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

Stage 1 / Activity 4
(Work-package 3)

Study regarding the optical measurements and tests assurance

High power laser mirrors are extremely important component of the laser mechanism and they should meet strict criteria: good resistance - high levels of optical intensity, high optical quality - good flatness (λ/20), low roughness (target being less than 2 nm), and minimal wavefront distortion to maintain beam quality and low reflection losses- reflection losses should be minimum to maintain the strength of the laser beam. The thermal deformation of the mirror is a major limitation of the high power laser system. Because of this, wave-front comes to have aberration and far-field optical pattern become divergent.

Studying the literature referring to the measurements and tests in this area, we found that the parameters from the table below are critical:

No.	Measurement required	Method used for the measurement
1	Flatness	*Hartmann–Shack wavefront sensor* *Phase Shifting Interferometry* *Shearing interferometers* *Coherent Diffraction Imaging* *White Light Interference Optical Profilers*
2	Roughness	*Optical profilometry* *Light and x-ray scattering* *Scanning probe microscopy*
3	Group Delay Dispersion (GDD)	*White Light Interferometer*

This study presents the methods found capable to ensure these measurements.

1) A *Hartmann–Shack wavefront sensor* is an optical instrument used for characterizing an imaging system. It is a wavefront sensor commonly used in adaptive optics systems. They can provide real-time feedback for adaptive optics systems. A Shack-Hartmann wavefront sensor consists of a 2D array of micro lenses and a CCD camera detector. After passing through the microlens field, a flat wavefront generates a regular grid of points on the detector whose spots have the same array separation distance as the microlenses. If the wavefront has a curvature, the spots generated by the microlens are displaced in x and y correspondingly. From the shifts of these grid points, the wavefront can be reconstructed. With strongly curved wavefronts, however, the spots in the proximity of adjacent spots can move out of their "home aperture," or the immediate region surrounding the reference point's location [1].

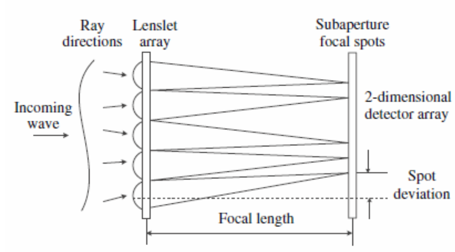

Fig 1. Schematic of a Hartmann-Shack sensor

The advantages of the Hartmann–Shack sensor are its simple structure and rapid data processing; these merits allow the use of the sensor in measurement of dynamic wavefronts, evaluation of laser beam quality, and realization of closed-loop wavefront control in combination with adaptive optics. Given its limited number of micro-lenses, low resolution is an inherent disadvantage of the Hartmann–Shack sensor and tested sample area also (under 100 mm sample size) [2].

Another way to inspect the mirrors is by the classic method- *Interferometry*, which determine the phase distribution and detect wavefronts. The light wave to be measured initially interferes with a regular spherical or planar reference wave to generate interference fringe patterns, and the resultant phase distribution is extracted from the recorded fringes using various methods, including phase shifting and fringe carriers. Interferometry is remarkably sensitive to environmental turbulence, such as mechanical vibration and air fluence.

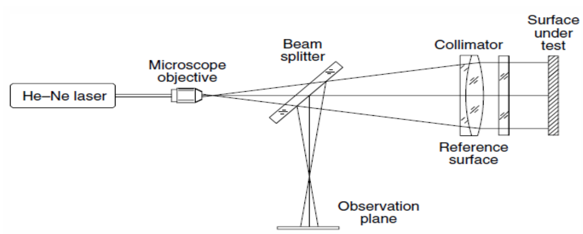

Fig. 2- Basic Fizeau interferometer configuration

The drawback of this method is the limit in application in high power laser systems, because it has to possess large apertures up to half a meter. Another difficulty is associated with the reference standard mirrors and related optical components which translate into higher cost of the interferometer exponential with the diameter. For example, NIF VEECO (USA) developed large Fizeau interferometer with diameter of up to 610 mm, with a $\lambda/10$ PV measurements precision and French Atomic Energy Commission (CEA) has a diameter of 800 mm.

