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THRILL

TECHNOLOGY FOR HIGH-REPETITION-RATE INTENSE LASER LABORATORIES

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About THRILL

The THRILL project deals with providing new schemes and devices for pushing forward the limits of research infrastructures (RI) of European relevance and ESFRI landmarks. To do so, the project partners have identified several technical bottlenecks in high-energy high-repetition-rate laser technology that prevent it from reaching the technical readiness level required to technically specify and build the needed devices, and guaranteeing sustainable and reliable operation of such laser beamlines at the partnering RIs. Advancing the technical readiness of these topics is strategically aligned with the long-term plans and evolution of the ESFRI landmarks FAIR, ELI (-BL) and Eu-XFEL, and RI APOLLON, bringing them to the next level of development and strengthening their leading position.

The project is focused and deliberately restricted to three enabling technologies, which require the most urgent efforts and timely attention by the community: high-energy high-repetition-rate amplification, high-energy beam transport and optical coating resilience for large optics. To reach our goals, the major activity within THRILL will be organized around producing several prototypes demonstrating a high level of technical readiness. Our proposal is addressing not yet explored technical bottlenecks - such as transport over long distances of large-aperture laser beams via relay imaging using all-reflective optics - and aims at proposing concrete steps to increase the performances and effectiveness of the industrial community through the co-development of advanced technologies up to prototyping in operational environments.

The project is not only pushing technology, it is also offering an outstanding opportunity to train a qualified work force for RIs and industry. With this in mind, the structure of THRILL promotes synergetic work, fast transfer to industry and integrated research activities at the European level. Access to the RIs will be granted as in-kind contribution.

Executive summary

Deliverable D17 reports the development and testing of large-area anti-reflection and high-reflection coatings for high-energy, high-repetition-rate laser systems within THRILL Work Package 6. The work addressed a critical limitation for next-generation multi-petawatt and kilojoule-class laser facilities: the availability of large optical components that combine uniform optical performance with resistance to laser-induced damage.

The ELIAS coating system at ELI Beamlines was used to develop and manufacture metal mirrors, dielectric anti-reflection coatings, and multilayer high-reflection coatings on large-area substrates. The system demonstrated coating uniformity below 0.5% over a 1.2 m substrate plane and enabled the fabrication and testing of coatings on optics exceeding 1 m in size.

Gold mirrors with chromium adhesion layers and silica protective layers were deposited on substrates up to 1045 × 710 mm. These mirrors provided approximately 99% reflectivity at 1064 nm and were successfully installed in the L4 beam transport system. During operation of the L4 ATON laser, the coated optics transported 154 fs pulses with an energy of 786 J (nominal fluence value at the coating was ~200 mJ/cm^2), corresponding to approximately 5.1 PW peak power, without observed laser-induced damage.

Large-area dielectric anti-reflection coatings based on HfO_2/SiO_2 were also developed. Reflectivity below 0.1% was achieved for single-wavelength and dichroic designs. Dichroic anti-reflection coatings were deposited on 0.5 m optical windows and operated with nanosecond laser pulses exceeding 1 kJ without observed damage. The measured spectral uniformity was below 0.5%.

High-reflection multilayer dielectric coatings based on HfO_2/SiO_2 were developed for high-energy laser applications. Initial laser-induced damage threshold values of approximately 40 J/cm² were improved to 84.8 J/cm² by reducing defects associated with silica evaporation and replacing standard silica granules with silica beads. A high-reflection coating with a measured reflectivity above 99.5% at 1064 nm was deposited on a 250 × 350 mm substrate and successfully exposed to kilojoule-class nanosecond pulses without observed damage. Similar coatings have been deposited on components intended for installation in the L4 system.

The project also developed and commissioned a large ion source for plasma-assisted deposition. Tests demonstrated the oxidation of tantalum during evaporation and identified limitations related to increased absorption in hafnia films and etching of the tungsten source grid. Replacing the tungsten grid with tantalum reduced the associated absorption and enabled further process development.

Overall, the results demonstrate that ELIAS can produce large-area metal and dielectric coatings suitable for demanding kilojoule- and petawatt-class laser applications. The work reduces a significant supply bottleneck for large optical components and provides a basis for further deployment in European high-energy laser infrastructures. Further research is required to optimise plasma-assisted densification, reduce environmentally induced spectral shifts and coating crazing, and extend the maximum substrate size beyond the current 1.2 m configuration.

