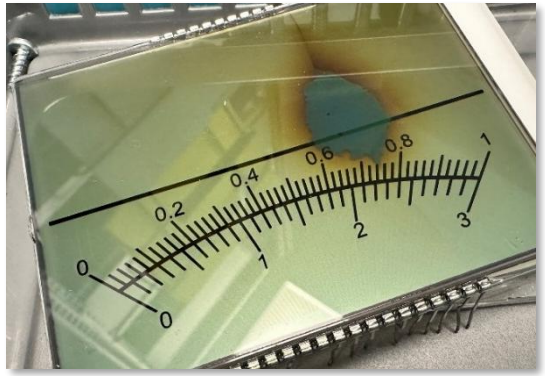
THREATS TO HUMANS AND EQUIPMENT

- Indirect when bad laser beam diagnostics compromise operations
- Direct when detector not used within specs







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SYSTEMIC APPROACH

- Protecting people = end goal
- Diagnostics and targets are part of the hazard chain
- Good, safe, accurate laser performance diagnostics will:
  - Improve processes and confidence in laser product reliability
  - Anticipate failure modes
  - Reduce system maintenance costs
  - Reduce paperwork/reporting
  - Protect assets, secure facilities
  - Potentially increase budgets

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GOOD / BAD / UGLY MEASUREMENTS

- Good: representative, accurate, traceable
  - Is repeatable enough?
- Bad: safe but useless

  - Calibration overdue?
  - Invisible damage?
  - Detector saturated, overheated, misaligned, high noise, offset, wavelength mismatch…
- Ugly: useless and dangerous

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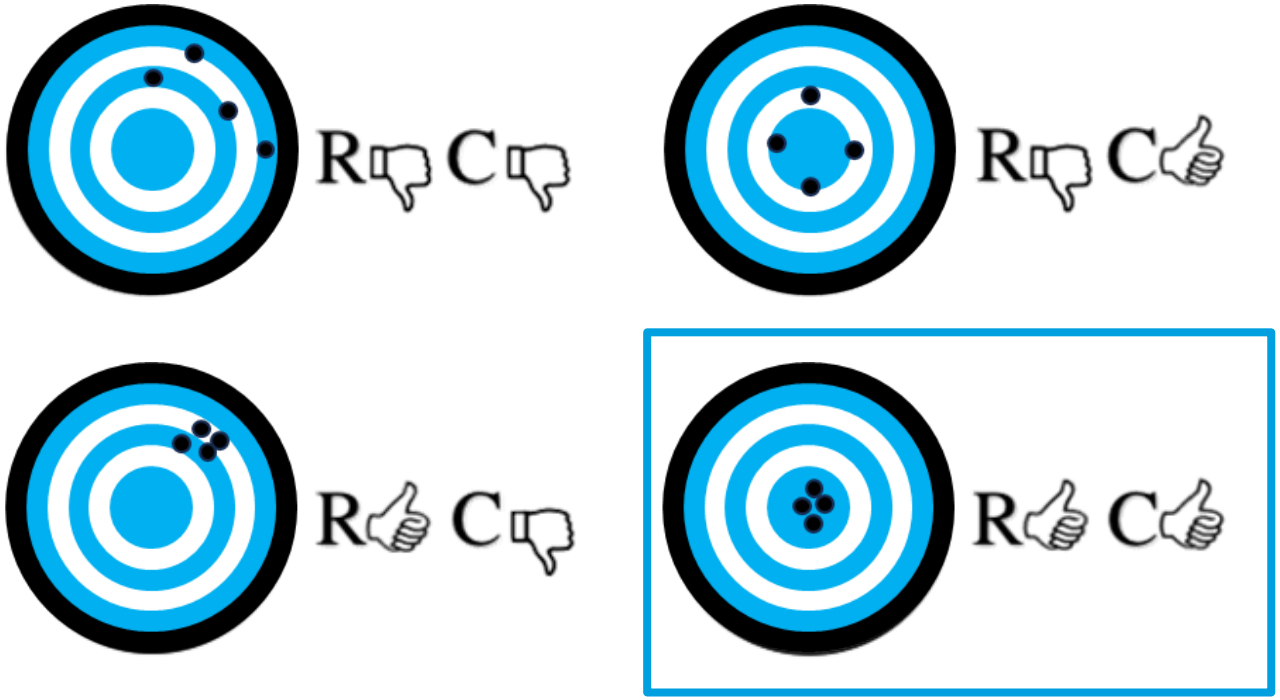
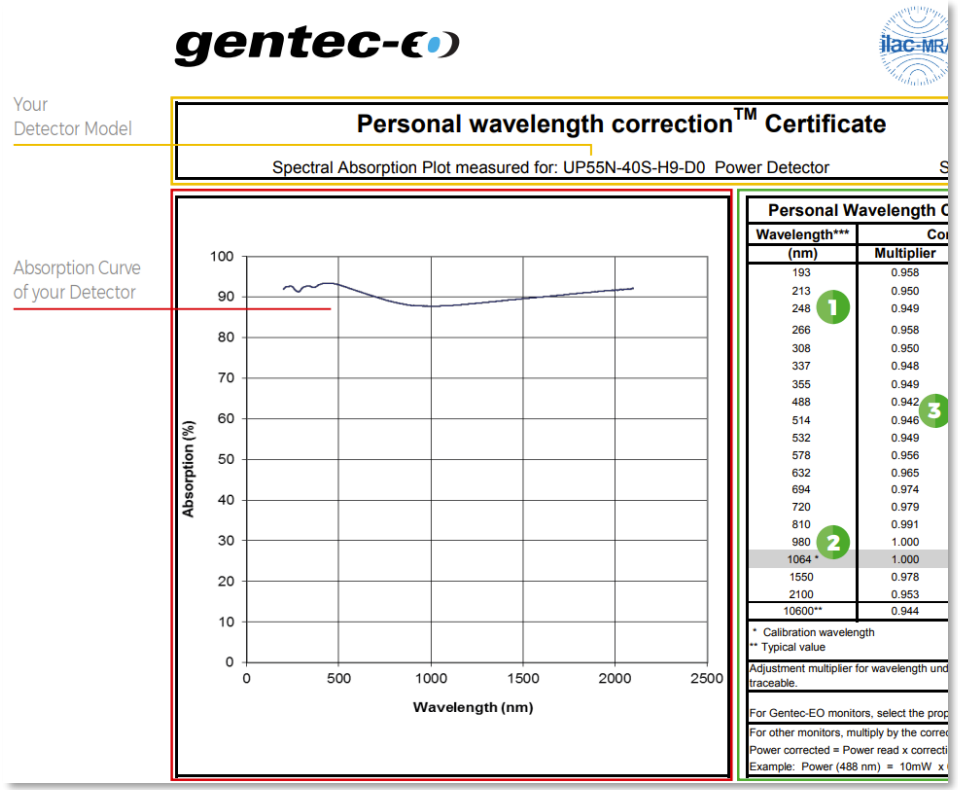
PARTNERS FOR ACCURACY

- Measurement Accuracy =

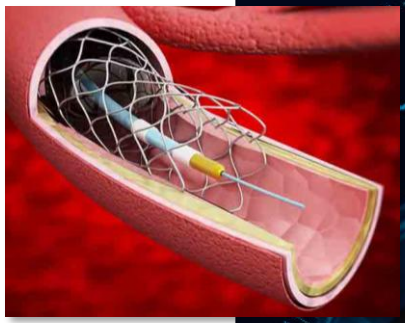
  Repeatability (random error) + **C**alibration uncertainty (systematic error)