Shearing interferometers are a good alternative to to traditional interferometers for measuring the quality of optical elements and light beam wavefronts. Shearing interferometers can be classified into lateral and radial shearing interferometers. Shearing interferometers are now widely used for optical testing, since they eliminate the need for a reference surface. The most commonly used types of shear are *lateral* shear and *radial* shear. In a lateral shearing interferometer two images of the test wavefront are superimposed with a mutual lateral displacement, while in a radial shearing interferometer one of the images is contracted or expanded with respect to the other.

The drawback of this method is the complicated imaging processing and wavefront reconstruction algorithms are necessary to retrieve the wavefront from the differential data, thereby limiting the applications of shearing interferometers.

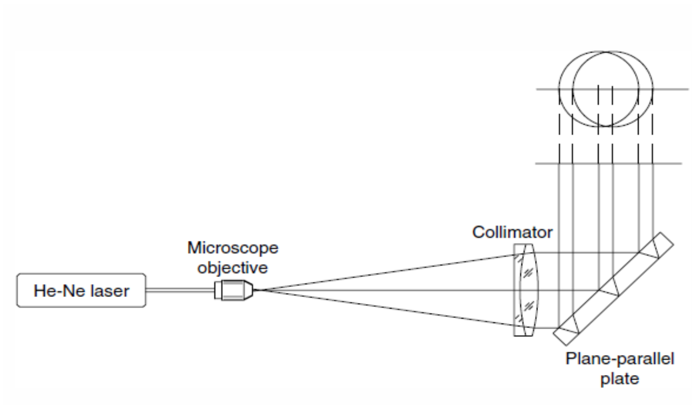

Fig. 3- Lateral shear interferometer

An alternative to characterize extensive surface areas and transmitted wave fronts is to measure subapertures of the surface and stitch the results together to synthesize a full aperture map- *Stitching interferometry*. Because the relative position of each subaperture measurement is not known exactly, there is some ambiguity when the individual subapertures are combined into a full aperture map. Accurate resolution is the fundamental task faced by all subaperture stitching methods. The uncertainty is largely due to alignment errors (small, unknown displacements) and noise in the individual subapertures maps. Subaperture stitching thus poses an optimization problem: The goal is the minimization of the discrepancies between multiple data sets.

Stitching interferometry in its most basic form was introduced to allow cost-effective tests of large flat parts. Although a variety of related techniques have been developed, they are used mainly for testing parts that are nominally flat. Subaperture stitching can also be used for testing other surface shapes. However, significant new challenges, particularly in the motion and algorithm components, appear when subaperture stitching techniques are applied to non-plane surfaces.

This measurement method has been used to measure large optical elements with sizes of up to 800 mm x 400 mm at Laser M´ega Joule and NIF.

The use of subaperture stitching interferometers significantly reduces cost and increases spatial resolution and measurement accuracy. However, the subaperture stitching method possesses inherent disadvantages. First, this method requires a high quality standard mirror, which is difficult to fabricate. Second, error transfer and the unstable solution are unavoidable sources of errors, which make it difficult to obtain sufficiently high measurement accuracy.

Another modern method for measure wavefronts and predict focus of the high power laser systems is *CDI (Coherent Diffraction Imaging)*. CDI is a phase-retrieval method based on computer iterative calculations. The main advantages of the CDI method are simple setup, compact structure, and low environmental requirements [3].

In 2000, CDI was first used to measure the phase of high power laser beams. The intensity of the laser beam at two different planes vertical to the optical axis were recorded, and the Fresnel phase-retrieval algorithm based on the G–S algorithm and the Fienup phase-retrieval algorithm was used to reconstruct the complex amplitudes of these two recording planes.