Abbreviations

Abbreviation	Definition
LIDT	Laser-Induced-Damage-Threshold
QWOT	Quarter Wavelength Optical Thickness
AR	Anti Reflection
HR	High Reflectivity

1 Introduction and objectives

The THRILL project dealt with providing new schemes and devices for pushing forward the limits of research infrastructures (RI) of European relevance and ESFRI landmarks. Before the project it was identified that laser-induced damages to optical components, especially those implemented at HEHRR facilities, set critical constraints to the maximal peak power attainable and to the maintenance costs. Therefore, a steady supply of critical large area high quality optical components is crucial for stable performance of laser research infrastructures. Within the framework of the project THRILL, the objective was to develop large area anti-reflection and high reflection coatings for ultrafast high energy laser systems. In this report we will summarize the output of the THRILL technical work package WP6 and its deliverable D17.

For adequate evaluation of the progress within the THRILL report, an overview of the current key laser systems is necessary. Chapter 2 is devoted to this and describes the demand from HEHRR facilities for large area optical components. Chapter 3 describes current progress of ELIAS system in ELI-BL. Chapter 4 is dedicated to evaluate future progress in optical components and to identify necessary research activities.

2 Coating requirements in HEHRR laser systems

ELI Beamlines in Czech Republic has two PW class laser systems: L3 HAPLS and L4 ATON. L3 is designed to have 1PW power with beams of <30 fs and >30 J energy. Frequency of the laser is designed to be 10 Hz. While L4 is designed to have 10 PW peak power pulses: 150 fs and 1.5 kJ. Repetition rate of L4 is designed to be 1 shot per minute.

Vulcan 20-20 system in STFC CLF facility is designed to deliver 400 J beam of 20 fs, giving 20 PW peak power. Designed repetition rate is 1 shot per 5 minutes. It should be mentioned that the project is still in design stage and beam characteristics may still change in time.

The NSF OPAL project in Rochester NY, currently in the final design phase, will generate 500 J / 20 fs pulses to reach 25 PW in two arms. Its largest aperture is very close to the ATON laser.

European XFEL facility is planning to build a multi-kJ class long pulse laser system with PW capability. FAIR project at GSI is also expected to build multi beam kJ class laser system with short pulse capability.

All aforementioned facilities use meter scale optics or larger, which must withstand high fluences without being damaged. Multi-PW and kJ class laser beams are in high demand from the scientific community. Therefore, it is crucial to have reliable suppliers here in Europe before building next HEHRR laser systems.

3 ELIAS Coating Developments

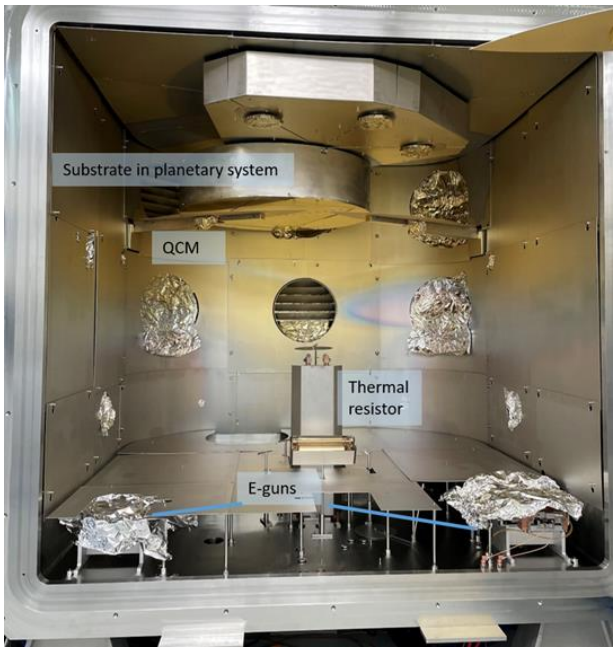
3.1 ELIAS system

ELIAS (ELI Advanced deposition System) is a coating plant designed for 1.2 meter size optics development and manufacturing. The chamber is presented in Fig. 1. It is equipped with two electron guns: one for low refractive index material (mainly silica) and other for high refractive index material (hafnia, tantala, alumina, etc.) evaporation. For the deposition of metal coatings (gold, silver, etc.) ELIAS is equipped with a thermal resistor. The whole process is controlled by measuring physical thickness of individual layers with multiple QCMs (quartz crystal monitoring). Additionally, three masks are mounted for coating thickness uniformity improvement. Planetary rotation of the substrates and a long distance between evaporation sources together with the masks allows to achieve better than 0.5 % coating uniformity within 1.2 meters aperture within the substrate plane.

