Work on Coatings

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Motivation:

- Qualification of optics for ADM-Aeolus mission (ALADIN instrument)
- Extensive test campaigns (IR, UV, VIS) to identify optics exposed to critical fluence levels

Issues:

Testing under application-oriented conditions
(high vacuum, dry pump systems, laser parameters comparable to the ALADIN laser system)

- Development of a vacuum laser damage test bench

Important aspects:

Scaling of LIDT to Gshot levels from data based up to $10^4$ shots/site?
Vacuum effect on coating performance?

Introduction
Laser damage test bench: IR optical setup
Nd:YAG Laser

lambda/2 plate

Aperture 2.2 mm

HeNe (stab.)

Wedge

f = 750 mm

Optical shutters

Pulse counter

Pyroelectric detector

Chopper 3 kHz

600 mm

Sample under vacuum

Low noise diode

Flow box area

PC

SHG / THG unit

Pol.

12 bit CCD

Pyroelectric detector

Laser damage test bench: UV optical setup
### Laser damage test bench: specs and error budget of laser source

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SI Units</th>
<th>Laser Source 1</th>
<th>Laser Source 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1064 nm</td>
<td>355 nm</td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>100 Hz</td>
<td>&lt; 0.001 %</td>
<td>&lt; 3 %</td>
</tr>
<tr>
<td>Pulse energy (IR pump energy 300 mJ)</td>
<td></td>
<td>70 mJ</td>
<td></td>
</tr>
<tr>
<td>Pulse duration (FWHM)</td>
<td>3.5 ns</td>
<td>3 ns</td>
<td></td>
</tr>
<tr>
<td>Pulse to pulse energy stability (IR pump energy 300 mJ)</td>
<td>&lt; 1.3 %</td>
<td>&lt; 3 %</td>
<td></td>
</tr>
<tr>
<td>Pulse to pulse spatial profile stability</td>
<td>&lt; 3.3 %</td>
<td>&lt; 2 %</td>
<td>&lt; 25 µrad</td>
</tr>
<tr>
<td>Pulse to pulse temporal profile stability</td>
<td>&lt; 5 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse to pulse pointing stability</td>
<td>&lt; 10 µrad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pointing stability (horizontal / vertical direction)</td>
<td>&lt; 25 µrad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam quality</td>
<td>M² &lt; 1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linewidth</td>
<td>&lt; 250 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linewidth</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Far field beam profiles (lhs: IR, rhs: UV)
Background pressure: $18 \times 10^{-6}$ mbar

Typical pressure rise: $4 \ldots 8 \times 10^{-6}$ mbar

**Damage monitoring via scatter probing and transient pressure sensing**
• Test of scattering samples (light trap absorbers)
• Vibration insensitive
• Misalignment (drift) insensitive
• Useful as backup signal
• Fast (up to kHz bandwidth)
• No interference with optical channels
• Sensitive to front and back surface
• No detection of bulk damage!

Features of the transient pressure sensing
Laser damage test bench: 1w / 3 w beamline / multi-functional vacuum chamber
<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data acquisition</td>
<td>up to 800 Hz, multi channel</td>
</tr>
<tr>
<td>Automation status</td>
<td>semi- / fully automated</td>
</tr>
<tr>
<td>Energy preselection algorithm</td>
<td>binary / random; input &amp; output parameter: pulse energy</td>
</tr>
<tr>
<td>Damage detection modes</td>
<td>1. Lock-in based, collinear scatter probing</td>
</tr>
<tr>
<td></td>
<td>2. transient pressure sensing, cold cathode sensor</td>
</tr>
<tr>
<td>Lifetime testing</td>
<td>up to 50 Mio. Shots (flashlamp lifetime)</td>
</tr>
<tr>
<td>Sample positioning</td>
<td>completely inside vacuum</td>
</tr>
<tr>
<td>Laser beam analysis</td>
<td>12 bit CCD, 4.4 µm pitch (Spiricon FireWire); online beam profiling; adaptation to sample position</td>
</tr>
<tr>
<td>Laser wavelengths</td>
<td>1w &amp; (2w; 3w) separate beam lines</td>
</tr>
<tr>
<td>Mode of operation</td>
<td>burst (intermittent) / non-burst operation</td>
</tr>
<tr>
<td>Typical vacuum quality</td>
<td>5 (10^{-6}) mbar, oil-free pump system</td>
</tr>
</tbody>
</table>

**Main features of damage test bench**
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Fluence $F$ [J/cm$^2$] vs. Number of pulses $N$

**Empirical fitting curve:**

$$F = F_1 e^{-N/c_1} + F_2 N^{-c_2}$$

- Exponentially decaying part $F_1 e^{-N/c_1}$
- Slowly decaying part $F_2 N^{-c_2}$