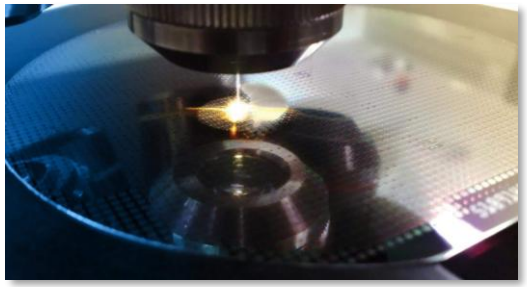




COST OF BAD MEASUREMENTS

- Underestimating power = unsafe implementation
- Overestimating capability = system misuse, inefficient
- False beam quality data = unexpected exposure zones, potential hot spots in back reflections
- Misleading laser acceptance tests
- Increased risk to personnel and optical components





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COST OF BAD MEASUREMENTS

- Detector replacement (not a good fit)
- Downtime
- Damaged optical components
- Investigation, additional tests, reporting
- Recalibrate more often
- Reputation: doubts on laser performance

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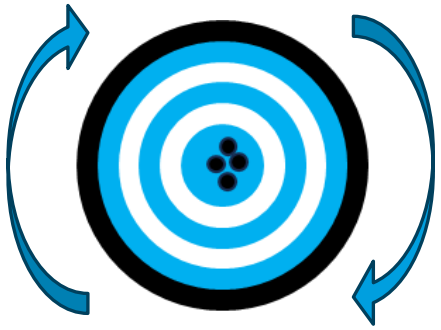
MEASUREMENT = SAFETY FUNCTION

- Measurement errors = unsafe decisions downstream
- Protect people from stray beams, back reflections, overheating parts, damages, unexpected laser power…
- Protect systems: control performances, plan field service and maintenance accurately, increase confidence…
- Protect facilities: manage downtime, reporting duties, fire alarms!



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PULSED LASERS

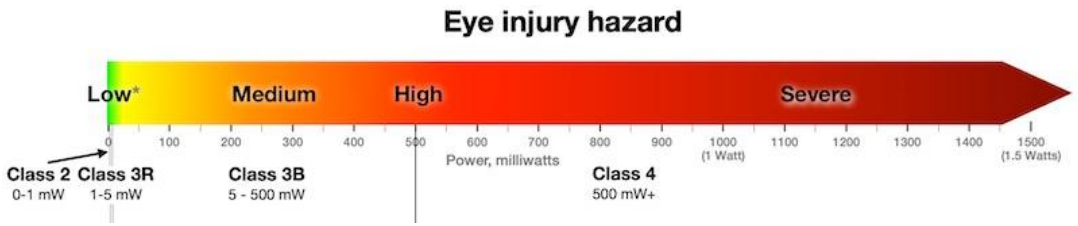
Category	Applications	Typical wavelengths	Pulse energy	Pulse width	Rep rate	Average power
Precision Scientific	spectroscopy nonlinear optics fs eye surgery	700-1100 nm (Ti:Sa 800 nm, Yb 1030 nm) harmonics 515/343 nm	1 nJ – 100 µJ	30 fs – 10 ps	100 kHz – 100 MHz	1 – 50 W
Medical Telecom	dermatology lithotripsy laser communication	532 nm, 755 nm, 810 nm 1064 nm, 1550 nm, 2100 nm	1 mJ – 5 J	100 ps – 1 ms	1 Hz – 10 MHz	10 – 200 W
Ultrafast industrial micromachining	semicon processing OLED manufacturing precision drilling, etching	Yb 1030 nm harmonics 515/343 nm	10 µJ – 1 mJ	200 fs – 10 ps	100 kHz – 10 MHz	50 – 1000 W
Industrial macro-processing	metal cutting, welding, cleaning, drilling	1030-1080 nm (Nd:YAG fiber lasers)	0.5 mJ – 100 mJ	10 ns – 10 µs	10 kHz – 1 MHz	500 W – 20 kW
Extreme high-power pulsed systems	directed-energy fusion drivers	1030-1080 nm 1053 nm → 351 nm (fusion harmonic conversion)	1 J – 10 kJ+	1 ns – 20 ns	<1 Hz – 10 kHz	10 kW – 100 kW+

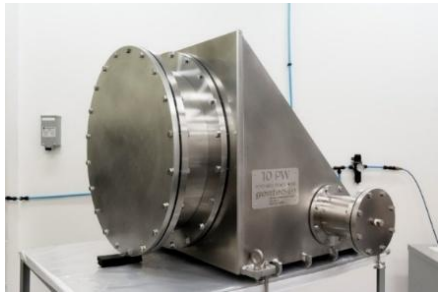
CW LASERS

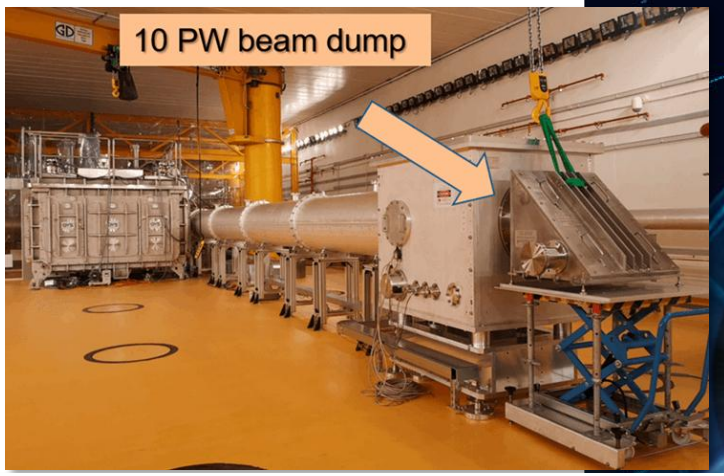
Category	Applications	Typical wavelengths	Beam quality/mode	Intensity control	Average power
Precision Scientific	spectroscopy interferometry holography	266-1100 nm (HeNe 633 nm, CW DPSS 532 nm, CW Ti:Sa tunable)	single-frequency narrow linewidth TEM_{00}	CW or low-frequency modulation (<kHz)	mW – 10 W
Medical Telecom	phototherapy surgery (diode) fiber communication	405-1550 nm (980, 1310, 1550 nm typical)	stable CW beam multimode or single-mode fiber-coupled	directly modulated (kHz, GHz for telecom)	10 mW – 100 W
Industrial fine processing	marking micro-welding additive manufacturing	515-1080 nm (green DPSS 532 nm, Yb fiber 1064 nm)	high beam quality (M^2 ~1-2), Gaussian or near-Gaussian	analog modulation (kHz-MHz range)	50 – 1000 W
Industrial macro-processing	cutting, welding cladding, cleaning	1030-10600 nm (fiber ~1070 nm, CO_2 ~10.6 µm)	multimode or high-power fiber delivery top-hat / multimode profiles	continuous or gated CW	1 kW – 20 kW
Extreme high-power CW systems	directed energy fusion drivers (steady-state heating) large-scale material processing	1 µm class (fiber / thin-disk)	large mode area fibers beam combining	quasi-CW or continuous	10 kW – 100 kW+

SYSTEM EFFICIENCY ≠ ONLY BETTER LASERS

- Diagnostics face extreme environments (kW pyros, 1 MW power meters, 10 PW dumps…)
  - Internal (pick-off, matching driving current with resulting output power, documenting laser medium aging)
  - External (calibration, free-space, fiber-coupled, factory controls, field service, lab setting)
  - Vulnerable
  - Limit back reflections







ALL LASERS ARE DANGEROUS

- New laser over-performing = wrong LSO calculations
- Old laser under-performing = need to adjust attenuation and process

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MEASUREMENT DEVICES = TARGETS

- ≠ process targets (material, tissues, sensors, samples, holraum)
- Power meters, joulemeters, beam profilers:
  - Thermopile, pyroelectric, photodiode, CMOS
  - Designed to absorb photons and provide calibrated electrical signal
  - Often assumed to be “safe by default”
  - Full disclaimer: they are not!