The series of developments have been made in ELIAS for different optical coatings: metal mirrors,

antireflection coatings and high reflectivity mirrors. All three coating types were deposited on large area substrates (>1 meter) and tested in high energy laser systems.

Figure 1 – Picture of ELIAS coating plant.

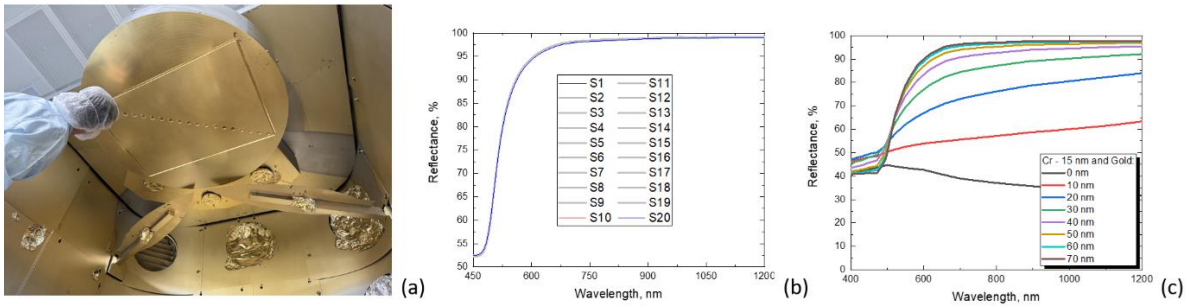


3.2 Development of metal coatings

Initially, it was decided to develop metal coatings for large area optics in order to commission 10 PW-class L4 laser system in time. Due to high reflectivity and inert chemical properties, gold material was chosen for metal mirrors. Since gold has poor adhesion with glass, a sublayer of chromium was coated for all of the mirrors. Additionally, silica was also coated on top of the gold to prevent mechanical damage. An optimized multilayer design for gold mirrors consisted of 15 nm Cr, ~200 nm of Au and 10 nm of SiO2. Initial designs used 70 or 100 nm of gold, but there was potential to reach higher LIDT, therefore 200 nm were selected as target value. First test was used to determine the uniformity of the coating for 1.2 meter size optics. 20 pieces of 1'' diameter were placed across the diagonal of 710 x 1045 mm size substrate holder (see Fig. 2 a)). Spectral measurements of all samples indicated almost perfect match indicating close to ideal spectral uniformity of gold mirror within 1.2 meter size optics (see Fig. 2 b)). It should be mentioned that spectral performance of gold does not change after ~70 nm as shown in Fig. 2 c). Therefore, some thickness discrepancies can still be at the edge of the optical component, but that has no impact on mirrors spectral reflectivity.

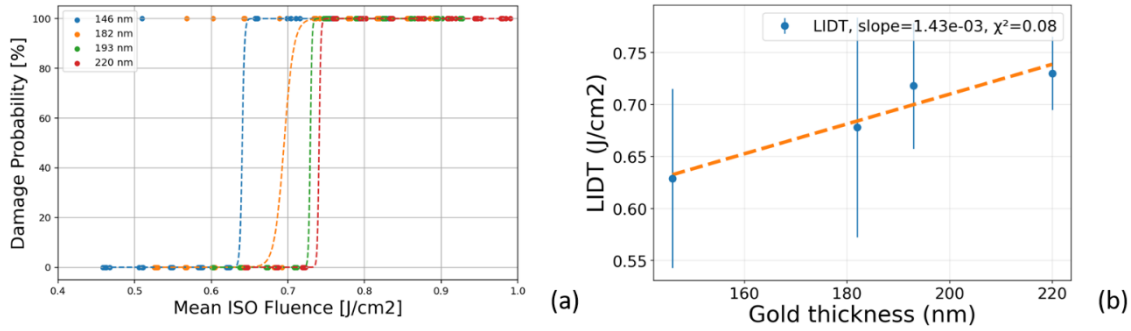
Figure 2 – (a) Gold coated ELIAS chamber with the witness samples. (b) Measured reflectance of each

witness sample. (c) Modelled reflectance of the gold with different thickness.



