I.FAST

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Improvement of the laser intensity on target

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ABSTRACT

This document describes the 1 PW and 10 PW stability of the Apollon laser system before improvement. It then gives the results obtained with prototypes of active loops to stabilize the position and the shape of the focal spot. Based on this description, a plan for the future of focal spot stabilization is given.

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

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Executive summary

This document presents the results of a study carried out as part of WP6 of the I-FAST project, on improving the focal spot position of a laser with the aim of achieving stability of the order of +/- 0.1 µrad RMS.

1 Introduction

WP 6 of the I-FAST project is dealing with compact plasma accelerators.

These accelerators are approaching their implementation phase following the dramatic development of laser wakefield acceleration.

Performances are expected to be limited by several factors, one of the most challenging being the high intensity laser driver stability on target, whose specifications are dictated by the choice of laser plasma acceleration.

One of the factors of intensity instabilities is focal spot size and shape instabilities, since pulse duration and pulse energy are already quite stable.

After the study of the probable causes of the focal spot shape and pointing instabilities described in the MS24-64 report, this document gives the results obtained with two first prototype of active loops.

2 Focal spot Pointing stability measurement

The measurements were taken on the Apollon research infrastructure.

The 1PW beam is 21J at 21fs and has a diameter of 14cm.

The 10PW beam is currently only at a 3.7 PW level, with 78J at 21fs. It has a diameter of 40cm.

These two beams can be sent to two separate experimental rooms: the so-called long-focus are (LFA) with beam apertures of the order of f/40 and the so-called short-focus area (SFA) with beam apertures of the order of f/2.5.

2.1 1 PW Beam

In March 2022, a first set of measurements was made in the long-focus area.

For this, we installed a camera, without lens, in the interaction chamber at the best focus of the focusing optics (spherical mirror with a focal length of 9m, with a focal spot diameter of 67µm, close to the diffraction limit). To avoid damaging the camera, we attenuated the beam at the amplification output with VG9 plates, introducing no distortion of the focal spot (aberration less than λ/10).

We then recorded the position of the focal spot centroid over a period of one hour at a repetition rate of 1 shot per minute. Figure 1 shows the position of the focal spot expressed as a percentage of the diameter of the diffraction limit. As the diffraction limit represents an angle of 7,2 µrad, the measurements show a stability of the order of +/- 3 µrad PTV (Peak To Valley).

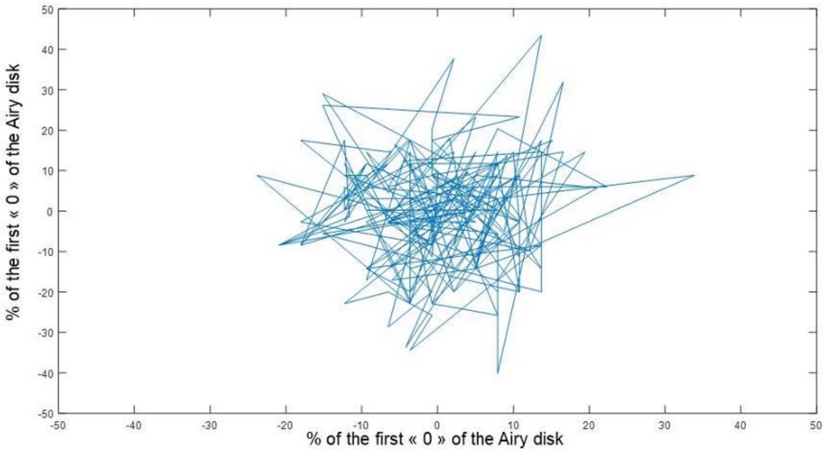

Figure 1 : 1PW SFA beam stability measurement

In September 2022, a second set of measurements was made using the same technique in the so-called short-focus area (off-axis parabola with a focal length of 42cm, and a focal spot diameter of 6µm). The results show similar stability.

However, with these measurements we were not able to tell which mechanical structure we needed to act on to improve final stability.

In June 2023, a third series of measurements was therefore made using a device we developed for stability measurement during the EUPRAXIA project. This device enables us to measure the stability of a beam, but above all to see the full spectrum of vibrations involved in instabilities. Using a taping method, it can also determine the influence of each optical component in the chain on the final stability at focus.

Figure 2 shows the measurement when we placed this device in the target chamber of the 1 PW beam in the Long Focal Area near by the focal spot. We can see all the frequencies of the pointing instability. Once we have done this basic measurement, we tap each mount of the laser beam and check which frequencies rise up. This way we are able to determine which mount is the source of each frequency. We can see in the spectrum the 50 Hz peak due to the lights of the room. However, for this specific basic spectrum we were not able to find which optic was the source of the 10 Hz peak.

Figure 3 shows the measurements made when we placed this device in the target chamber of the Short Focal Area, in the 1 PW beam, close to the focal spot. Similarly, for this spectrum, we were unable to determine which optic was the source of the 7 Hz and 12 Hz peaks.