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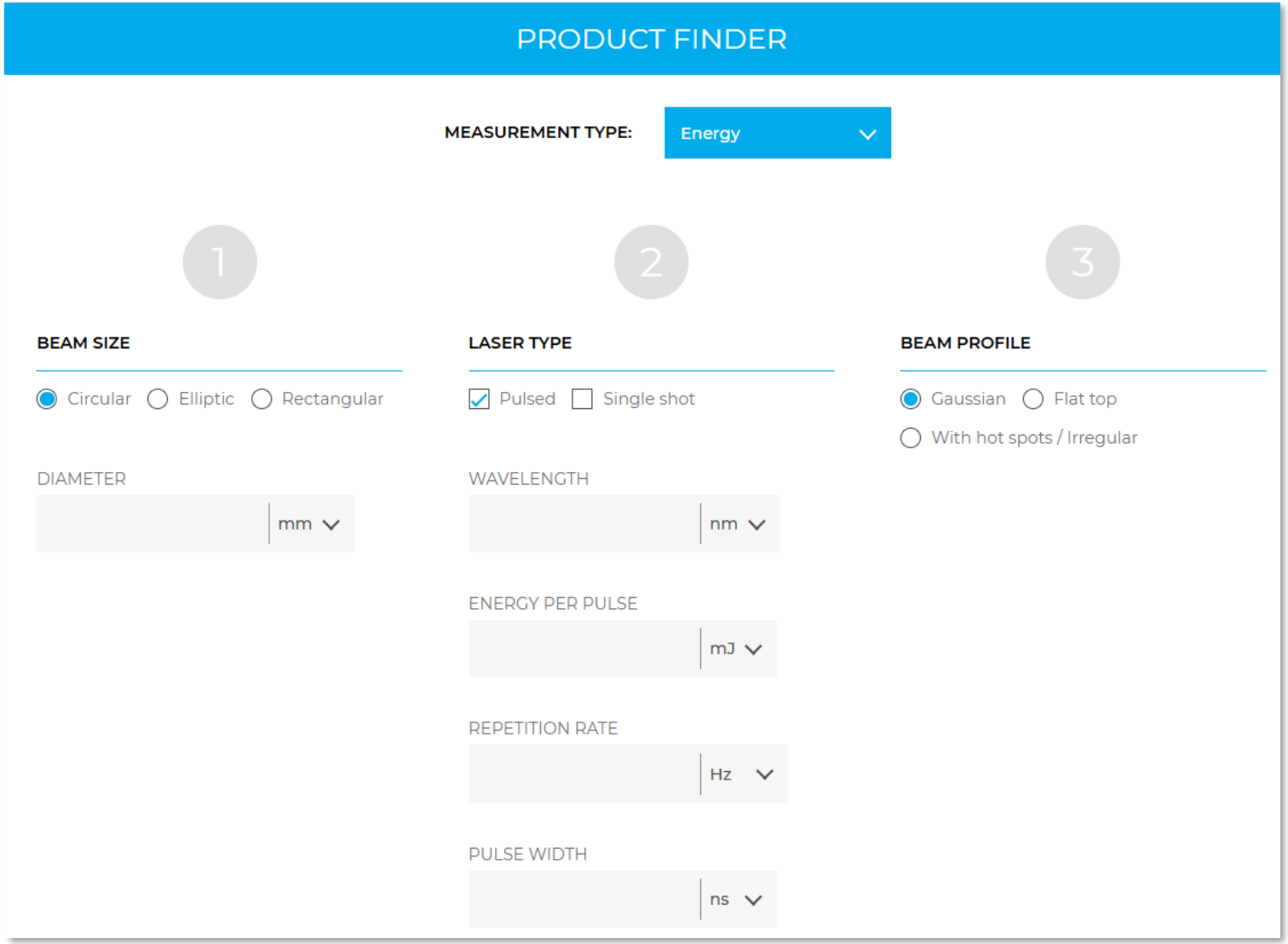
PARTNERS FOR ACCURACY



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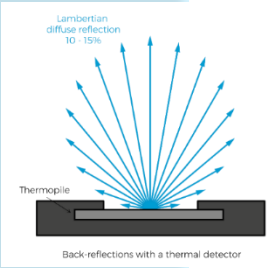
LASER POWER DETECTORS

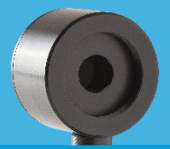
Water calorimeters (HP)
100 W - 120 kW +
0.19 - 20 µm

Thermopiles (XLP, UP, PRONTO)
30 µW - 2.5 kW
0.19 - 20 µm



Pyroelectric + chopper (UM)
100 nW - 20 mW
0.1 - 20 µm

Photodiodes (PH)
200 pW - 750 mW
210 - 1650 nm



pW nW µW mW W kW

Average power

Precision high-power (IS)
20 µW - 1 kW (high damage thresholds)
340 – 1100 nm

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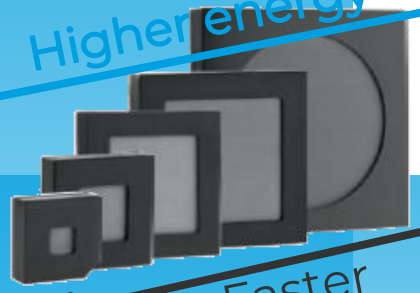
LASER ENERGY DETECTORS

Integrating spheres (M6)
pJ - 20 mJ
350 - 2500 nm

Repetition Rate

100 kHz
10 kHz
1 kHz
100 Hz
10 Hz
1 Hz
0.1 Hz

Higher energy

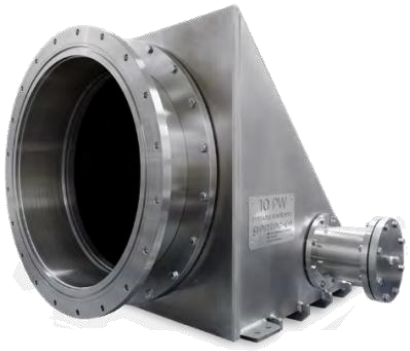


Faster

Pyroelectric detectors (QE)
µJ - 700 J
0.19 - 20 µm

Photodiodes (PE)
fJ - 80 nJ
210 - 1650 nm

Calos & Thermopiles (UP in SSE mode)
mJ - 16 kJ
0.19 - 20 µm



pJ nJ µJ mJ J kJ

Energy per pulse

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DAMAGE THRESHOLDS

- “Test Your Laser Compatibility”

Congratulations!

The instrument you selected is a great match for your laser specifications.

Power density (peak intensity)

Damage threshold	450 W/cm^2
Your laser	1.273 W/cm^2

Energy density

Damage threshold	6 J/cm^2
Your laser	0.1273 J/cm^2

GET A QUOTE

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SAME LASER / DIFFERENT READINGS?

- Detector responds but:
  - Reading drifts over time
  - Consistent offset compared to other detectors
  - Offset varies between measurements (zero issue?)
  - Non-linearity with power/energy
  - Bad repeatability with beam position/incidence angle
  - Wear/damage not always visible
- Used within specifications?
- Recalibration needed with potential repair?

LASER OR DETECTOR?

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BUILDING THE DETECTOR'S HISTORY

- As-Left versus As-Received sensitivity measured

Variance Report

	Last Calibration	As Received	New Calibration
Date	January 25, 2023	February 19, 2024	February 19, 2024
Sensitivity (mV/W)	0.605	0.610	0.610
Difference (from last calibration)	---------	0.005	0.005
Change (%)	---------	0.9	0.9
Status	Within Tolerance	Within Tolerance	Within Tolerance

Remark: When no repair is made to the detector, the "As received" and "New Calibration" values are the same.

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DESIGNING GOOD DIAGNOSTICS

- Proper detector head selection
- Alignment practices: beam expansion, defocusing and/or attenuation
- Damage thresholds!
  - Laser power + ambient heat = total thermal load
  - Power density can lead to internal damages
  - Energy density can lead to surface damages

EXPAND YOUR BEAM!