Several depositions with slightly different gold thickness were evaluated by measuring their LIDT using ultrashort pulse (150 fs) at 1064 nm wavelength. Laser damage probability curves for each of the sample are presented in Fig. 3 (a). Deterministic nature of damage probability is typical for ultrafast pulses. LIDT for each sample was evaluated according to ISO standard and plotted vs the gold physical thickness (see Fig. 3 (b)). The trend indicates that damage threshold grows with films thickness. Such observation was also reported several times in the past [1] and it might enable further LIDT increase in future developments.

Figure 3 – (a) Laser damage probability measurement results for different gold thickness mirrors. (b) Measured LIDT values of gold mirrors with different gold thickness.

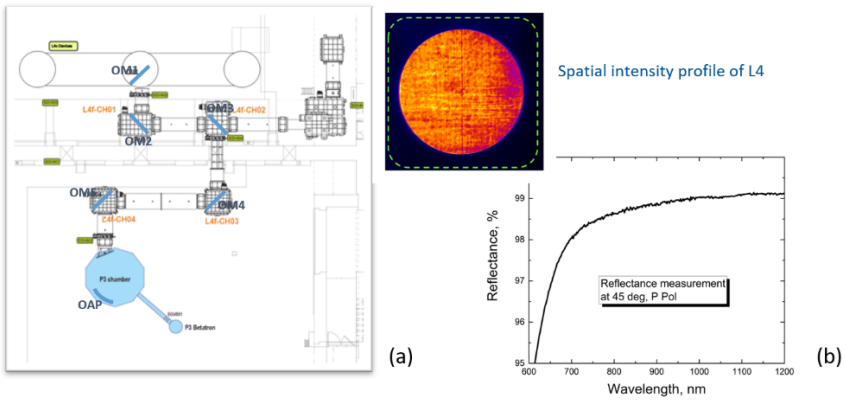


Lastly, gold coatings (with Cr underlayer and SiO_2 protection film) were deposited on different fused silica substrates of >1 m size. Largest substrate had the same dimension as the substrate holder for uniformity test – 710 x 1045 mm. Such components were installed in L4 beam transport system as shown in Fig. 4 (a). Each mirror reflected 99 % of light at 1064 nm as shown in Fig. 4 (b).

Recently, the L4 ATON laser system was commissioned with 154 fs pulses and record 786 J energy. Nominal fluence value at the coating was ~200 mJ/cm^2, but due to intensity modulations some spots had higher fluences. This was enabled by our gold-coated mirror coatings, which withstood the 5 PW peak power without damage. Beam profile is shown in Fig. 4. This demonstrates that ELIAS is capable of coating metal mirrors for multi-PW class laser systems, in this case 5.1 PW peak power. This gives confidence in the scalability of small laser spot Au coating LIDT test data to realistic large

beam with intensity modulations.

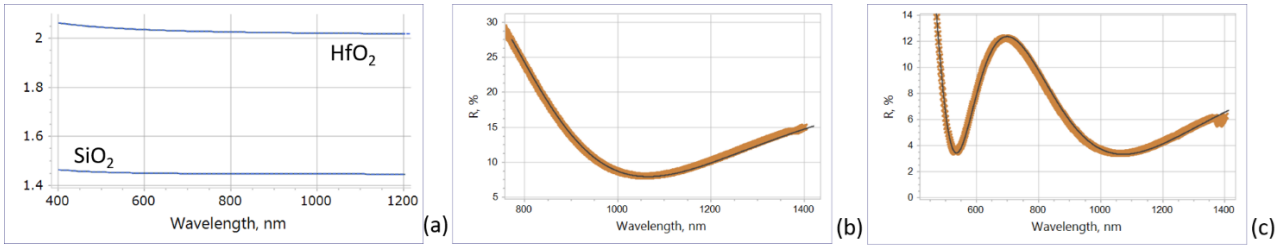
Figure 4 – (a) Beam transport system of L4 laser from pulse compressor to P3 chamber. (b) Measured reflectance of one of the gold transport mirrors. Spatial beam profile was measured across 500mm aperture only.



