Achievement of technologies and testing methods for resilient mirrors under high power laser pulse, suitable for CETAL and ELI infrastructures

Stage 1 / Activity 2
(Work-package 2)

Study regarding the optical coatings resistant under high power laser pulses

Starting from the project's objective that is to establish all needed technologies in order to perform large mirrors resistant under high power pulses, the first step was to acquire knowledge from scientific papers, to find materials that can be used in this purpose and also to find solutions to manage large optics during the technological flow. In this regard, a list of materials and accessories needed to start the experiments in the next stages of the project was made. Regarding the parameters that can influence the damage threshold of the coating, several of these seem to be detached:

1. <u>Quality of the substrate:</u> roughness, scratches, intrinsic defects or microscopic particles are factors that can contribute to the LIDT of the optical part;
2. <u>Coating design</u>: Internal stress of each deposited layer and compatibility of the materials that form the coating stack, in terms of the total internal stress are factors that can contribute to the LIDT of the optical part. Also, the design must take into account the distribution of the electric field intensity into the entire coating package;
3. <u>Coating technology</u>: Parameters of the coating technology can determine the strength of adhesion, the compactness and the stoichiometry of each layer and consequently, can influence the LIDT of the coating.

Related to these factors, in the next rows are gathered some quotes from the found articles:

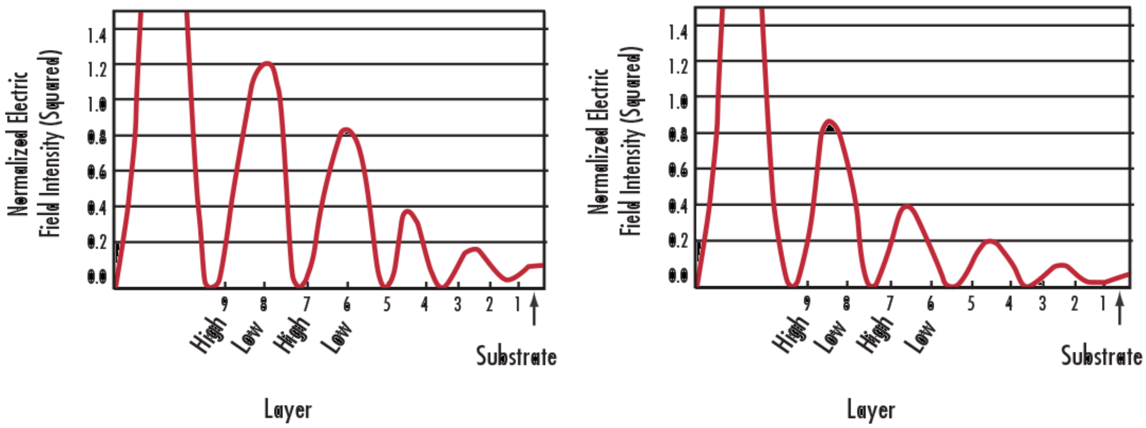
1. Related to the quality of the substrate:

In the article "The Complexities of High-Power Optical Coatings" from Edmund Optics [1] is written: *Regarding the quality of the substrate, must be tacked into account including its cleanliness. It is very known* the fact that *any organic or particulate residue from polishing or cleaning may absorb laser energy and is therefore a potential damage site. For this reason, the substrate and coating interface is a critical area in achieving high damage thresholds. Consequently, making high-power optical coatings requires tight control of every aspect of production, from initial substrate manufacturing to final packing. Before the optical element even reaches the coating chamber, its surface quality, subsurface quality, and cleanliness must be assured. The substrate must also be* *free of subsurface defects. This can be avoided through proper machining, grinding, and polishing methods prior to cleaning and coating. The first step is to begin with a blank large enough to allow for all necessary substrate removal. When machining, coating technicians carefully choose the appropriate tool feed, tool speed, and coolant flow in order to reduce subsurface stress and damage. Grinding is then done in incrementally smaller steps so as to achieve a more controlled surface. Finally, roughly 0.01 - 0.03mm is removed by polishing, which is used to remove subsurface damage caused by the previous steps* [1].

2. Related to the coating design:

The article "Dielectric mirrors for high power laser applications" from Bulletin of Material Science [2] contain the paragraphs: "*Development of low loss dielectric high reflecting mirrors for high power laser applications presents some problems in selecting suitable thin film materials and in understanding their optical constants. Some of these problems have been solved by a systematic study of the dependence of optical constants on different evaporation parameters for a number of thin film materials. Using the data thus obtained high reflecting dielectric mirrors for different laser applications in the ultraviolet, visible and near-infrared regions were successfully developed indigenously by the method of vacuum evaporation*" [2].