-> valid for all types of samples tested
-> valid for 1064 nm / 355 nm wavelength
-> independent of atmospheric conditions

**Characteristic damage curve: laser fatigue effect**

Chi$^2 = 0.00498$

R$^2 = 0.98613$

- $c_1 = 10.13052 ± 1.50773$
- $c_2 = 0.01201 ± 0.00305$
- $F_1 = 3.81689 ± 0.5483$
- $F_2 = 5.09429 ± 0.10386$

Sample: ES_LC_AR_096
Pressure: 5·10$^{-6}$ mbar
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Degradation under vacuum

1 bar N₂

Vacuum

F = F₁ e^{N/c₁} + F₂ N^{c₂}

Chi² = 0.00105
R² = 0.99776

c₁ = 5.79939 ± 0.32053

c₂ = 0.00051 ± 0.00108

F₁ = 3.18984 ± 0.13933

F₂ = 5.62741 ± 0.04031

Pressure: 1000 mbar N₂

Chi² = 0.00498
R² = 0.98613

c₁ = 10.13052 ± 1.50773

c₂ = 0.01201 ± 0.00305

F₁ = 3.81689 ± 0.5483

F₂ = 5.09429 ± 0.10386

Pressure: 5 × 10⁻⁶ mbar

Sample: ES_LC_AR_096
**Effect of gas thermal conductivity**

Fluence $F$ as a function of the number of pulses $N$ for two different pressure conditions:

- **Vacuum**
  - Sample: ES_LC_AR_099
  - Pressure: $5 \times 10^{-6}$ mbar - $5 \times 10^{-5}$ mbar

  - Chi-squared ($\chi^2$): 0.01148
  - R-squared ($R^2$): 0.945
  - $c_1$ = 12.90994 ± 5.09142
  - $c_2$ = 0.00759 ± 0.00434
  - $F_1$ = 1.21662 ± 0.27352
  - $F_2$ = 5.72651 ± 0.16983

- **4 bar He**
  - Sample: ES_LC_AR_098
  - Pressure: 4 bar (He)

  - Chi-squared ($\chi^2$): 0.00425
  - R-squared ($R^2$): 0.97465
  - $c_1$ = 10.65326 ± 3.21496
  - $c_2$ = 0.00984 ± 0.00263
  - $F_1$ = 1.82971 ± 0.53515
  - $F_2$ = 5.76169 ± 0.10323

The equation used is $F = F_1 e^{-N/c_1} + F_2 N^{c_2}$.
**Effect of vacuum residence time**

Immediate testing

Sample: ES_LC_AR_099
pressure: 5x10\(^{-6}\) mbar - 5 \(10^{-5}\) mbar

\[
F = F_1 e^{\frac{-N}{c_1}} + F_2 N^{c_2}
\]

Chi\(^2\) = 0.01148
R\(^2\) = 0.945

\(c_1\) = 12.09994 ± 5.09142
\(c_2\) = 0.00759 ± 0.00434
\(F_1\) = 1.21662 ± 0.27352
\(F_2\) = 5.72651 ± 1.6983

42 h under vacuum

Sample: ES_LC_AR_099
pressure: 5 \(10^{-4}\) mbar

Chi\(^2\) = 0.00273
R\(^2\) = 0.98766

\(c_1\) = 33.22866 ± 8.58043
\(c_2\) = 0.01121 ± 0.00396
\(F_1\) = 0.75737 ± 0.1074
\(F_2\) = 5.14173 ± 0.13947
testing of 14 different types of optics, 38 samples overall