3.3 Development of anti-reflection coatings

Dielectric thin films are necessary to form interference based anti-reflection coatings. Deposition parameters for HfO_2 and SiO_2 materials were optimized to obtain lowest light losses: hafnia is deposited at 0.5 Å/s rate with oxygen backfill at around 10^{-4} mbar pressure, while silica is deposited at 2 Å/s rate without any oxygen backfill. Both materials are coated at 150º C temperature. Such research was especially crucial for hafnia, since evaporation target material is Hf metal. Obtained refractive indexes of both materials are presented in Fig. 5 (a). OTF Studio software was used to model anti-reflection coatings for single laser wavelength or two (dichroic anti-reflection coating). Measured reflections and its match with model spectra for one side of the substrate are shown in Fig. 5 (b) for single wavelength AR and in Fig. 5 (c) for dichroic AR coatings. In both cases reflectivity below 0.1 % has been reached for one substrate side.

Figure 5 – (a) Refractive index dispersions of hafnia and silica deposited with ELIAS. (b) Modelled and measured anti-reflection coating ARp@ 1064 AOI=45 deg. Back side reflection was not neglected. (c) Modelled and measured anti-reflection coating AR@ 532+1064 AOI=0 deg. Back side reflection was not neglected.

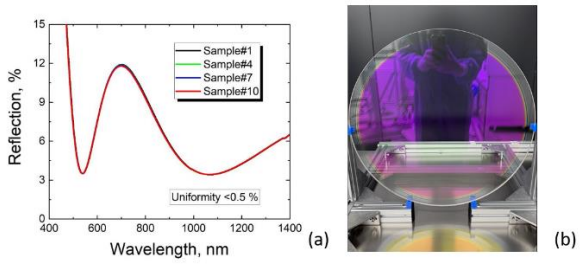


Another antireflection coating has been deposited for the UV at 355 nm. It was tested in HiLASE using 5 mm beam spot, 8.5 ns pulses and raster scanned throughout a large area. Fluence was

ramped up to 4 J/cm^2, but no damage was detected. Such results indicate that developed coatings can be used in high power laser systems for UV as well.

Single wavelength antireflection coating at 1064 nm has been also deposited on one side of 710 x 1045 mm size floating glass and used in the L4 system for testing downstream the pulse compressor. This 1.2 meter size component was used during the commissioning of L4 system at powers exceeding 1 PW. Additionally, uniformity test was done using multiple 1'' substrates and dichroic coating design. Measurements, shown in Fig. 6 (a), indicate that coating uniformity of <0.5 % (or < ±0.25 %) was achieved in ELIAS system. Finally, such a design has been coated on both sides of 0.5 m size substrates as optical windows (see Fig. 6 (b)) in second harmonic generation laser system. First harmonic nanosecond laser beam of ~1100 J energy was used for second harmonic generation using KDP crystal. No damage was detected in the optical elements. Therefore, it was demonstrated that AR coatings from ELIAS can withstand kJ class laser beams.

Figure 6 – (a) Reflection measurements of dichroic AR coating for multiple samples within 0.5 m radius. (b) A photo of dichroic antireflection coating on 0.5 m glass substrate.



3.4 Development of high reflectivity mirrors

High reflectivity mirrors require many layers and constructive interference effect to be capable of reflecting more than 99.5 % of the light and to minimize the optical absorption. Same hafnia and silica materials were used to model and deposit mirrors based on QWOT (quarter wave optical thickness) design. Several evaporations of multilayer coatings indicated that uniformity for dielectric coatings is below 0.5 %. LIDT values for the nanosecond beam reached ~40 J/cm^2, which was not sufficient for the L4 operations for the most demanding elements. After the inspection of laser damage morphologies, many defects have been observed and their origin has been identified as silica evaporation. Therefore, from standard irregular silica granules we switched to silica beads. This led to reduction of defects and LIDT increased up to 84.8 J/cm^2 (measurements were performed in HiLASE). Full mirror has been deposited on a 250 x 360 mm size substrate for the L4 system before compression. Three mirrors from high-end coating vendors previously suffered laser damage at that location. The kJ class nanosecond beam was being reflected by the mirror during the nominal operation and no damage has been detected. Spectral performance of the coating and LIDT

measurements with nanosecond pulse are shown in Fig. 7 (a) and (b). For the P polarization the reflectivity at 1064 nm was measured to be 99.5 %. LIDT values were sufficient for kJ class radiation of L4. Similar design MLD coatings have been deposited on multiple off-axis parabolas and are being installed in L4 to commission beyond 5 PW power.

