Stage: II. Testing of the mirrors optical quality

1. Testing of the optical quality for fs-laser mirrors using small apertures optics

The most important accomplishment was the identification of the carbon layer present on the mirror surface using the X-ray reflectivity (XRR) technique. A commercial mirror was investigated for plasma cleaning process. In Fig. 1 the XRR curves acquired from as-received and carbon contaminated process are shown. By fitting these curves the depth composition of the carbonized mirror was obtained, as one can see in Table 1. The carbon layer has a 23 nm thickness, a 2.1 g/cm^3 density and a 5.7 nm roughness. XRR was also used to measure the removal of carbon contamination layer following plasma cleaning process.

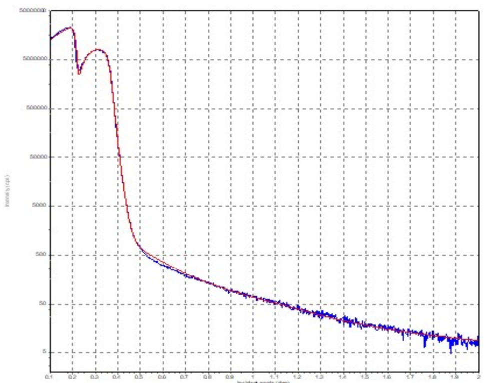
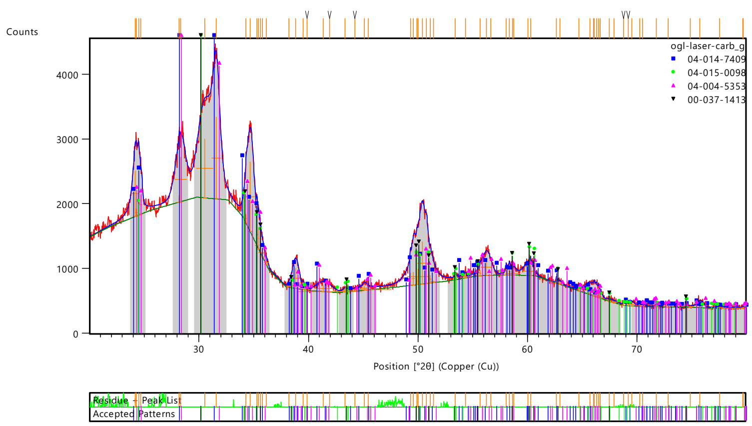


Fig. 1. *XRR curves acquired from a commercial mirror and carbonized mirror.*

Tab. 1. *XRR curve and its simulation for a commercial mirror that was carbonized*

Layer	Layer Description	Density (g/cm3)	Thickness (nm)	Roughness (nm)
2, 0	DensityOnly, C	1.985	22.789	5.757
1, 0	DensityOnly, SiO_2	2.113	253.349	0.116
Substr.	DensityOnly, HfO_2	8.2	600000	5.755

In Fig. 2 the XRD patterns acquired from the same mirror and the identification of crystalline phases are displayed. The mirror consists of several HfO_2/ZrO_2 layers. According to XRR data, these layers were capped by a protective amorphous SiO_2 layer, which is chemically stable and mechanically hard. We used the same technique to monitor the thickness evolution of the carbon layer during plasma cleaning process, as displayed in Fig.3. According to the XRR results, the plasma cleaning treatment can increase the surface roughness. Various ways to mitigate this process will be implemented in the next year.



No.	Ref. Code	Chem.	Score	Color
1	04-014-7409	HfO2	44	Blue
2	04-015-0098	ZrO2	34	Lime
3	04-004-5353	HfO2	37	Fuchsia
4	00-037-1413	ZrO2	36	Black

Fig. 2. *XRD patterns acquired from the mirror which consists of several HfO_2/ZrO_2 layers*

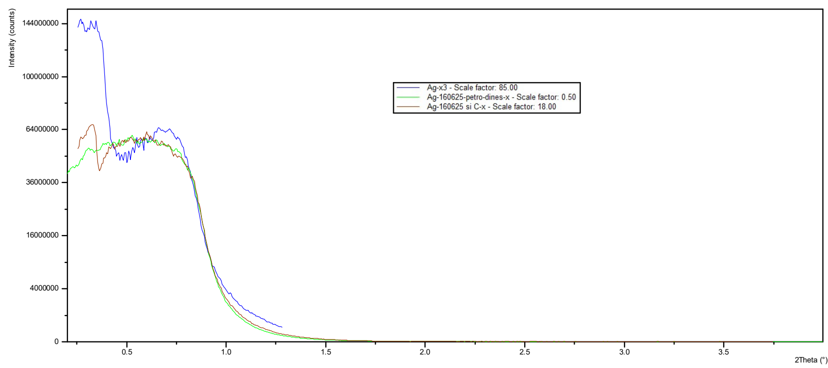


Fig. 3. *XRR curves acquired from contaminated and plasma cleaned (green trace) Ag mirrors.*

