Project goals

Since several years an increased number of scientific platforms use high power lasers coupled with Fabry-Perot cavities. These facilities experience thermal deformations in optical components induced by power absorption in the coatings and substrates. The thermal lenses and thermal expansions generate optical aberrations that strongly degrade the stability and the performance of these setups. The THEOS project aims at developing a new thermally deformable mirror (TDM) with the goal to enhance cavity coupling by compensating any thermally induced optical aberration. Such device is intended to be vacuum compatible and should not introduce thermal or mechanical noise. To our knowledge, no other adaptive optics solution provides corrections without introducing noise, either mechanically via the magnetic or piezo electric transducers, or because of relaxations of the liquid crystal in liquid crystal based wavefront modulators. Moreover no current solution is vacuum compatible. This development is thus mandatory for experiment like search for gravitational waves (LIGO and Virgo detectors) or in laser and electron beam interactions setups (ThomX and ELI-NP).
For one side, the project is focused on the development of a complete simulation tool, that allows to study and define the appropriate material and design required for a TDM. On the other side, an experimental realization of an adaptive optics system is made at the CALVA platform which is composed of several cavities: one mode cleaner cavity and a couple of suspended coupled cavities.
This will lead to the demonstration of the high order mode correction ability of the TDM in the context of the mode matching improvement. At the end of the project, a fully understood prototype and a proposition of its implementation in adequate adaptive systems have to be available.

Description of the achieved work

Different systems using high optical power or long baseline are composed mainly by Fabry-Perot cavities like gravitational wave detectors or compact high fluence X-ray sources. Injecting laser sources of more than 100 W into cavities of finesse of more than few hundred will lead to store power up to 1 MW. Such power creates thermal lenses by absorption inside coatings and substrates of the mirrors that make the cavity. These thermal deformations modifiy the geometry of the cavity modes and strongly limit the amount of stored energy. A second source of mismatching comes from the modal composition of the injected laser beam. It is very difficult to obtain a pure Gaussian mode: high order modes are added to the fundamental mode during its propagation through the optics used to match the laser output to the cavity input. The aberrations can be induced by static defects in the optics or thermal ones as the laser power is superior to few 100 W. If the mode send to the cavities contains high order modes, only the fundamental mode will be coupled into the cavities and an important part of the power will be lost by reflection (and can also be a source of noise via scattered light). The control of phase aberrations that is time varying, or static but unpredictable, in a laser beam can be performed by a so-called *adaptive optics system.* A system of adaptive optics is composed of 3 elements, which are a system able to *detect* the phase aberrations, a system able to *compute* the corrections from the error signal and a system able to *apply* them. As the thermal aberrations can be time varying or unknown, an adaptive system appears then essential to correct constantly the distortions. Such

system, and particularly the corrective device, has to be compliant with very high requirements on optical quality, being vacuum compatible and not introducing noise in the system.
The main idea of the thermally deformable mirror (TDM) is to control the optical length of a mirror via the substrate temperature. The temperature and its shape are controlled with an array of resistors (see figure 1). A full simulation using Matlab has been set-up to study the two main parameters in temperature control: the thickness and the thermal conductivity. The main outcomes of this study show that thickness has a low influence in the response amplitude for the spatial frequency range we plan to correct. On the contrary, the thermal conductivity is really important whatever the spatial frequencies to be corrected. A second study using a finite element simulation has been done to test the size of the actuators and the different possible material substrates that can be used to construct the TDM. The study shows the shape of response is independent of the size of the actuators and of the thickness of the substrate. It allows to compare the optical and thermal properties of different materials and define the TDM response in each case. The material needs to exhibit a large change in amplitude while it is kept at a reasonable temperature to avoid any damage. The common material used in optics like fused silicate or BK7 fulfill this requirements.