Beam power [kW]	Damage threshold [1] [kW/cm²]	Min. 1/e² beam diam [2 3] [cm]
0.5	80	0.6[4]
1	70	0.6[4]
2	60	0.6[4]
3	50	0.6
4	40	0.7
6	30	1.0
8	25	1.3
10	20	1.6

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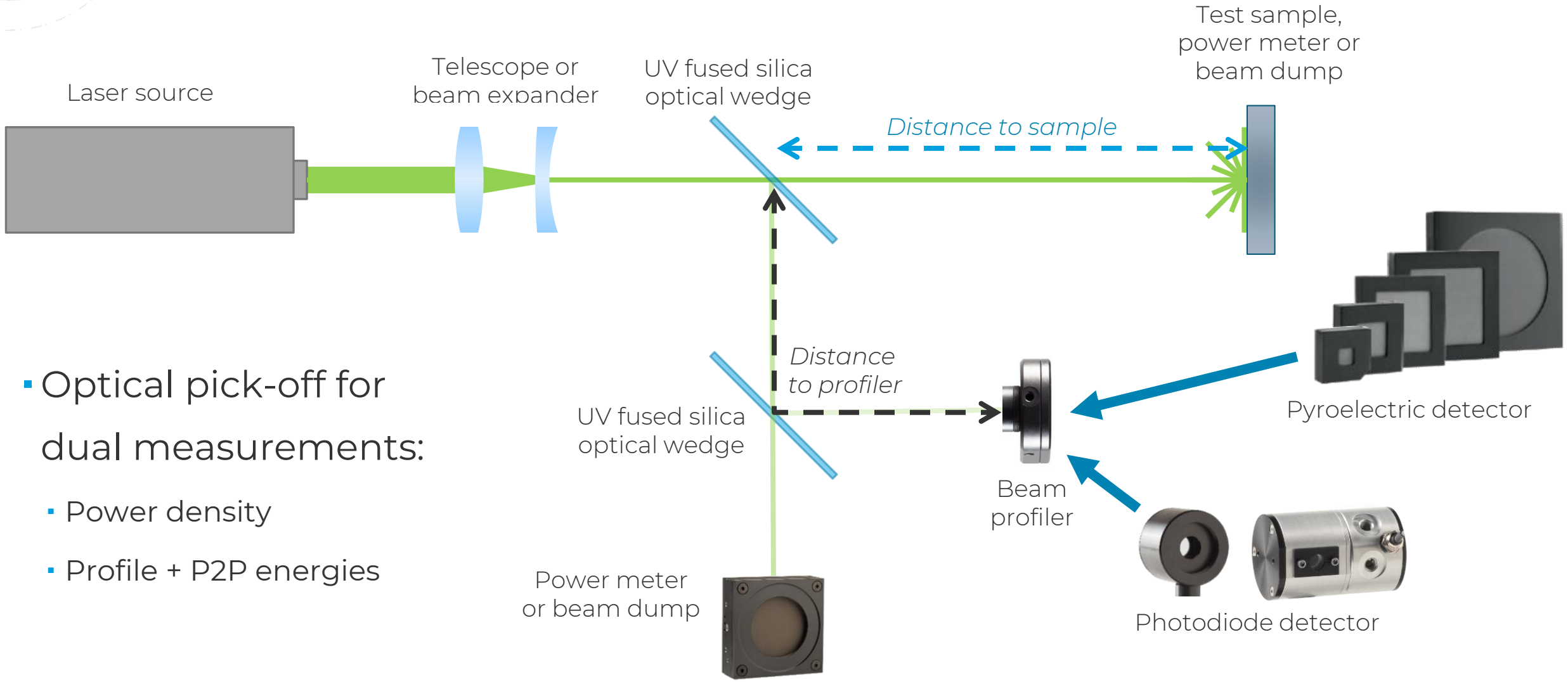
DESIGNING GOOD DIAGNOSTICS



- Optical pick-off for dual measurements:
  - Power density
  - Profile + P2P energies

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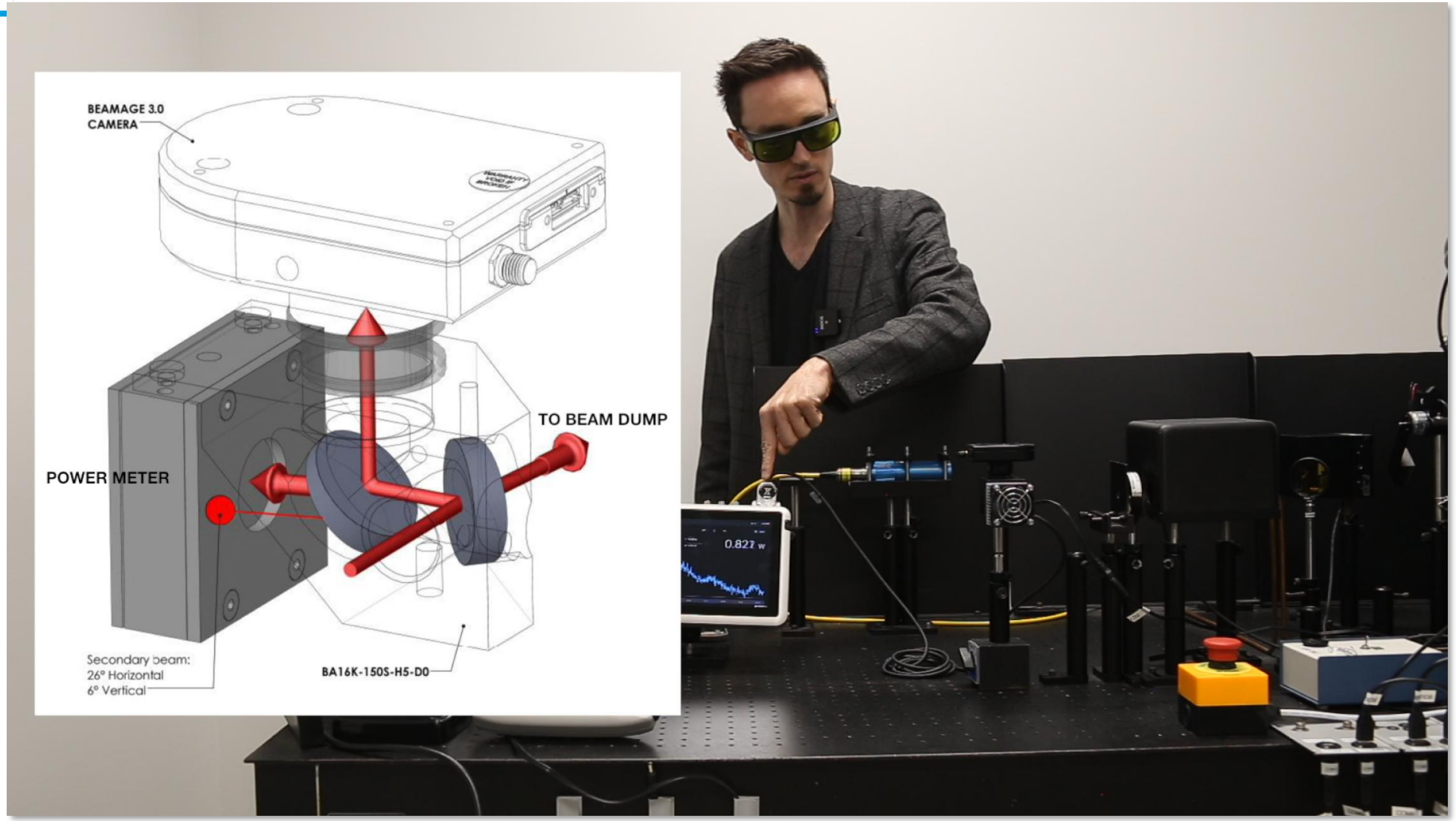
DESIGNING GOOD DIAGNOSTICS