2. Investigations of the fs-LIDT physics

Carbonization and Optical Degradation of Laser Mirrors: Characterization and Cleaning Approaches

This phase focused on the performance and durability of metallic mirrors (silver- and aluminum-coated) under laser-induced damage threshold (LIDT) testing with particular emphasis on carbon contamination layers of varying thickness. The objective is to understand how surface contamination affects the mirrors' optical and damage-resistance properties and to evaluate cleaning methods that restore optical performance.

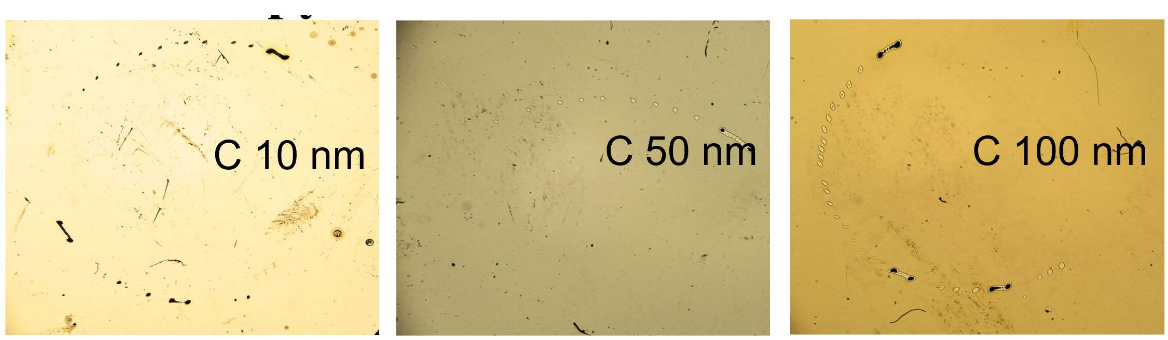


Fig. 4. *Ex-situ optical microscopy images of different Carbon layer thicknesses for offline LIDT detection using the microscope 1X*

The influence of contamination was assessed through dispersion characterization, LIDT tests following both ISO standard methods and a novel Langmuir Probe and Target Current (LPTC) method, and microscopic observation. The LPTC method emerged as a sensitive diagnostic tool that aligns with ISO standards but offers the potential for in situ monitoring of optical durability during high-power laser exposure.

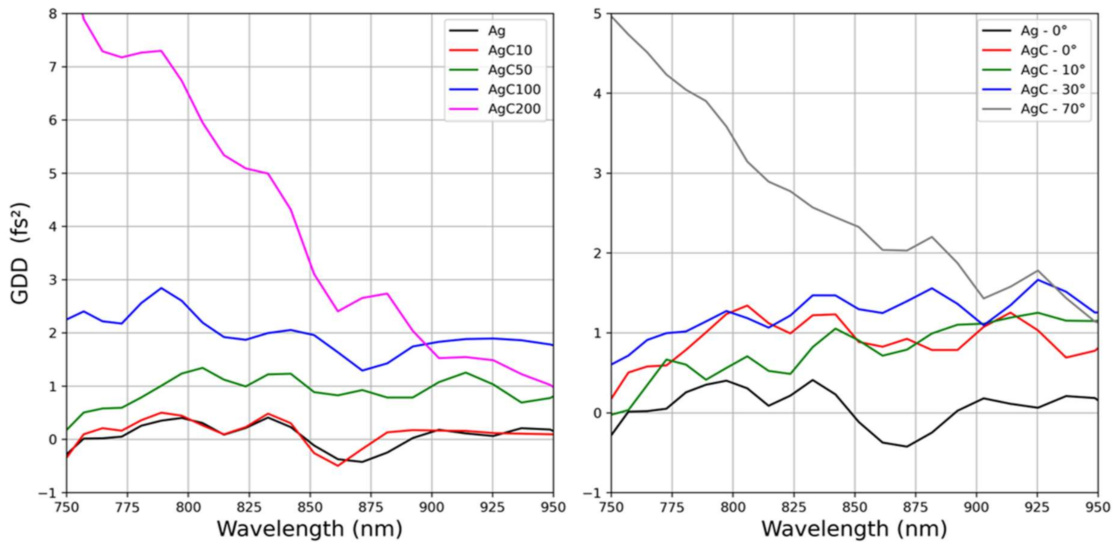


Fig. 5. *Proof of concept for contamination detection via dispersion measurements: Left –measured GDD for different carbon layer thicknesses; Right – a 50 nm Carbon layer tested at various incidence angles (10°–70°)*