A mirror from project partner GSI was also deposited within the framework of THRILL project (see Fig. 8). Due to delayed shipment of hafnium material for this 413 x 353 size mirror the deposition was postponed to the end of October. Coated mirror was center at 1064 nm and matched the designed spectra. During the project we encountered hafnium supply issue several times. Due to geopolitical situation the price of hafnium is rising and purchasing it is becoming increasingly difficult. Therefore, it was decided to test some alternatives. Tantala coatings may cover some optics with lower LIDT requirements. During the conferences and meetings, several RIs suggested to use a rare earth oxide as a substitute for hafnium oxide. Oxide and metal form have been purchased and will be tested in the near future in ELIAS.

Figure 7 – (a) Reflection measurements of the HR coating for both polarizations together with the simulation spectra. (b) Damage probability measurements of the HR@ 1064 AOI=0 deg.

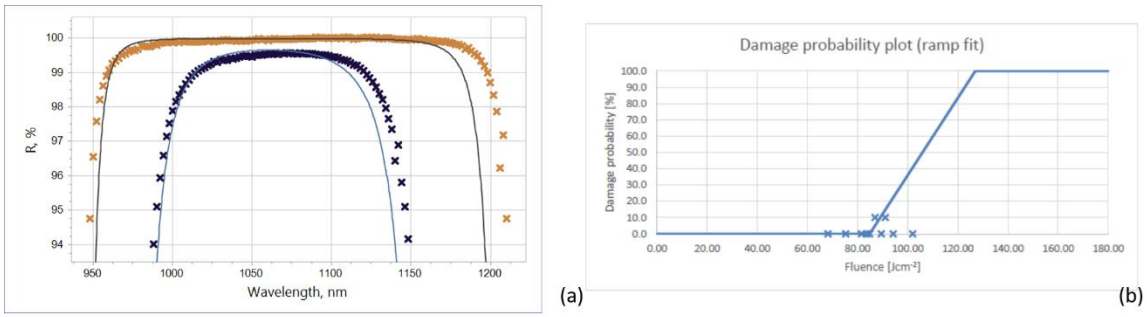
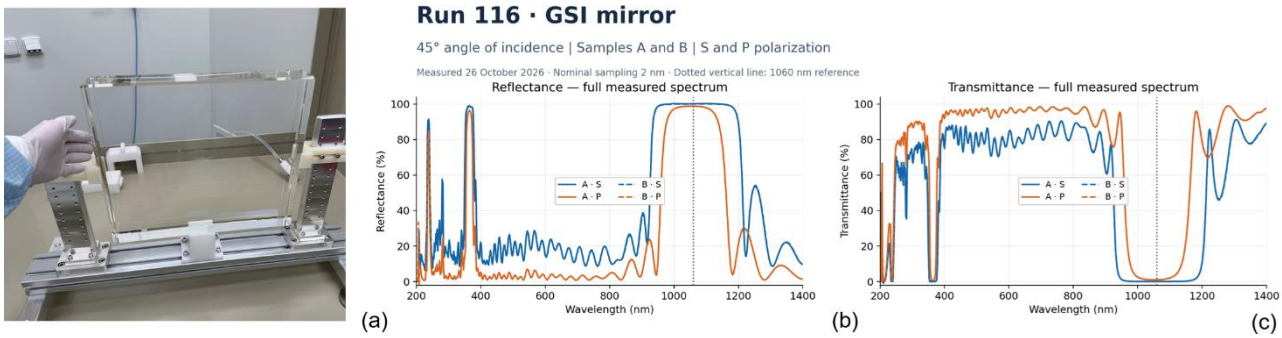


Figure 8 – (a) GSI substrate loaded for the cleaning. (b) Reflectance and (c) transmittance of the coated GSI mirror.