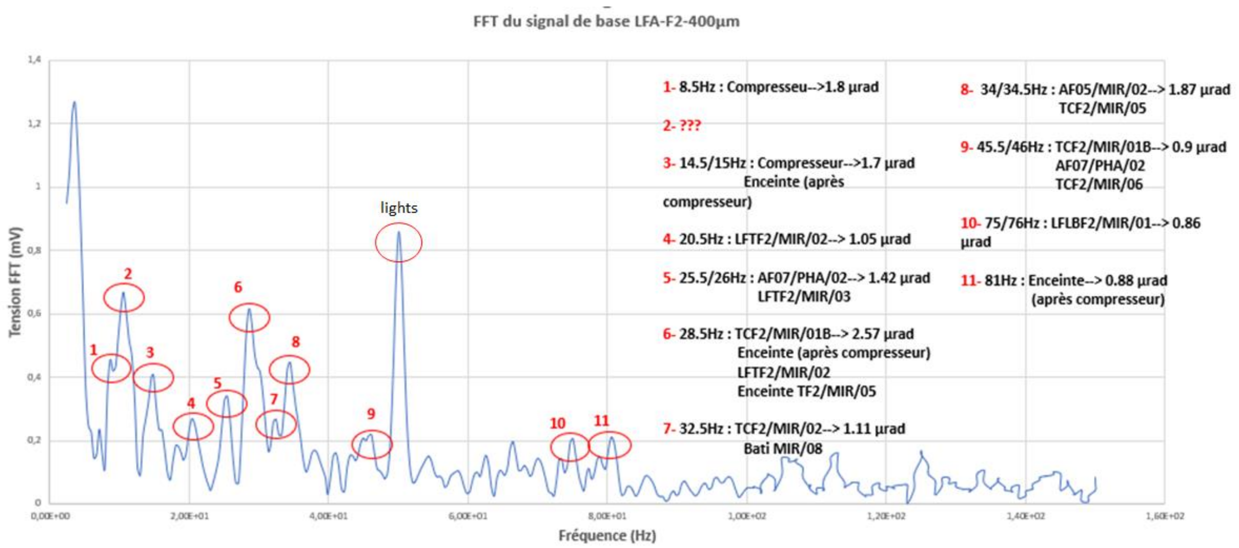

Figure 2 : Basic spectrum for 1 PW in LFA.

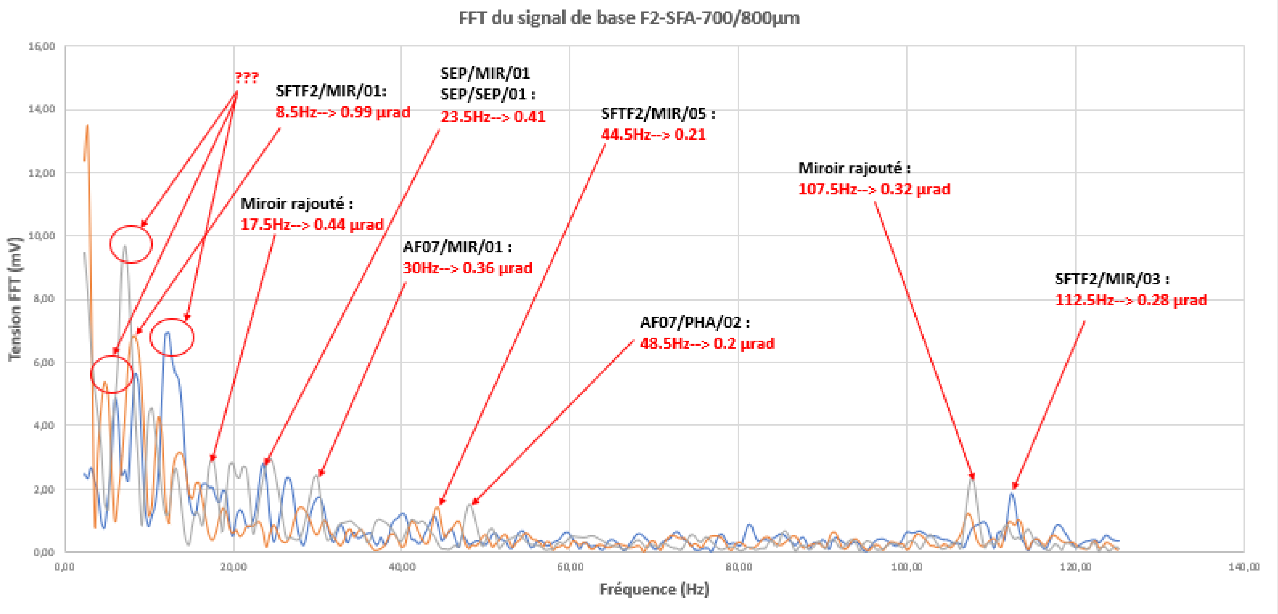

Figure 3 : Basic spectrum for 1 PW in SFA.