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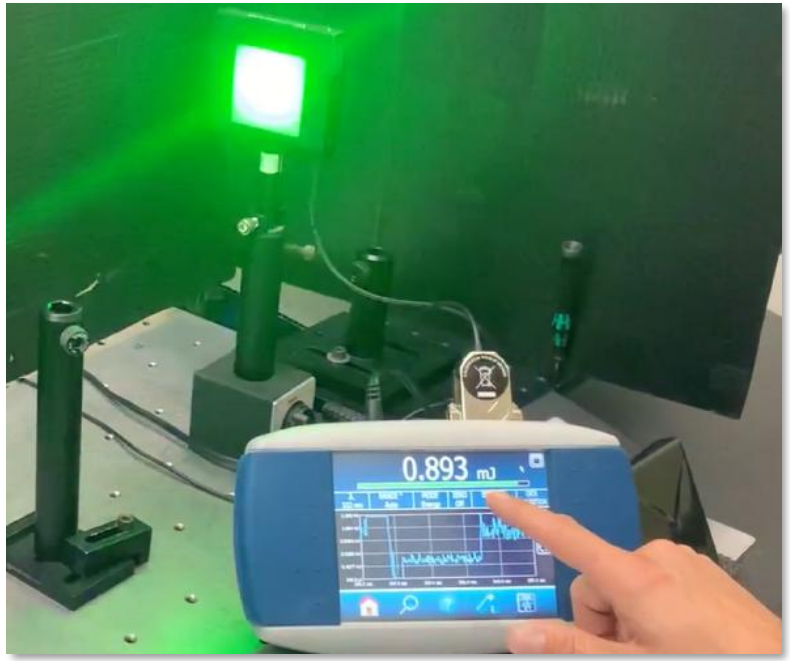
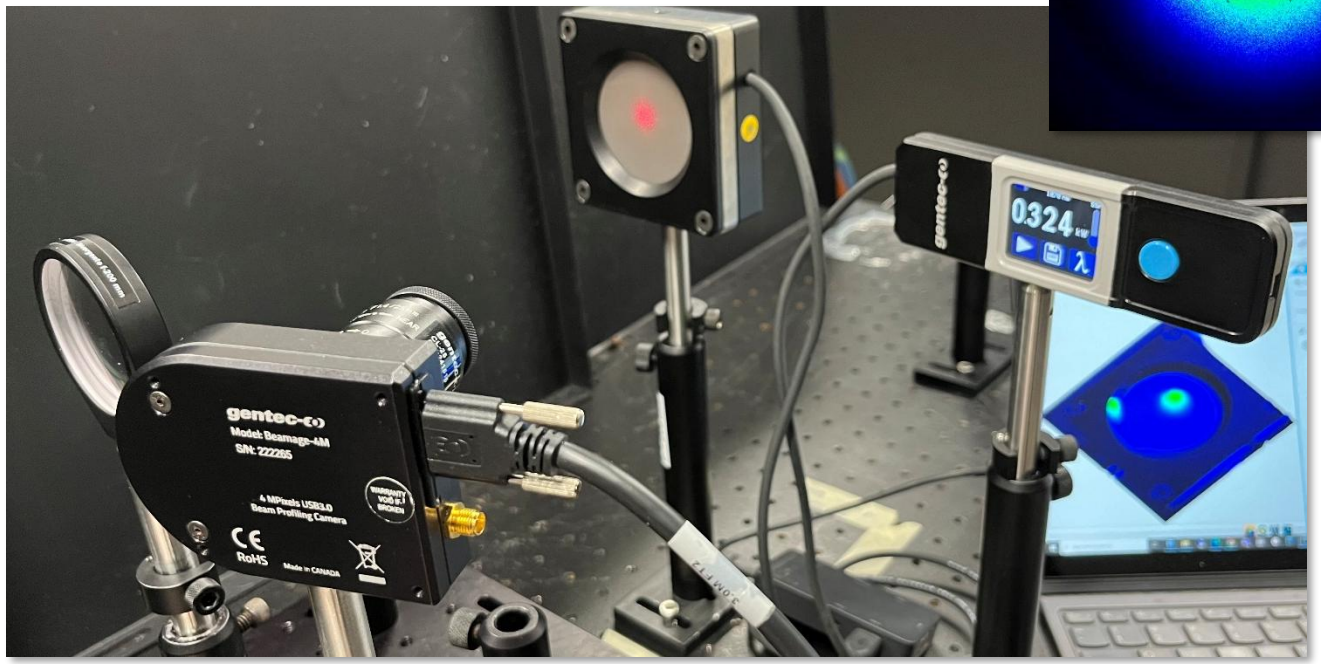
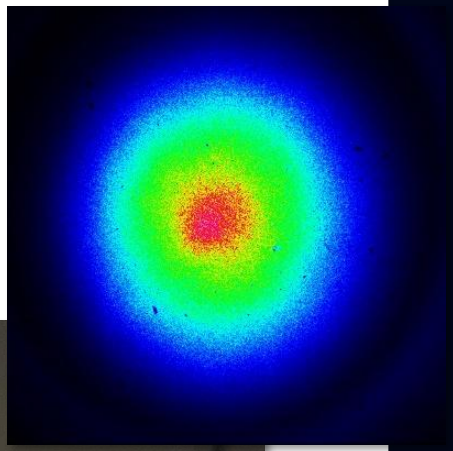
DESIGNING GOOD DIAGNOSTICS







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HOW DETECTORS GET DAMAGED

- 1- Power/energy density
- 2- Thermal load
- 3- Peak power (pulse energy/pulse width)
- 4- Repetition rate
- 5- Spectral response
- 6- Water issues
- 7- “Errare Humanum Est”

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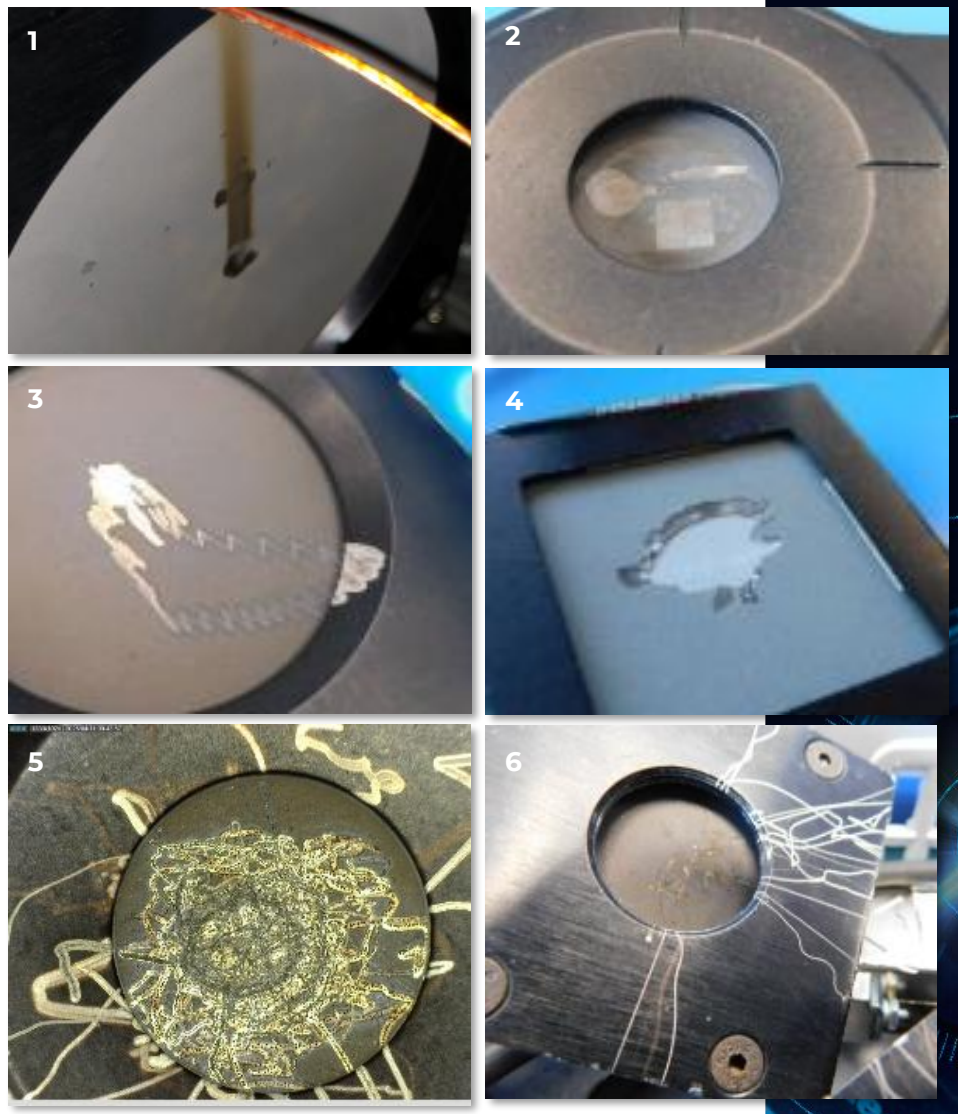
1/7: POWER/ENERGY DENSITY