In 2006 Brady and Fienup measured a concave spherical mirror using the CDI method, where a He–Ne laser was filtered by a microscope objective and a pinhole placed near the center of curvature of the concave spherical mirror was used as the illumination beam; the intensity distributions of the resulting diffraction spots were measured using a CCD mounted on a computer controlled translation stage, which could accurately shift along the optical axis.

The CDI method can be used to measure large phase slopes, complex reflectance or transmittance of large elements.

In 2010, the CDI algorithm was used to form a FSD (focal spot diagnostic) to predict the focus of an OMEGA EP laser at the University of Rochester's Laboratory for Laser Energetics. The short-pulse diagnostic package contained a FSD which received a sampled beam downstream and a far-field CCD camera imaging the far-field intensity of the sample beam.

A versatile method to inspect mirrors is with the *White Light Interference Optical Profilers*. White light interference (WLI) optical profilers use broadband illumination and work like an array of optical focus sensors where the position of the interference signal at each sensor determines the best focus position. The use of broadband illumination overcomes some of the limitations that are found in single and even multiple wavelength methods. A white light source used in an interference optical profiler has a broadband visible spectrum with wavelengths from about 380 up to 750 nanometers. The source has low temporal coherence because of the large wavelength bandwidth, and it is not considered a point source, which means that it also has low spatial coherence. The low temporal and spatial coherence of the source creates interference fringes that are localized in space. Different white light sources, such as a tungsten–halogen, incandescent or arc lamp, LEDs and SLDs can be used for illumination. These sources have different spectra and thus create different fringe envelopes. The width of the fringe envelope is determined by the bandwidth of the source spectra [4].

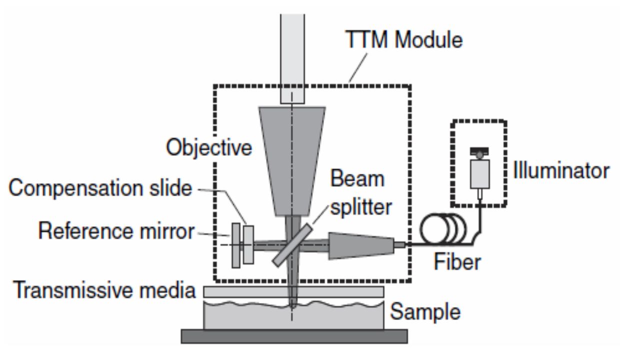

Fig. 4- Michelson type interferometric objective

A scanning interferometer uses conventional white light as its light source. A piezo drive system is used to "scan" the objective lens about a focal point. The sample to be measured is usually positioned on a precision X/Y stage. As the imaging system is "traversed" through its range by the piezo drive system the focal point is noted for each pixel in the CCD array. The major benefit of such a measurement system is that large numbers of points (typically 1024x1024) can be measured with very high lateral resolution (circa 0.3 microns) and vertical resolution (typically less than 0.1nm) in just a few seconds. By changing the magnification of the objective lens, larger areas can be assessed in a single measurement. It should be noted that in this case the lateral resolution is reduced proportionally: for an instrument with a 1 megapixel CCD measuring an area of 5mm by 5mm the lateral resolution will be 5 microns. An example of this type of gauge is the CCI instrument which can achieve Z resolutions of 0.1Å and Ra repeatability of better than 3pm.

2) Testing the roughness of the high power laser mirrors could be performed with different methods, such as: *Optical profilometry, Light and x-ray scattering and Scanning probe microscopy*.

Optical profilometry has the advantage to be rapid, non-contact method with a sub-nanometer height resolution (NA objective dependent). Has also the capability for stitching algorithm. The limitation of this method is the diffraction-limited spatial information and the artifacts from transparent thin films.

Light and x-ray scattering has also the advantage to be rapid, non-contact method and insensitive to vibration. The limitation of this method is that relies on models, assumptions to relate scattered beam to surface spectrum and the maximum analysis size (around 5 mm).