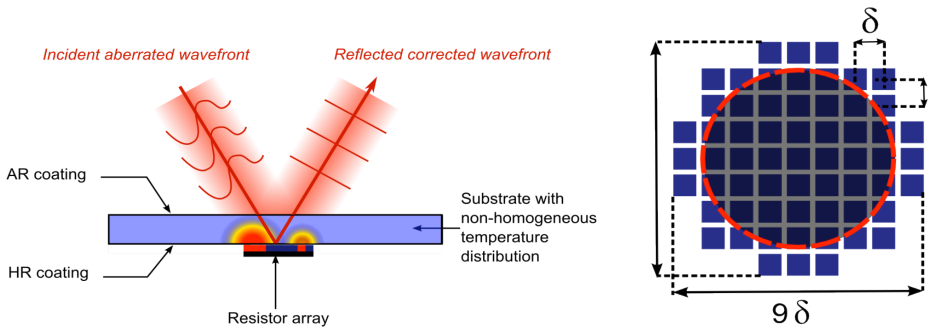

Figure 1 : (Left) Schematic view of a thermally deformable mirror (TDM) where the substrate is heating with an array of resistors modifying the optical path and then being able to correct an incident wavefront. (Right) Disposition of 61 actuators used in the TDM.

The spatial frequency of optical aberrations to be corrected will then define the design of the TDM. According to the requirements, an achievable trade-off between the actuators size and the gap in-between is to use 61 actuators of 1 mm2 separated by 0.2 mm (see figure 1).

The second stage of this work is to understand how to use such device in a optical mode matching system. A complete correction in amplitude and phase require two TDMs on the setup. A full study has been done to define the correct separation distance between the two objects by computing the complete propagation of the fields in the system. As we decide to limit the system up to fifth order in term of defects we need to have a distance that corresponds to a phase propagation of pi/5 between the two TDMs. We also decide to use a third TDM in our optical setup to mimic any defect that the two others mirrors will be able to control. Some early tests have been made. An example of correction of one of the high order mode is shown in figure 2. The mode is attenuated but some lower order modes increase as well. They correspond to misalignment and focus which can be controlled by additional systems in the setup (telescope for the focus and mirrors with tip/tilt mirrors for the alignment).

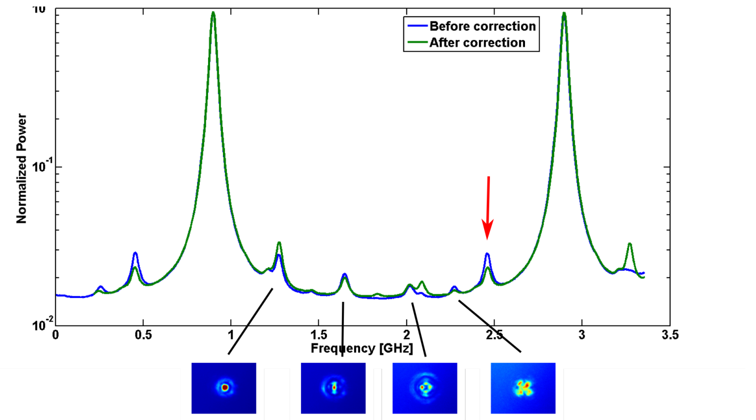

Figure 2 : Scanning a free spectral range of a triangular cavity in Calva to test the matching setup based on 2 TDMs. In this example one of the high order mode was controlled and reduced (red arrow).

The next steps will be to put in place an automatic alignment loop to control the low order modes. The systematic study of the correction performance for different modes has then to be pursued extensively to understand the limits of the mode matching setup. Afterwards, the implementation of the devices in the main projects has to be prepared through vacuum and noise compatibility studies.

Publications

- Kapsrzack et al, Performance of a thermally deformable mirror for correction of low-order aberrations in laser beam, Applied Optics 52, 2909 (2013).
- Kasprzack Marie, thesis from the University Paris-Sud, defended the 26th of September 2014 with the title: “Thermally deformable mirrors: adaptive optics scheme for gravitational wave interferometers”.

Relevance of the project within P2IO

The problem of high power lasers stored in optical cavity is seen in different fields within the P2IO labex: gravitational wave detectors with the Virgo projects but also in laser-electrons beams interaction. This problem is for example one of the limitations of the MightyLaser project for the creation of an X-ray polarized compact source. The first studies done in ThomX or ELI-NP show these experiments will face the same type of problem and then will need such adaptive optical system.

Possible valorization

We do not plan to have an industrial valorization however we already have some discussions with the ThomX and ELI-NP to use systems similar to the TDMs to solve the heating problem they will face with the power stored in their optical cavities.

Expenses

The following table is given in euros

Optics	20952
Electronics	2749
IT	973
Mechanics	1682
Others	1171
Total	27527