- Discoloration, marking, spotting, ablation of coatings
- ”Expand your beam diameter to 10 mm”
- Wobbling patterns do not help
- External or internal melting of coatings, glues, thermocouples, pyroelectric crystals
- Align laser beam before firing, don’t hit housing (compromises integrity, specular reflections!)
- Local minor absorbing defects = added uncertainty



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1/7: DEFOCUS TO COVER >50% SURFACE

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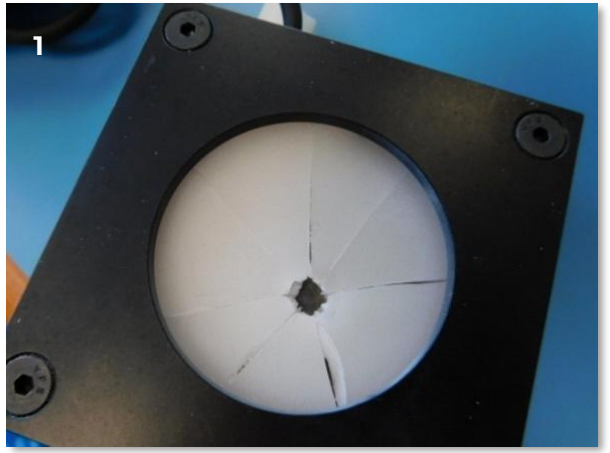
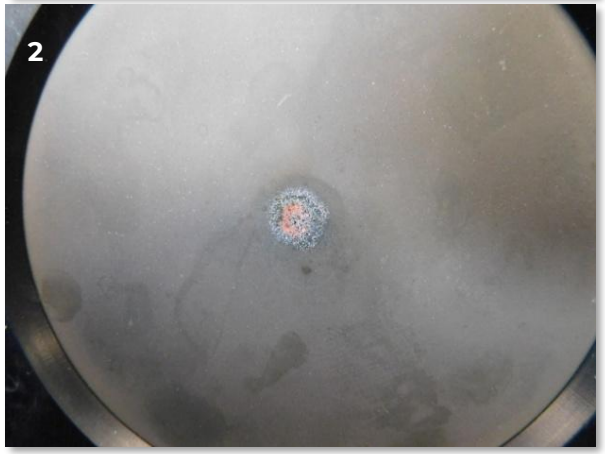
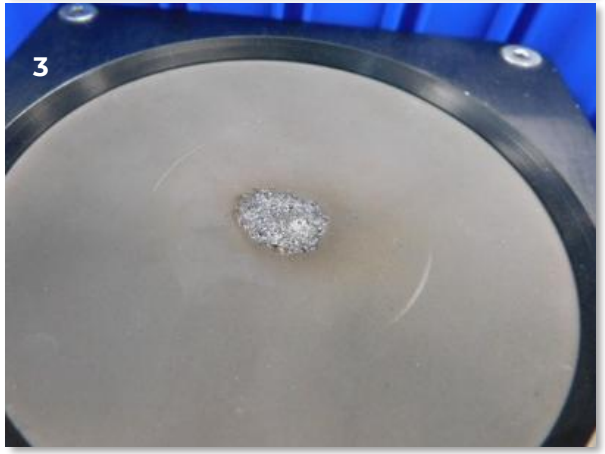
2/7: THERMAL LOAD

- Accumulated heat, cooling issues
- Even if beam not that small
- Damage thresholds in power/energy density decrease with laser average power
- Typical failure mode:
  - radial cracks due to thermal stress
  - melted absorber surface (specular reflections!)
- Not always able to resurface (copper or aluminum mass right behind with HP)
- Too hot can result in overestimation of laser power (HP) or underestimation (saturation of thermocouples in UP)







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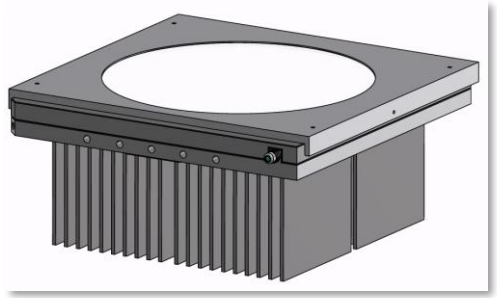
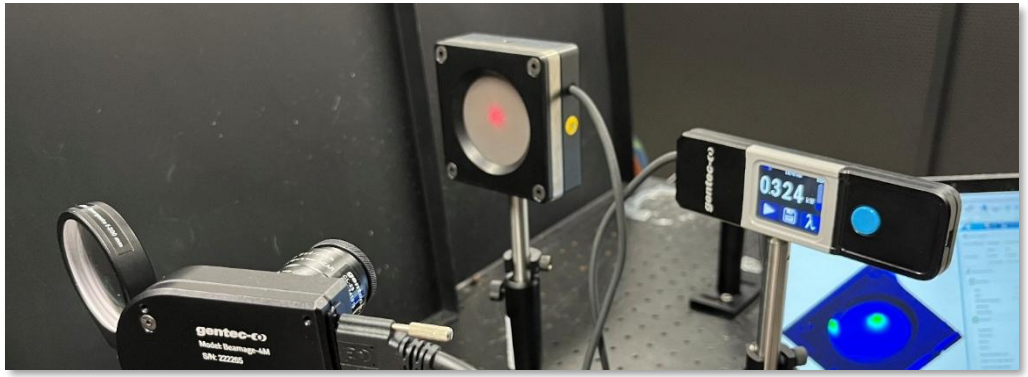
2/7: EXTRACT TOTAL THERMAL LOAD



- Laser beam + enclosure + environment
  = build up of temperature
- QE195LP pyroelectric detector
  - up to 350W, 200 Hz, 200 uJ to 700 J
  - smaller up to 10 kHz, max 10 W
- Watch out continuous vs 1 min measurement spec
- Let it rest?



