Automated stations for LIDT measurements in nano- and femto-second pulses using ISO 21254-1,2,3,4 standards

George Nemeș¹,², Aurel Stratan¹, Constantin Fenic¹, Alexandru Zorilă¹,³, Laurenţiu Rusen¹, Săndeł Simion¹, Ioana Dumitrache¹,³, Constantin Blănaru¹, Liviu Neagu¹

¹ISOTEST Laboratory, NILPRP, 409 Atomiştilor Str., 077125 Măgurele-Bucharest, Romania
²ASTiGMAT™, 3409 Pecky Cedar Ct., Sacramento, CA 95827, USA; gnemes98@hotmail.com
³"Politehnica" University of Bucharest, 313 Splaiul Independenţei, 060042 Bucharest, Romania
Team

Alexandru Zorilă
Săndel Simion
Aurel Stratan
Scientific Manager

Ioana Dumitrache
Liviu Neagu
George (Jimmy) Nemeș
Project Director

Laurențiu Rusen
Constantin Blănaru
Constantin Fenic
Technical Manager
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  - Audience - interest

POS CCE
"Investments for your future"

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"Facility for laser beam diagnosis and ISO characterization / certification of behavior of optical components/materials subjected to high power laser beams / ISOTEST"
OUTLINE

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1. Introduction
ISOTEST Project overview

ISOTEST = Facility for testing optics and laser beam diagnosis using high power lasers according to ISO standards.

- ISO = International Organization for Standardization (Geneva, Switzerland).
- High power lasers (for ISOTEST Project):
  - Repetitively pulsed Nd:YAG laser + SHG, THG capability; $t_p \approx 5 \text{ ns}; f_{\text{rep}} = 10 \text{ Hz}; E_p = 0.7 \text{ J} \, @ \, 1064 \text{ nm}; P_{\text{ave}} \, (@1064 \text{ nm}) \approx 7 \text{ W}.$
  - Repetitively pulsed Ti:sapphire laser; $t_p \approx 200 \text{ fs} - 400 \text{ fs}; f_{\text{rep}} = 2 \text{ kHz}; E_p = 0.6 \text{ mJ} \, @ \, 775 \text{ nm}; P_{\text{ave}} \, (@775 \text{ nm}) \approx 1.2 \text{ W}.$
- Testing optics and optical materials $\rightarrow$ Laser-Induced Damage Threshold (LIDT), S-on-1 procedure (ISO 21254-2:2011); Assurance of laser power/energy handling capabilities ("durability test", ISO 21254-3:2011) $\rightarrow$ Automated test stations.
- Laser beam diagnosis
  - For beam characterization $\rightarrow$ Measuring energetic, temporal (ISO 11554:2000), and spatial (ISO 11146-1,2,3/2004,2005) beam characteristics.
  - For LIDT measurements $\rightarrow$ Measuring specific quantities for a pulsed spot.
- ISOTEST Project length: 36 - 40 months; Budget: $\approx$1.2 M€.
ISOTEST Project objectives

O1. Developing / implementing methods for laser beam diagnosis

O2. Developing automated test stations for measuring LIDT of optical components (ISO 21254-1,2,3,4:2011)

O3. Developing procedures for laser beams diagnosis and for LIDT

O4. Accreditation of ISOTEST Lab. of NILPRP by the Romanian Accreditation Association (RENAR) to perform tests/measurements and ISO certifications by using the ISOTEST Lab. equipment
2. Evolution history for LIDT standards


  **Main quantities of interest:** Damage threshold fluence \((\text{J/cm}^2)\) and irradiance \((\text{W/cm}^2)\).

  **Other quantities refer to spot** (section of a pulsed beam) **diagnosis:** \(A_{\text{eff}}, t_{\text{eff}}\).


After 1984 published data: up to 3 orders of magnitude discrepancy of results between different labs \(\rightarrow\) Need for standards.


**Today, a 25% overall uncertainty in damage threshold fluence/irradiance \(\rightarrow\) good.**

**Note:** - Developing a new ISO standard takes in average \(\sim\)10 years.

  Updated versions may take less (3-5 years).