The optimal choice for roughness measurements is the *Scanning probe microscopy*. The main advantage is the high-resolution of the measurement with a lateral resolution limit of around one angstrom and the 3-D surface profile (0, 1 nm for AFM and 0, 01 nm for STM). The limitation of this method is the small areas tested, the sensitivity to vibration and the scanning speed.

3) The dispersion characterization of laser mirrors is important for obtaining proper performance of femtosecond lasers. Most approaches for the measurement of the group-delay dispersion (GDD) of optical elements have been based on a *white-light interferometer* that contains the dispersive element in one arm, keeping the other arm as a reference. The-cross-correlation pattern reveals the wavelength-dependent optical path difference between the two arms [6]. White-light source, used in combination with a standard Michelson interferometer, has been an elegant method for the study of the dispersive properties of optical materials, especially for the femtosecond lasers were the dispersion must be accurately controlled to yield the shortest pulses.

Initial dispersion measurements with white light involved measuring the centroid of the interference pattern produced with a Michelson interferometer and a filtered white-light source at various wavelengths. The relative group delay between the different frequency components introduced by an optical component placed in one arm of the interferometer is obtained directly. The same information can be obtained by a Fourier transform of a single measurement when the full bandwidth of the white-light source is used.

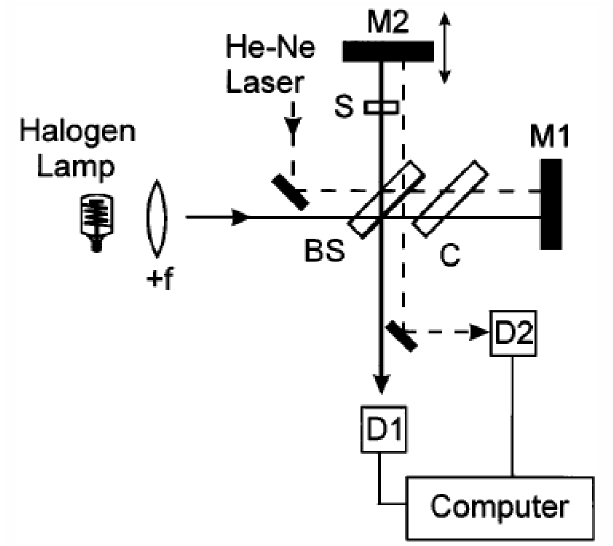

Fig. 5- Experimental setup for recording white-light interferogram.

The Optical and Photometric testing Laboratory (LOF) measurement of the mirrors during the technological chain are performed with the phase shifting V-100/P Fizeau interferometer. It has a HeNe laser (633 nm) with an output of 1mW. Standard testing diameter is 100 mm, but can be used special accessory- expander optics- to measure up to 150 mm. Quality of the system is $\lambda/50$ for plane flats and $\lambda/20$ for spherical surfaces.

Regarding the tests for the laser induced damage threshold (LIDT), these will be done in collaboration with our partners from INFLPR (CETAL), according to an agreement previously agreed, but details about this subject will be presented in the next report, after establishing the method.

Bibliography:

1 Jeffrey J. Widiker, Scott R. Harris, and Bradley D. Duncan, "High-speed Shack–Hartmann wavefront sensor design with commercial off-the-shelf optics "

2 http://www.laserfocusworld.com/articles/print/volume-51/issue-11/features/optics-characterization-shack-hartmann-wavefront-sensor-enables-flexible-characterization-of-lenses.html

3 HaiyanWang, Cheng Liu, Xiaoliang He, Xingchen Pan, Shenlei Zhou, Rong Wu, and Jianqiang Zhu, "Wavefront measurement techniques used in high power lasers"

4 Daniel Malacara, "Optical Shop Testing"

5 Supriyo Sinha, Justin D. Mansell, and Robert L. Byer, "Deformable Mirrors for High-Power Lasers"

6 Tayyab Imran ; Kyung-Han Hong ; Tae Jun Yu ; Chang Hee Nam, "Measurement of the group-delay dispersion of optical elements using white-light interferometry"