MAX AVERAGE POWER
(CONTINUOUS / 1 MINUTE)

15 W / 30 W

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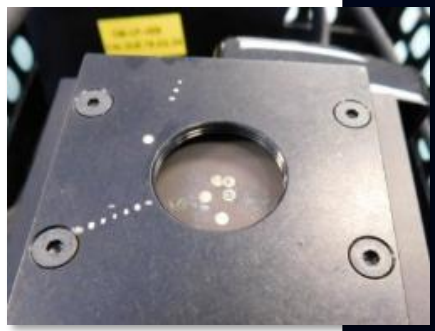
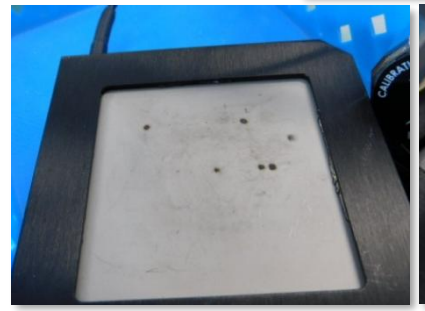
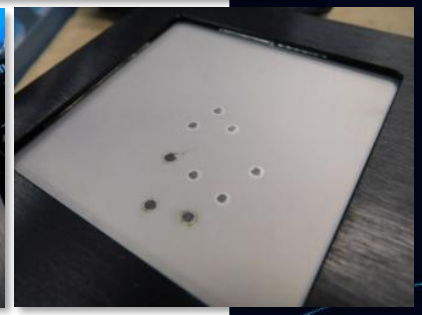
3/7: PEAK POWER

EXPAND YOUR BEAM!

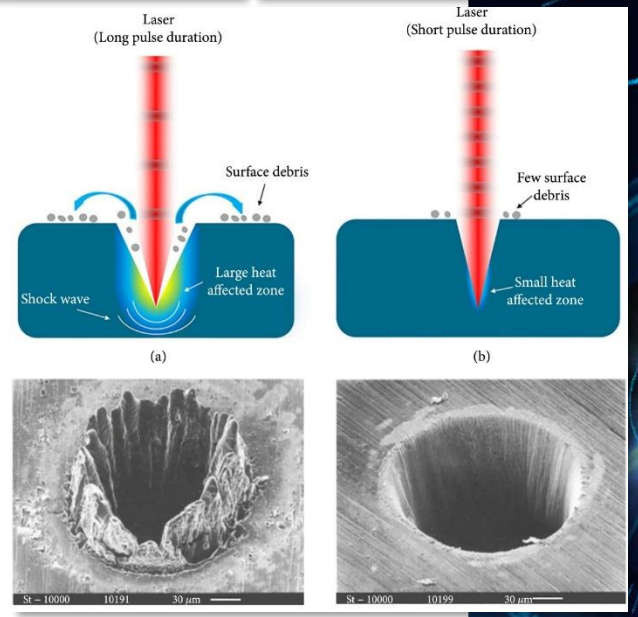


- Ultrafast pulses
- Coating damage, surface pitting
- Catastrophic when compromising components behind absorber (deeper penetration, axial energy transfer with pyroelectric detectors vs radial for thermopile)
- Peak power density damage threshold (ns versus fs)





Pulsed laser damage thresholds [l m]		
1.064 µm, 150 µs, 10 Hz	1200 mJ/cm^2	14 J/cm^2
1.064 µm, 7 ns, single-shot	--	16 J/cm^2
1.064 µm, 7 ns, 10 Hz	600 mJ/cm^2	8 J/cm^2
532 nm, 7 ns, 10 Hz	--	6 J/cm^2
266 nm, 7 ns, 10 Hz	500 mJ/cm^2	1 J/cm^2
Absorber	MB	QED



- Could absorb more or less = inconsistent offsets

Zhenyuan Lin, Minghui Hong.
Femtosecond Laser Precision Engineering: From Micron, Submicron, to Nanoscale. *Ultrafast Sci.* 2021;2021:DOI:10.34133/2021/9783514

4/7: REPETITION RATE

- Combined effects
- Accumulated pulses at DT in energy (grades of discoloration)
- More severe for pulsed UV (DT depends on wavelength)
- ”works on good region of absorber” but not linear, offset, added uncertainty and lack of space after a while!
- Averaging out errors if beam covers large areas
- Not absolute anymore
- Damaged areas can result in specular reflections
- Recoating may be possible

EXPAND YOUR BEAM!

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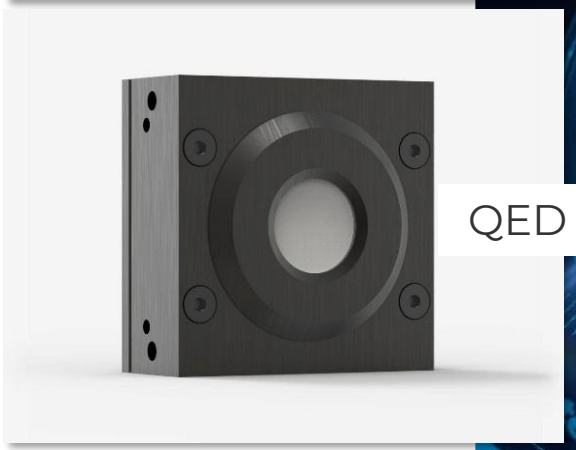
5/7: SPECTRAL RESPONSE

- Absorber not designed for the wavelength
  - Heating of unintended regions of detector
  - Error in measurements
- Unexpected reflections (system hazard)
  - H: 193 nm - 20 µm, flat absorption ~90%, 45 kW/cm2
  - W: 193 nm - 10 µm, 100 kW/cm2, not for CO2 lasers (no signal = become mirror = safety concern!)
  - QED: 266 nm - 2.5 µm, 100 kW/cm2, 16 J/cm2, ~50% back reflection (Lambertian)



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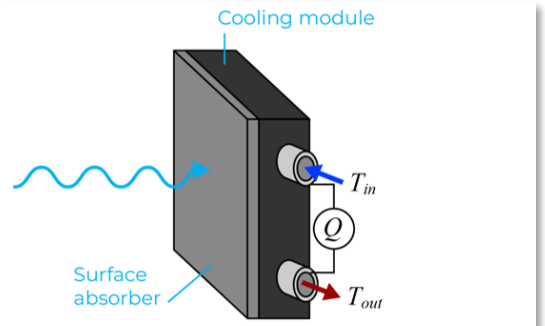
6/7: WATER ISSUES



$$Power \propto Q \bullet (T_{out} - T_{in}) / S(\lambda)$$

Q = cooling water flow rate

$(T_{out} - T_{in})$ = temperature difference

$S(\lambda)$ = calibrated sensitivity

- Safety concern for UP
- Safety and accuracy concern for HP
- Galvanic corrosion from wetted materials in cooling circuit
  - Nickel plating + SS + plastic, brass
  - Anodized aluminum + plastic + brass + SS+ nickel plating
  - … can customize!
- Life! (algae)

Made with AI

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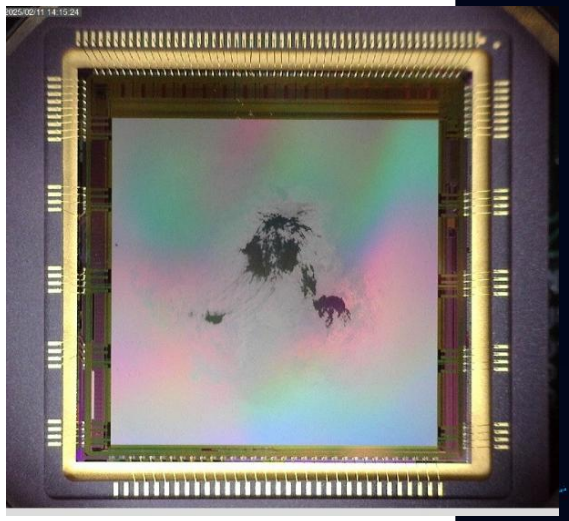
7/7: “ERRARE HUMANUM EST”

- Don’t attempt cleaning without guidance
- CMOS beam profiler (ND filter but no protective glass behind, for no fringing effects)
- Dust melting on surface, result in inaccuracy
- Oil (fingers) and dust will cook with laser energy
- Careful with transport, detector drop, cable snap, turn on cooling (water, fan), …