Experiments included 1-on-1 and S-on-1 LIDT tests conducted in air and vacuum environments on aluminum and silver mirrors with different carbon contamination thicknesses. Dispersion measurements quantified contamination levels, showing increased sensitivity with larger incidence angles. Oxygen plasma discharge cleaning proved highly effective, achieving approximately 88% recovery of LIDT and over 95% recovery of dispersion properties, confirming its utility in removing carbonaceous deposits and restoring mirror performance.

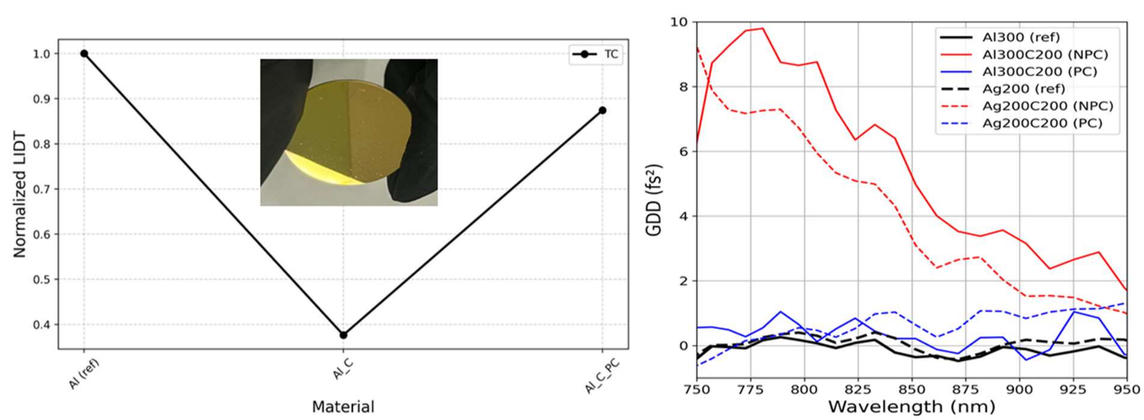


Fig. 6. *Experimental results of plasma cleaning (PC) effects with respect to Left) LIDT and Right) Dispersion*

The study also illustrated that optical materials such as ZrO_2 thin films display sub-threshold laser damage behaviors detectable by the LPTC system, which demonstrated consistency with ISO standards. This supports the idea that LPTC diagnostic tools can provide early indicators of damage onset, useful for managing component longevity in laser systems.

Key Findings on Laser-Induced Damage Threshold (LIDT) physics of Metallic Mirrors

- Metallic mirrors (Al, Ag) show decreased LIDT with increased contamination, but oxygen plasma cleaning can nearly restore original damage resistance.

- The LPTC technique for LIDT estimation provides enhanced sensitivity and potential for real-time monitoring.
- LIDT values are influenced by contamination thickness, mirror material, ambient environment (vacuum vs air), and incidence angle, with grazing incidence showing significantly higher damage thresholds.
- Carbon contamination on mirrors can be quantitatively assessed by dispersion measurements, an effective method sensitive to incidence angle.
- Langmuir Probe and Target Current measurements applied in this context provide a non-destructive, in situ alternative to classical ISO standard LIDT tests.

Implications and Applications

These findings have practical implications for the design and maintenance of high-power laser systems where mirror contamination and damage limit operational reliability. Plasma cleaning techniques can extend mirror lifetime by removing detrimental carbon layers without physical damage. Additionally, integrating LPTC diagnostic systems in laser facilities allows for proactive monitoring, early detection of damage onset, and reduced downtime.

The validation of contamination and LIDT assessment methods across multiple mirror materials and test environments strengthens confidence in deploying these approaches in diverse settings, such as nuclear physics laser facilities and industrial laser applications.

Supporting Laser Damage Research

Related research indicates a multi-pulse LIDT decrease over extended use, particularly for materials like copper and silver, and highlights the importance of surface roughness and purity in damage resistance. Grazing incidence angles generally increase LIDT, making operational angle optimization another key parameter in mirror design.

This report summarizes the carbon contamination effects, cleaning restoration, and innovative LIDT assessment techniques on laser mirrors critical for ensuring the performance and durability of optical components under high-power laser exposure.