- Lifetime of an ISO standard spans in average also \(\sim\)10 years.
3. Specific ISO Standards for LIDT

ISO 21254-1,2,3,4:2011. Main parameters of interest

- **S-on-1 test (ISO 21254-2:2011):**
  - Effective spot area on target ($A_{eff}$) - cm$^2$ → pulsed spot diagnosis
  - Effective pulse duration ($t_{eff}$) - fs, ns → pulsed spot diagnosis
  - Pulse peak power ($P_{pk}$) - W
  - Pulse energy density (fluence) on target ($H$) - J/cm$^2$
  - Pulse power density (irradiance, *not intensity*) on target ($E$) - W/cm$^2$
  - Maximum number of identical pulses applied on the same site ($S$)
  - Number of identical pulses irradiating a site of the target for which a damage characteristic curve is calculated ($N$); $1 \leq N \leq S$
  - Many sites (hundreds) on sample
  - **Damage characteristic curves:** damage threshold fluence vs. $N$ → $H_0(N)$; $H_{50}(N)$

- **Assurance of laser power/energy handling capabilities ("durability" test, type 2) (ISO 21254-3:2011):**
  - Pass/Fail - type test for predetermined value of fluence/irradiance, large spot size ($\geq 2$ mm), few sites (4 - 6) on sample.
4. Automated station using nanosecond laser pulses

Types of laser damage tests
- Damage S-on-1 (ISO 21254-2)
- Assurance of power/energy handling capabilities (durability test) (ISO 21254-3)

Type of laser
- Nd:YAG laser → Quantel type Brilliant B-10-SLM: \( t_{\text{eff}} = 4 \text{ ns} - 6 \text{ ns} \); \( f_{\text{rep}} = 10 \text{ Hz} \);
  \[ \lambda: \ 1064 \text{ nm} / 532 \text{ nm} / 355 \text{ nm}; \ E_{\text{pMax}}: 0.7 \text{ J} / 0.25 \text{ J} / 0.1 \text{ J} \]

Temporal diagnosis → Real-time fast photodiode/oscilloscope (0.4 ns rise time)

Parameters for S-on-1 test
- \( S = 500 \)
- Adjustable, large spot (0.2 mm - 0.6 mm), near-gaussian spatial profile on target
- Using 4-12 steps of different fluence intervals between 5 % and 95 % damage probability (automatic selected by computer)
- Number of irradiated sites for 25 mm dia. sample: 100 - 300 (programmable)
- Duration of automated measurement \( \approx 4 \text{ h} - 5 \text{ h} / \text{sample} \), including the test report

ISO recommendations we follow for durability test
- Very large spot (≥ 2 mm), near flat-top spatial profile on target → zoom optics
Automated nanosecond station
Experimental setup - simplified schematic
Automated nanosecond station
Experimental setup - actual view
Automated nanosecond station - graphical interface
Automated nanosecond station
Spatial and temporal profile

Spatial profile of original laser beam, 1064 nm

Spatial profile in the equivalent target plane, 1064 nm (with VariSpot™)

d_{eff} = 0.25 mm

d_{eff} = 2.1 mm

Typical temporal profile, 1064 nm

\[ t_{eff} = 5.8 \text{ ns}; \quad t_{FWHM} = 4.4 \text{ ns} \]

(Typical = average of 10 pulses)
Automated nanosecond station
Summary of main characteristics

- Test Standards: ISO 21254-1,2,3,4:2011
- Test procedures: S-on-1 (S = 500); Durability (type 2)
- Wavelengths: 1064 nm; 532 nm; 355 nm
- Pulse energy: 700 mJ; 250 mJ; 100 mJ
- Temporal profile: smooth (injection-seeded Nd:YAG Laser)
- Effective pulse duration, $t_{\text{eff}}$: 6 ns; 5 ns; 4 ns
- Repetition frequency: 10 Hz
- Spatial profile: Near gaussian to near flat top
- Effective spot diameter, $d_{\text{eff}}$: 0.2 mm – 2.0 mm (adjustable); $f_{\text{VS}} = 1000$ mm
- Beam incidence angle on sample: $0^0 – 60^0$
- Polarization state: Linear or circular
- Test environment: clean, controlled temperature / humidity lab.
- Automated test, operator initiated and supervised
Automated nanosecond station - Example 1 of damage results

Sample: Metallic mirror; New P-BK7

Black: $H_0(N)$
Red: $H_{50}(N)$

Nomarski micrograph of damaged site
1.5 J/cm$^2$, 1 pulse
Automated nanosecond station - Example 2 of damage results

Black: $H_0(N)$
Red: $H_{50}(N)$

Sample: HR @ 1064 nm

Nomarski micrograph of damaged site
22 J/cm², 5 pulses
Automated nanosecond station - Example 3 of damage results

Sample: AR @ 1064 nm; MgF₂, LASF40

Measured and extrapolated S-on-1 damage threshold vs. number of pulses, N.