The article from Edmund Optics speaks about the importance of the distribution of the electric field intensity between the coating layers: "*LIDT values can be further increased by manipulating the coating layers in one of several ways. The electric-field distribution can be averaged across several layers, thereby avoiding a high electric-field concentration within a relatively small number of layers. Figures 2a – 2b show the normalized electric-field intensity (EFI) squared within a reflecting quarter-wave dielectric stack. The peak EFI values occur at layer interfaces and the highest EFIs occur at the layers closest to the air boundary. These EFI values can be reduced, however, by modifying the thicknesses of the four layers closest to air in a nine-layer stack. This has the effect of shifting the high-intensity resonant peaks from layer interfaces to locations within the film continuum. The highest-intensity resonant peaks can be positioned within the layers of the thin-film material demonstrating the highest damage threshold* [1].



Fig, 1 Comparison of EFI to Layer within a Nine-Layer Stack Design with Layer Thicknesses Unoptimized (a) and optimized to decrease EFI (b) [1]

3. Related to the coating technology

As with standard optical coatings, there are three deposition methods available to coating technicians: thermal evaporation, ion-beam technology, and advanced plasma reactive sputtering (APRS). However, not all are suitable for high-power optical coatings. Iain Macmillan [3] observed that *"the thermal evaporation method is the most common method of producing high-power optical coatings in industry today. When enhanced with ion-assisted deposition (IAD), the thermal evaporation method (Figure 2) allows for more compact coatings with properties closer to those of the bulk materials. IAD also allows for greater control over layer thicknesses, which can decrease EFI values* [3]. *Many parameters play critical roles in the deposition of a high-power optical coating, including the rate of deposition, substrate temperature, oxygen partial pressure (used in designs including dielectric metal oxides), thickness calibration, material-melt preconditioning, and electron-gun sweep. A poorly controlled evaporation process produces spatter from the source, resulting in particulate condensates on the substrate surface and within the depositing coating. These condensates are potential damage defect sites. Unfortunately, some materials that can be used for high-damage-threshold coatings are difficult to deposit smoothly. The settings applied to the electron-gun sweep can be the difference between the production of a clear, high-damage-threshold coating and the production of a high-scatter coating with a much lower power capability.*

The rate of deposition, substrate temperature, and oxygen partial pressure (for dielectric oxides) determine the stoichiometry of the growing film, which significantly affects the metal oxide chemistry in the depositing film. These parameters must be optimized and controlled to produce a homogeneous layer with the desired metal-oxygen content and structure.

For example, in producing high-power anti-reflection (AR) coatings, thickness accuracy of the depositing films is an important factor in meeting the desired low reflectance. High-power high-reflective (mirror) coatings are generally less sensitive to small thickness errors as a result of relatively broad reflectance band afforded by the refractive index ratio of the high and low index layers. Deep-UV (DUV) mirror coatings are an exception, however, because material limitations in this spectral range produce relatively narrowband reflectors.”

A scheme and a picture of the coating machine that is now scheduled to be used in this project are presented in the figures 2 and 3:

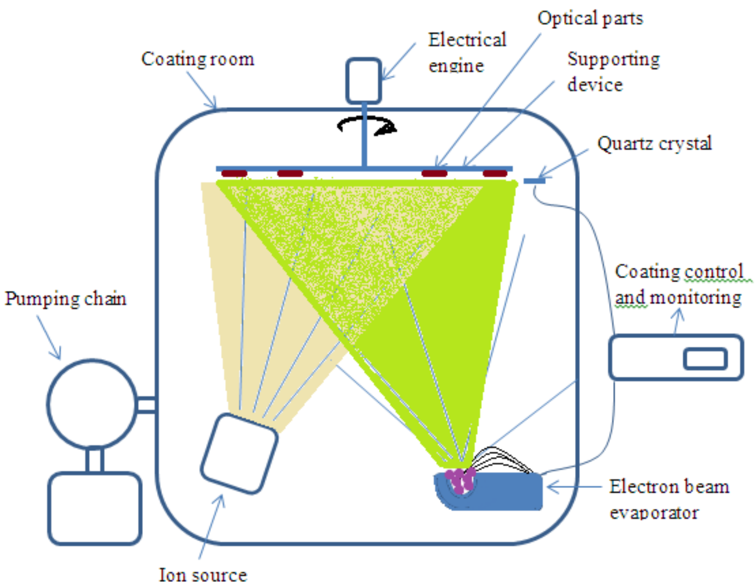


Figure 2: The scheme of the coating machine

Figure 3: The technological room of the coating machine Leybold L560

Another issue that must be solved by the optical coatings work-package is to find solutions to handle and to hold the large and heavy substrates into the technological room of the coating machine, in order to ensure the best uniformity of the layers thickness. In this regard, first step was to be made preparations in order to start a series of batches with the purpose of analyze the current uniformity on the entire radius of the technological room. Also, a concept of a holder device with adjustable diameter was developed (fig. 4), but its final design will be done in the next stage of the project.

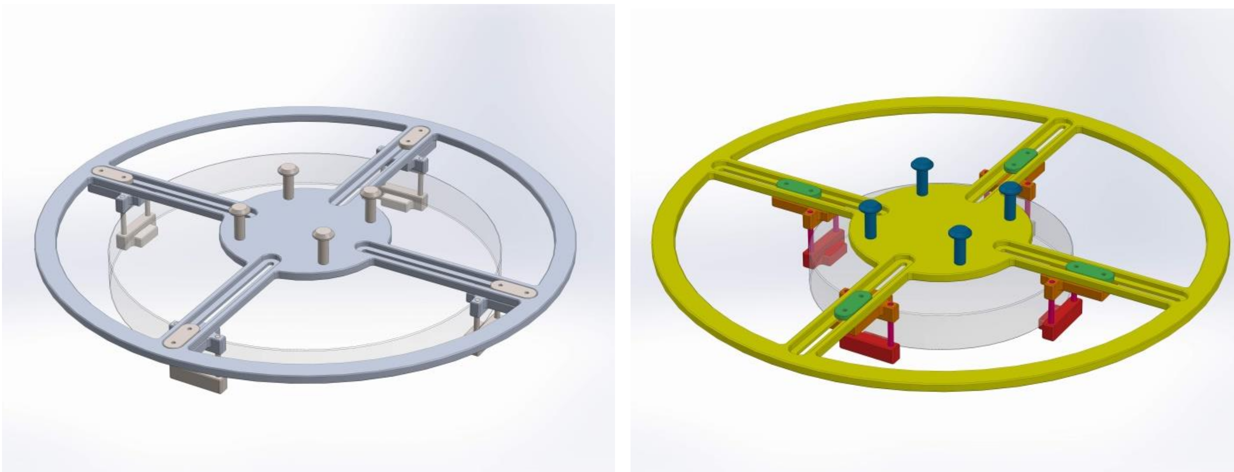


Figure 4: The holder device designed to sustain the large optical part during the coating

In the next stage a series of coating batches will be performed using different combinations of optical materials, recording technological parameters for each, and doing structural analyses, measurements, and tests as in the table below:

Item to be noted	Comments
Coating formula	Identification code
Coating parameters	Pressure; Temperature; IAD parameters etc
Substrate roughness	Measured using AFM or other method
Coating roughness	Measured using AFM or other method
Total reflectivity	Will be measured having as etalon the reflectivity of pure silver and pure aluminium
Group Delay Dispersion (GDD)	Measurements ensured in collaboration with a team from ELI
Damage threshold info	Tests done in collaboration with teams from CETAL (INFLPR) and ELI

Other measurements, investigations and tests will be planned and done depending on the new ideas that will come during the project progress.

[1] Edmund Optics - *The Complexities of High-Power Optical Coatings* - https://www.edmundoptics.com/resources/application-notes/optics/the-complexities-of-high-power-optical-coatings/

[2] Apparao, K.V.S.R. - *Dielectric mirrors for high power laser applications* - Bull. Mater. Sci. (1986) 8: 339. https://doi.org/10.1007/BF02744142 (1986)

[3] Iain Macmillan - *Creating high-power optical coatings is complex* – LaserFocusWorld (2002) http://www.laserfocusworld.com/articles/print/volume-38/issue-5/features/optical-coatings/creating-high-power-optical-coatings-is-complex.html

[4] LYNN SAVAGE - *High-Energy Laser Optics Require Coatings in Their Own League* - Photonics spectra (2010) - https://www.photonics.com/Article.aspx?AID=44258

[5] H. E. Bennett - *Comparison of technology for high-power laser mirrors and synchrotron radiation mirrors* - Physics Division, Research Department Naval Air Warfare Center Weapons Division China Lake, California - http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/25/028/25028722.pdf