3 Elaboration and testing of plasma cleaning systems

As basic principle, plasma cleans surfaces contaminated by carbon residues by gas phase chemical processes, where reactive plasma radicals, like O atoms, N atoms, OH molecules react with solid phase carbon, leading to carbon containing gaseous reaction products which desorbs from the surface and are removed by gas flows from the cleaning chamber. In case of mirror cleaning, the requirements imposed to the cleaning processes relates to the preservation of the optical quality of the surface, and the prevention of further contamination with carbon or metallic contaminants. Therefore, the plasma generated in contact with surfaces must produce species reactive to carbon, in mild conditions to prevent ionic bombardment, and in a metal and carbon free environment. To fulfill these conditions, we designed and evaluated the operation of two electrodeless plasma sources based on 13.56 MHz radiofrequency discharges, one working in vacuum conditions (low-pressure), and one working at ambient conditions (atmospheric pressure).

Plasma cleaning system operating under vacuum conditions

The configuration of the low-pressure plasma cleaning system is shown in Fig. 7. The vacuum chamber consists of a large vertical glass cylinder (outer glass cylinder in Figure 7) of 60 cm diameter and 60 cm height, closed by two metallic flanges on its top and bottom. The upper flange is provided with an aperture (4 cm diameter) allowing the vacuum tight insertion of the plasma source. The bottom flange is connected with by a vacuum tight pipe to an oil free vacuum system. Inside the vacuum chamber a sample processing chamber was assembled, supported by three glass holders, fully made from glass pieces, as follows: a) a bottom glass plate, b) a glass cylinder of 20 cm diameter (inner glass cylinder) and, c) a top glass plate. A central hole (~ 4 cm diameter) was performed in the top glass plate, allowing the plasma source penetrating in the processing chamber, while a 6 mm glass tube penetrating the lower plate and the bottom flange insures the system with the discharge gas. The plasma source has cylindrical shape and was designed as a central metallic electrode fully enclosed in an external glass tube of 4 cm diameter. The source is tightly mounted in the top flange of the vacuum chamber and can be positioned at desired distances from the bottom glass plate, on which the sample to be processed is placed.

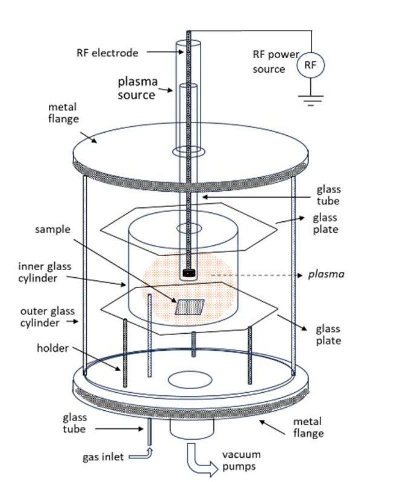


Fig. 7. *Schematic view of the low pressure-plasma cleaning setup*

In the above-described design plasma contact with any metallic surface is avoided, so the contamination with metallic traces is avoided. Also, the cleaning of the samples is performed in carbon free environment, as ensured by the vacuum maintained by the oil-free pumps and the contact of plasma with only glass surfaces.

Plasma cleaning system operating under ambient conditions

The system operating in ambient conditions is based on a RF Dielectric Barrier Discharge plasma jet (presented in Figure 8). Plasma is generated inside a glass tube (6 mm outer diameter, 4 mm inner diameter) in flowing argon between two outer copper electrodes, placed face to face, wrapping longitudinally the tube. Various electrode sizes have been evaluated, and a stable and diffuse plasma jet was obtained with electrodes having 30 mm length and 4 mm width. The plasma source was covered with a metallic jacket (not shown in Figure), connected to the grounded electrode, which minimize the electromagnetic radiation of the RF power to the environment. Again, like in the case the vacuum plasma cleaning system, the plasma created by the atmospheric pressure plasma jet is free of metallic or carbon contaminants, because the discharge proceeds in flowing pure gases (Ar is used as a carrier gas, injected with Oxygen as a reactive gas) and metallic electrodes do not come in direct contact with plasma.

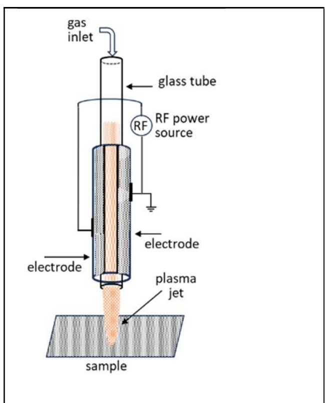


Fig. 8. *Schematic view of the low pressure-plasma cleaning setup*

The advantage of this system is its versatility. It is used for cleaning surfaces in combination with scanning procedures. In view of application for *in-situ* mirror cleaning, this system can be further used in combination with a robotic arm.