3.5 Development of the ion assisted process

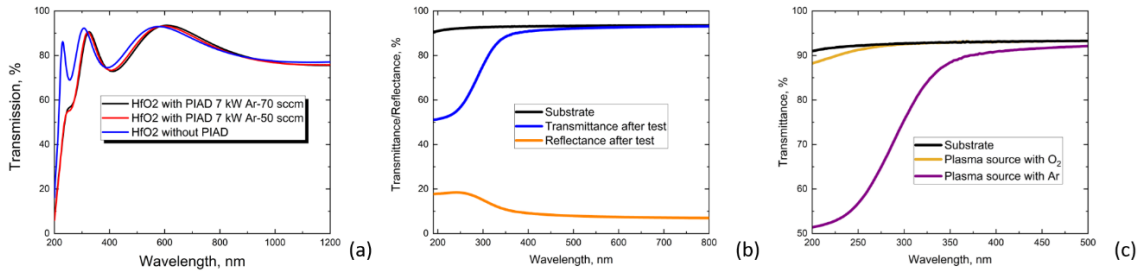
During the THRILL project, the prototype of large ion source was developed and commissioned in ELIAS (see Fig. 9). Multiple tests were performed for evaluation of the plasma source using oxygen and argon gases. Hafnia thin films, deposited with 7 kW plasma source power, showed increased absorption in the UV region compared to the layers deposited without any assistance (see Fig. 10 (a)). After additional tests, it was clear that Argon with the plasma was etching the tungsten grid of the source itself. Such conclusion was clear after exposing the plasma to a bare substrate using oxygen and argon gases, shown in Fig. 10 (b-c). After changing the grid into tantalum, absorption from the plasma source was minimized. Ion source was successfully used to fully oxidize tantala (Ta_2O_5) material during the evaporation. Tantala has also lower LIDT values but is cheaper compared to hafnium and can be used for less demanding optics. One of such cases was a large mirror for the exhibition, which was deposited on 710 x 1045 mm size floating glass as shown in Fig. 9. It serves as an outreach tool to visitors but also as a test for spectral uniformity. Same coating was also deposited on palladium. Metal layer was deposited using magnetron sputtering technology. After the dielectric stack deposition, discoloration was observed as shown in the figure. This may be due to bad metal coating uniformity or weak adhesion between metal and dielectric layers. Additional investigation is needed to fully develop such metal/dielectric combinations.

Figure 9 – Plasma source with the ELIAS using Oxygen (left) and Argon (middle). Tantala/silica mirror deposited for the exhibition using the plasma source (right). Same mirror was deposited on platinum coating and is shown in the legend.



Figure 10 – (a) Transmission measurements of deposited hafnia thin films with and without the plasma ion assisted deposition. (b) Transmittance/reflectance measurements of the bare substrate before and after the exposure to the plasma source with an Argon gas. (c) Transmittance measurements of the bare substrate

before and after exposure with the plasma source working with Oxygen and Argon gas.



4 Future perspectives

The next step in ELIAS is the optimization of hafnia/silica coatings densification using plasma source, commissioned during THRILL project. Current coatings deposited without any plasma assistance have spectral shift when undergoing from vacuum to humid environment ad inverse. The spectral shift reaches at least 1 % and could potentially induce crazing due to excessive tensile stress. Densification can minimize the spectral shift and protect the coating from crazing by creating compressive stress. Densification is also crucial for the optics which are exposed to chemicals. Such steps are standard for MLD grating lithography processes. Therefore, successful implementation of the plasma source would allow us to coat essential layers for the MLD gratings. The ELI Beamlines team has started to consult experts about optimization of MLD coating stacks for large diffraction gratings. Such initiatives will pave the way for establishing a crucial technologies of gratings manufacturing here in Europe.

A significant effort is planned to make for the formation of enhanced metal coatings, which require good adhesion between metal and dielectric layers. During the project, we already started few combinations of such coatings: silica coated on gold and hafnia coated on palladium. Most of the processes were successful, but additional tests are needed to try different oxide materials on several metal coatings.

Current maximum size of the substrates, which can be loaded into the ELIAS chamber, is 1.2 meters. This limitation can be extended by reconfiguring the planetary system in the coating chamber. The physical size of ELIAS chamber inside is 2.5 x 2.5 x 2.4 (W x D x H) meters. Therefore, by crossing the center of the chamber it is possible to mount ~2 meters size optics. Thickness uniformity would be reduced due to changed configuration, but for the metal mirrors it should not be an issue. Spectral insensitivity to the metal layer thickness would allow to coat high-quality optics. Moreover, by using solar rotation only, nearly 2 m size aperture can be coated without crossing the central point of rotation.

Inspection of large optics is also very important in development of any state-of-the-art component. Therefore, ELI is already commissioning scanning metrology for meter scale optics. It will be possible to measure transmittance/reflectance and take pictures of defects within the whole aperture. Obtained results will allow to evaluate the uniformity of the coatings and inspect the optical quality. Provided feedback will be essential for the development of better optics in HEHRR facilities.

Conclusions

ELIAS coater has contributed noticeably for the development of large area coatings used in HEHRR laser systems. Availability to obtain high quality mirrors and anti-reflection coatings for kJ and multi-PW class laser systems would diminish this bottle-neck. Performance of coatings developed in this project was demonstrated in actual laser operations supporting experimental users. Full manipulation, metrology, cleaning and coating chain was demonstrated by MLD coating a large mirror for the GSI facility. All main coating runs are supported by reproducible LIDT testing to validate the expected performance.