<table>
<thead>
<tr>
<th>Ref. Name; Substrate</th>
<th>Coating type</th>
<th>Test mode</th>
<th>Sample dim’s</th>
<th>$F_{10 \text{,} 000}$ [J/cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveplate; crystal quartz</td>
<td>AR</td>
<td>S-on-1</td>
<td>15 x 15 x 0.2 mm</td>
<td>12.4</td>
</tr>
<tr>
<td>Piezo mirror; UV grade fused silica</td>
<td>PR</td>
<td>S-on-1</td>
<td>25.4 x 3 mm</td>
<td>12.0</td>
</tr>
<tr>
<td>HR mirror; UV grade, fused silica</td>
<td>HR</td>
<td>S-on-1</td>
<td>25.4 x 1.8 mm</td>
<td>18.4</td>
</tr>
<tr>
<td>Q-Switch; RTP crystal</td>
<td>AR</td>
<td>S-on-1</td>
<td>9 x 9 x 3 mm</td>
<td>5.8</td>
</tr>
<tr>
<td>Polarizer; UV grade, fused silica</td>
<td>S-on-1</td>
<td></td>
<td>25.4 x 3 mm</td>
<td>27.0</td>
</tr>
<tr>
<td>MO rod;</td>
<td>AR / HR</td>
<td>S-on-1</td>
<td>12.8 x 3 mm</td>
<td>6.3</td>
</tr>
<tr>
<td>Polarizer cube; Fused silica</td>
<td>AR</td>
<td>S-on-1/b</td>
<td>12.7 x 12.7 x 12.7 mm</td>
<td>16.5</td>
</tr>
<tr>
<td>Folding mirror; UV grade, fused silica</td>
<td>HR</td>
<td>S-on-1/b</td>
<td>25.4 x 3 mm</td>
<td>10.8</td>
</tr>
<tr>
<td>Telescope lens; UV grade, fused silica</td>
<td>AR</td>
<td>S-on-1/b</td>
<td>25.4 x 6.0 mm</td>
<td>23.5</td>
</tr>
<tr>
<td>SH; LBO crystal</td>
<td>AR</td>
<td>S-on-1/b</td>
<td>10 x 10 x 2 mm</td>
<td>10.1</td>
</tr>
<tr>
<td>TH; LBO crystal</td>
<td>AR</td>
<td>S-on-1/b</td>
<td>10 x 10 x 2 mm</td>
<td>6.6</td>
</tr>
<tr>
<td>Dichroic plate; UV grade, fused silica</td>
<td>Dichroic</td>
<td>S-on-1/b</td>
<td>25.4 x 3 mm</td>
<td>19.5</td>
</tr>
<tr>
<td>Folding mirror; UV grade, fused silica</td>
<td>HR</td>
<td>S-on-1/b</td>
<td>25.4 x 3 mm</td>
<td>7.4</td>
</tr>
<tr>
<td>Light trap</td>
<td>anodized</td>
<td>S-on-1/b</td>
<td>38.1 x 3 mm</td>
<td>0.8</td>
</tr>
</tbody>
</table>

* Stated are „best LIDT values“ for tested types of optics

LIDT-tested ALADIN laser optic components (wavelength 1064 nm)
LIDT-tested ALADIN laser optic components (wavelength 355 nm)

| Ref. Name; Substrate                  | Coating type | Test mode | Sample dim’s  | $F_{10,999}^*$ [
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveplate; crystal quartz</td>
<td>AR</td>
<td>S-on-1/1b</td>
<td>diameter 13 mm</td>
<td>5.6</td>
</tr>
<tr>
<td>Lens; Suprasil 1</td>
<td>AR</td>
<td>S-on-1/1b</td>
<td>25 x 2 mm</td>
<td>6.5</td>
</tr>
<tr>
<td>Beam splitter wedge; Suprasil 1</td>
<td>HR</td>
<td>S-on-1/1b</td>
<td>12 x 2 mm</td>
<td>1.7</td>
</tr>
<tr>
<td>Beam expander parabola; Suprasil 1</td>
<td>HR 45</td>
<td>S-on-1/1b</td>
<td>25 x 2 mm</td>
<td>3.6</td>
</tr>
<tr>
<td>Folding mirror; fused silica</td>
<td>HR</td>
<td>S-on-1/1b</td>
<td>25.4 x 1.6 mm</td>
<td>2.3</td>
</tr>
<tr>
<td>Dichroic plate, fused silica</td>
<td>HR45 @ 355nm</td>
<td>S-on-1/1b</td>
<td>25.4 x 3 mm</td>
<td>3.9</td>
</tr>
<tr>
<td>Beamsplitter polarizer; fused silica</td>
<td>AR 45</td>
<td>S-on-1/1b</td>
<td>25.4 x 3.0 mm</td>
<td>3.6</td>
</tr>
<tr>
<td>LBO crystal</td>
<td>AR 1084, 532, 355 nm</td>
<td>S-on-1/1b</td>
<td>12 x 12 x 2 mm</td>
<td>4.1</td>
</tr>
</tbody>
</table>

* Stated are „best LIDT values“ for tested types of optics
Test bench for LIDT vacuum testing at 355 nm / 532 nm / 1064 nm

Transient pressure sensing technique:
   suitable in a vacuum environment for online detection of laser damage

Air – vacuum effect:
   small negative fluence offset found under vacuum
   indication residence time effects
   thermal isolation under vacuum (no thermal conductivity -> no ambient gas)
   must be excluded as cause of vacuum degradation.

Laser fatigue effect:
   step-like degradation within several pulses
   leveling off along a slowly decreasing ramp (> 100 shots applied per site)

Summary
Last not least:

The support by the **European Space Agency**, Galileo Avionica and Astrium-F is gratefully acknowledged!

Thank you for your attention!