Preliminary tests of the two systems on contaminated surfaces

The preliminary cleaning tests have been realized on surfaces intentionally contaminated with carbon deposits. Amorphous carbon (a-C:H) thin layers have been deposited on optical transparent substrates (quartz-Q, or glass -G) by PECVD, in a dedicated chamber. The deposition was performed at $3x10^{-4}$ mbar in a RF plasma fed with Ar as main gas (Ar, 50 sccm mass flow rate) and with Methane (CH_4, 25 sccm flow rate) as chemical gaseous precursor.

The cleaning effects of the low-pressure plasma cleaning system are exemplified in Figure 9, while the effect of the cleaning with the scanning plasma jet is illustrated in Figure 10.

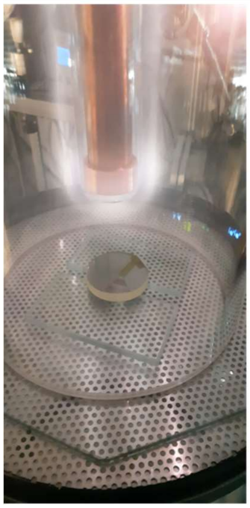
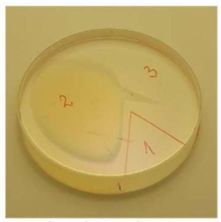


Image describing the plasma cleaning process at low pressure

Carbon deposited mirror, prior to cleaning (zone 1 - undeposited; zone 2 – deposited)



After plasma cleaning (zone 1 – undeposited; zone 2 – not cleaned; zone 3 – cleaned

Fig. 9. *Illustration of the low-pressure cleaning procedure. Parameters: RF power 100 W, O_2 flow rate 20 sccm, pressure $1.8x10^{-1}$ mbar, time 30 min*

Image of plasma exiting from the plasma jet source

Quartz sample deposited with a 50 nm thick carbon layer

Deposited quartz sample cleaned on the left half by plasma jet scanning

Fig. 10. *Illustration of the atmospheric pressure plasma jet cleaning procedure: Parameters: RF power 50 W, Ar flow rate 3000 sccm, O_2 flow rate 5 sccm, substrate distance 2 mm; 1 scan, scanning speed 0.12 mm/sec, distance between traces 1 mm*

A quantitative evaluation of the cleaning procedure was performed by XPS. The XPS spectra of the surface intentionally contaminated by carbon deposition and cleaned by scanning with the atmospheric pressure with a plasma jet are presented in Figure 11. The measurements were performed on a Quartz sample coated with a 200 nm thick Ag layer further deposited with a 200 nm a-C:H layer.

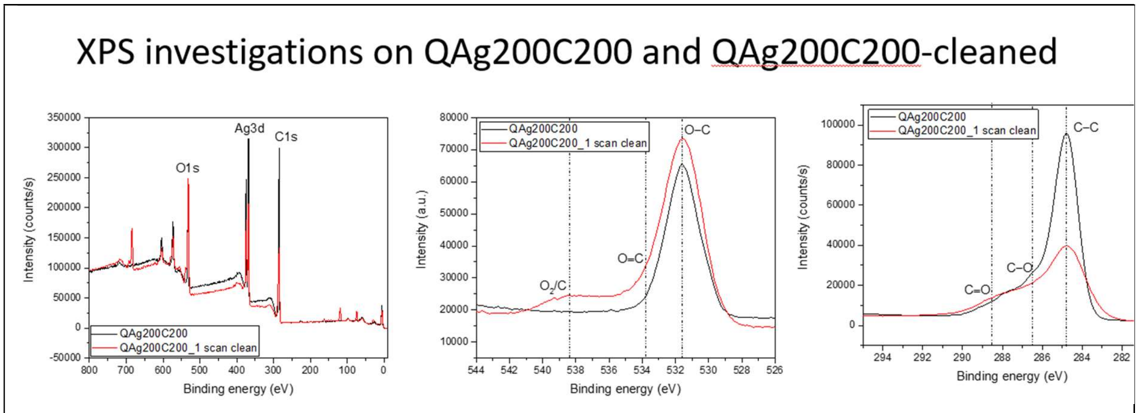


Fig. 11. *Effect of the cleaning with plasma jet of an intentionally contaminated surface*

The spectra clearly show the decrease in the concentration of carbon existing at surface. The remaining carbon traces are due to adventious carbon or are, possible, a sign of insufficient cleaning (for example too rough scanning raster - 1 mm between the scanning lines used in this experiment, or too high scanning speed). These aspects will be cleared in the future stages of the project.