Currently established infrastructures now have an additional supplier, and new laser systems can be designed in accordance with the obtained coating characteristics. We are already observing design changes in large projects to match the apertures available through ELIAS.

The main coating specifications delivered are summarized below:

a) Gold mirrors have been coated on 1045 x 710 mm size substrates weighing up to 185 kg. Spectral performance was uniform over the whole area. Coated components have been used to transport 5 PW power pulses (154 fs and 786 J, which gave nominal fluence value of ~200 mJ/cm^2.) without any damage despite increased intensity modulation.

b) Dichroic antireflection coatings (AR<0.1 %@ 527+1030 AOI=0 deg) have also been coated on 0.5 m size optics. It is currently in use with ns, pulsed, >1 kJ beams and no damage was observed. Coating consists of four HfO_2/SiO_2 layers. Spectral uniformity has been measured to be < 0.5 %.

c) High-reflection multilayer dielectric coating (HRp>99.7 %@ 1040-1080 AOI=45 deg) was deposited on 250 x 350 mm size substrate. Pulses of 1-2 ns duration and >1 kJ were used during user campaign and no damage was observed. Test sample with lower reflectivity was tested in HiLASE using 8.4 ns pulses and 213 µm spot size. Evaluated LIDT value was 84.8 J/cm^2. Measured spectral uniformity over one meter diameter was <1 %. Additionally, flatness was measured on witness sample. Measurements showed the change in power value from 0.133λ to 0.118λ, indicating very low stress values.

5 References

[1] - Krüger, J., Dufft, D., Koter, R., & Hertwig, A. Femtosecond laser-induced damage of gold films, Applied Surface Science, 253(19), 7815–7819, (2007)

6 Outreach

The following dissemination of the results achieved by the team:

Conference	Speaker	Talk	Relevance
ICUIL 2024, 9–13 September 2024, Cozumel, Mexico	**Daniel Kramer**; authors T. Tolenis, J. Oliver, D. Kramer, A. Chauvin, M. Havlík	**"Commissioning results of ELIAS very large aperture coating system for ultra-intense lasers"**	Explicitly presents LIDT results from commissioning depositions and initial ion-source integration results. ctomx.org
SPIE Optics + Optoelectronics 2025, Prague; paper **13532-4**	**Tomas Tolenis et al.**	**"Commissioning of ELI-Beamlines advanced deposition system for ultrahigh intensity laser systems"**	Dedicated ELIAS commissioning presentation; programme lists a 20-minute slot. spiecareercenter.org
Pacific Rim Laser Damage 2026, Hangzhou, China, 20–23 May 2026	**Daniel Kramer — plenary**	**"Large optics and thin layers for PW and multi PW lasers in ELI Beamlines"**	The abstract explicitly includes initial results from the **ELIAS 1.2 m aperture coating system**, alongside optics operation, LIDT and contamination findings. htcis.net
SPIE Laser Damage 2025, Rochester, New York	**Adrien Chauvin**	**"Functional LIDT: Influence of the LIDT testing process on**	Related coating-performance work. The public listing does

		the reflected beam properties"	**not explicitly establish that the samples were deposited in ELIAS**, so I would keep this separate from dedicated ELIAS results. THRILL Project
8 May 2025, 10th Symposium on Optical Coatings for Laser Applications, FTMC, Vilnius, Lithuania	**Daniel Kramer**, ELI Beamlines	**"Large optics for Extreme Light in ELI Beamlines"** — extended talk, **15:20–15:50**	The abstract explicitly includes the creation of the ELIAS coating laboratory and **its initial results**, alongside large optics, LIDT testing and coating qualification.
Optica OIC — Optical Interference Coatings 2025, Tucson, Arizona, USA	**Tomas Tolenis**, ELI Beamlines	**"Development of Large Area Optical Coatings for Ultra-High Intensity Laser Systems in ELI"** — **invited talk**	**21 May 2025, 15:00–15:25**, paper **WE.1**, session *Deposition Technologies III*
SPIE Laser Damage 2026, Denver, USA	**Tomas Tolenis**, ELI Beamlines	**"Metal, Hybrid and Dielectric coatings for multi-PW lasers" – invited talk**	**The presentation summarizes development of coatings within the THRILL project for PW class lasers**