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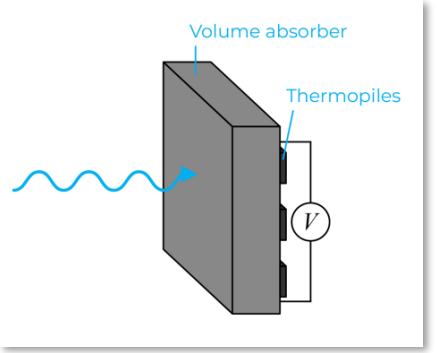
SAFETY, ACCURACY FOR ICF

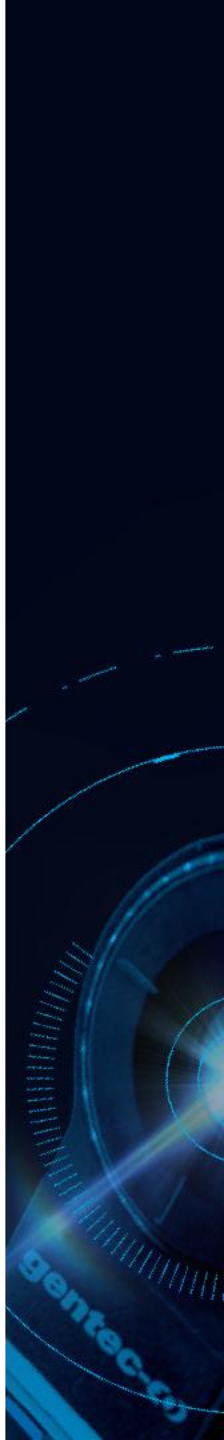
- Neodymium-doped glass pumped by flashlamps at NIF
  - 10 kJ * 192 beams, ns, 1053 nm → 351 nm (3 ω), 1 shot per day
  - Using established glass calorimeter technology
- Ytterbium-doped YAG pumped by laser diodes stacks?

  Direct drive with KrF?
  - 10 sources * 3 J * 10 Hz = 300 W within enclosure, and higher
  - 100's of beams (10 MW+ average power)
  - 10 Hz sweet spot for pyroelectric detectors but need active cooling
  - Driver for R&D



KEY MESSAGES FOR LSOs

- Specific duties and responsibilities of laser safety officers are listed under Appendix A of the ANSI Z136.1 standard. Includes:
  - The establishment of a laser safety program
  - Classify or verify the classification of lasers/laser systems
  - Approve standard operating procedures
  - Implement control measures to evaluate hazard in work areas
  - Recommend/approve laser protection equipment
  - Assure that proper laser safety training is provided
  - Perform laser safety audits
  - Perform medical examinations and investigate accidents



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KEY MESSAGES FOR LSOs

- Measurement errors are safety hazards
- Detectors are targets (verify suitability)
- Damage is often subtle (or not)
- Safe diagnostics = safer laser use = safer people = better systems = happier facilities
- Training users on measurement limits?
- Challenge measurement assumptions and calibrations
- Include diagnostics in safety reviews?
- Encourage dialogue
- Reinforce the LSO’s preventive role
- How do you approach this?

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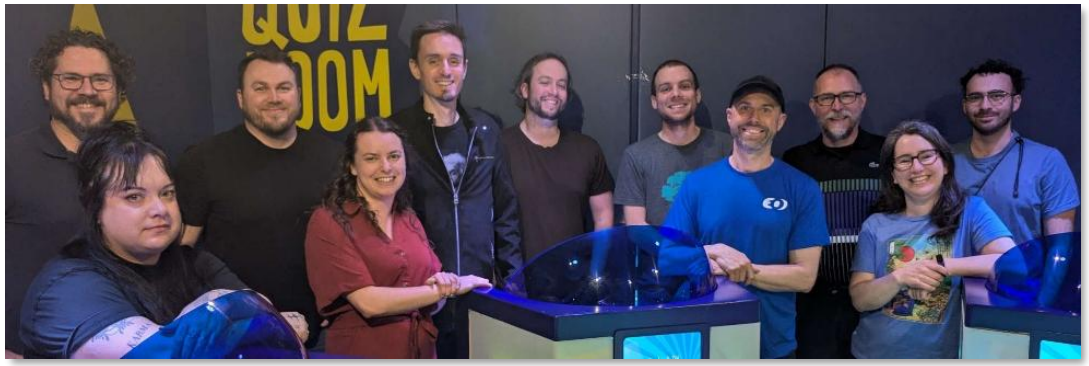
PARTNERS FOR ACCURACY



POWER & ENERGY METERS

BEAM PROFILING

TERAHERTZ MEASUREMENT

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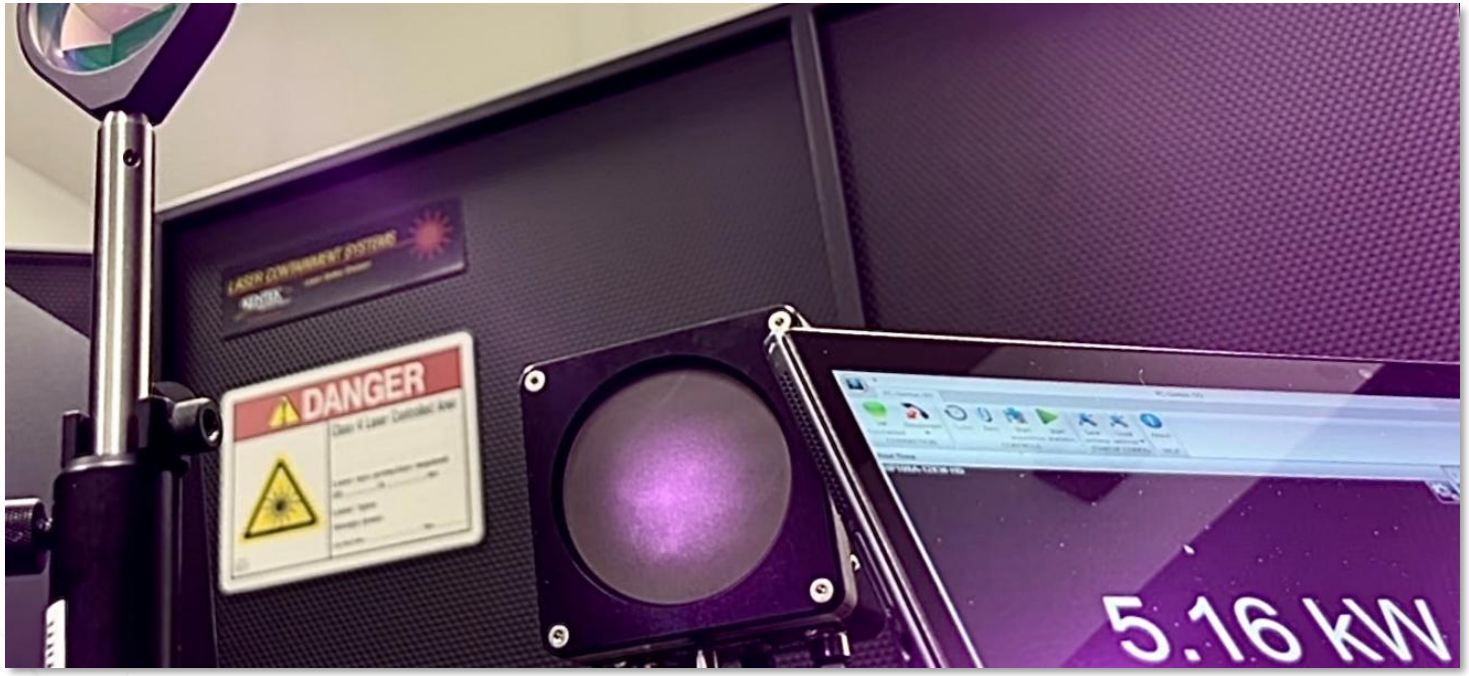
PROTECTING PEOPLE, SYSTEMS AND FACILITIES BY DOING SAFE LASER BEAM DIAGNOSTICS



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2026-05-19

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