X – number of pulses, N; for $N \leq S$, data from experiments;
   for $N > S$, extrapolated data

Y – threshold energy density at 0 % damage probability, $H_0(N)$ (J/cm²)

1 – experimental data
2 – extrapolated $H_0(N)$ for large $N$

Black: $H_0(N)$
Red: $H_{50}(N)$

Nomarski micrograph of damaged site 37 J/cm², 1 pulse
5. Automated station using ~300 fs laser pulses

- Type of laser damage test: S-on-1 (ISO 21254-2)

- Type of laser: Ti:sapphire → Clark-MXR model CPA 2101

\[ \lambda = 775 \text{ nm}; \ t_{\text{eff}} = 250 \text{ fs} - 400 \text{ fs}; \ f_{\text{rep}} = 2 \text{ kHz}; \ E_{\text{pMax}} = 0.55 \text{ mJ} \]

- Temporal diagnosis: GRENOUILLE (simplified FROG) device type G-8-50 USB

- Parameters for S-on-1 test:

\[ S = 100 \ 000 \]

Fixed spot size (≈0.15 mm), near-gaussian spatial profile on target
Using 4 - 12 steps of different fluences between 5 % and 95 % damage probability (automatic selection by computer)
Number of irradiated sites for 25 mm dia. sample: 100 - 300 (programmable)
Duration of automated measurement \( \approx 4 \text{ h} - 5 \text{ h} / \text{sample} \) (including test report)
Automated station using ~300 fs laser pulses
Experimental setup - simplified schematic
Automated station ~300 fs pulses
Experimental setup - actual view 1
Automated station ~300 fs pulses
Experimental setup - actual view 2
Automated station ~300 fs pulses
Spatial and temporal profile

$d_{eff} = 0.15 \text{ mm}$

Spatial pulse profile in the equivalent target plane

Typical temporal profile:
$t_{eff} = 280 \text{ fs}; \ t_{FWHM} = 250 \text{ fs}$

Typical = average of 10 displays GRENOUILLE
Automated station ~300 fs pulses
Summary of main characteristics

- Test standards: ISO 21254 -1,2,4:2011
- Test procedures: S-on-1 (S = 10^5)
- Wavelength: 775 nm
- Pulse energy: max. 0.55 mJ
- Pulse peak fluence: max. 3 J/cm^2
- Pulse repetition frequency: 2 kHz
- Temporal profile: smooth
- Effective pulse duration, \( t_{eff} \): 280 fs - 380 fs (laser adjustment dependent)
- Spatial profile: Near gaussian
- Effective spot diameter, \( d_{eff} \): 0.15 mm; \( f = 500 \) mm
- Beam incidence angle on target: 0° – 60°
- Polarization state: Linear or circular
- Test environment: clean, controlled temperature / humidity lab.
- Automated test, operator initiated and supervised
Automated station ~300 fs pulses
Example of damage results

Sample - R&D metallic mirror on BK7

Characteristic damage curve of the sample

X – number of pulses, N (N ≤ S) for which the damage probability is calculated
Y – threshold fluence, H(N) (J/cm²)
1 – threshold fluence, H₀(N) – experimental data
2 – threshold fluence, H₅₀(N) – experimental data
3 – H₀(N) - nonlinear fit
4 – H₅₀(N) - nonlinear fit

Measured and extrapolated S-on-1 damage threshold vs number of pulses, N.

X – number of pulses, N; for N ≤ S, data from experiments; for N > S, extrapolated data
Y – fluence, H₀(N) (J/cm²)
1 – experimental data
2 – extrapolated H₀(N) for large N
Automated station ~300 fs pulses
Example 2 of damage results

Sample: Thorlabs type PF10-03-P01: protected silver mirror on FS

Characteristic damage curve of the sample

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<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of pulses, N</td>
<td>threshold fluence, H(N) (J/cm²)</td>
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1 – threshold fluence, H₀(N) – experiment
2 – threshold fluence, H₅₀(N) – experiment
3 – H₀(N) - nonlinear fit
4 – H₅₀(N) - nonlinear fit

Measured and extrapolated S-on-1 damage threshold vs number of pulses, N.

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<td>number of pulses, N</td>
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1 – experimental data
2 – extrapolated H₀(N) for large N

Stated Thorlabs damage figure for 1064 nm, 10 ns, 10 Hz : 3 J/cm²

Results:
Extrapolated figure from Thorlabs data, for 775 nm, 380 fs: 0.14 J/cm²
Our extrapolated experimental result, H₀ (10¹²): 0.11 J/cm²
## 6. Comparison between ns and fs station

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<td>Moderate-good</td>
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<td></td>
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</table>
7. Conclusion

Accomplishments

- Developed two automated stations for LIDT measurements: ns; fs
- Implemented some original solutions: DSP; External control of N; VariSpot™
- Performing LIDT experiments

Further work

- Need to test repeatability (precision) of measurements (auto-comparison)
- Need to test reproducibility (and accuracy) of measurements (inter-comparison)
- Gradually moving from engineering of automated stations to physics of LID process
- Support for Romanian optical manufacturers (Ophir Optics; ProOptica; IOR)