The measurement made with this device gives an equivalent overall value to the measurement made using the camera. It has enabled us to determine which frames have the greatest impact on the installation.

2.2 10 PW BEAM

In March 2023, the same technique (using a camera) that was used to measure the 1 PW beam was used to measure the stability of the 10PW beam in a short-focus area. The only difference was that, to get sufficient beam size on the camera, we added a x10 microscope lens.

This measurement showed a very significant instability of the order of +-20 µrad, i.e. 6 focal spots. This instability was present even when several items of equipment were switched off (pump, cooling water, air conditioning, etc.). This instability was abnormal, and we attributed it to a mounting error on one of the optical mounts.

This type of measurement could not be carried out on the 10 PW beam in the long-focus area, as the beam transport and focusing system is not yet in place.

In July 2023, following on from the measurements made on the 1 PW beam, we used the device developed during EUPRAXIA for determining instability spectra. Figure 4 shows the measurement made when we placed the device in the target chamber of the Short Focal Area, in the 10 PW beam, close to the focal spot. The measurement is consistent with the one carried out in March 2023, and shows that the instability is mainly due to the mounting of the focusing of-axis parabola.

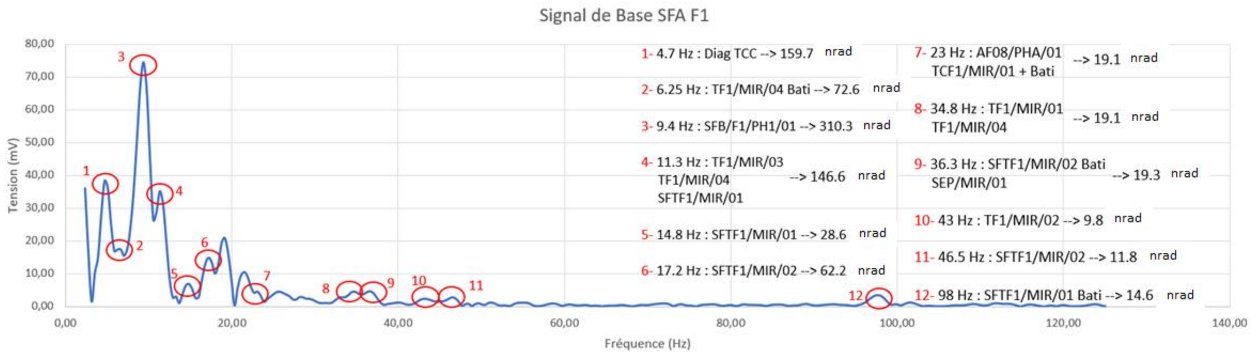

Figure 4 : Basic spectrum of the 10 PW in SFA.

Figure 5 shows the measurement made in the Long Focal Area when we placed the device in the 40 cm 10 PW beam after the 4 transport mirrors. In fact, entire focusing system was not yet in place, so there was no focal spot. Though this measurement was taken as an indication and not for a final analysis.

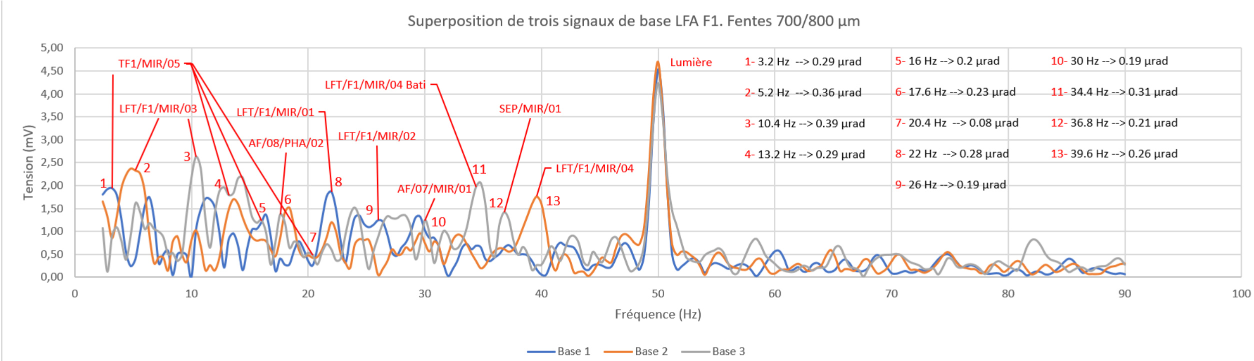

Figure 5 : Basic spectrum of the 10 PW in LFA.

We can see that, apart from the SFA focusing off-axis parabola mount, the values are very low, and that it will be very difficult to find a cause with a simple correction solution in the mechanical assemblies. This observation has prompted us to investigate solutions other than the reworking of mechanical components.

3 Focal spot shape stability measurements

A campaign to qualify the stability of the focal spot shape was carried out in November and December 2022.

This campaign enabled us to precisely quantify the value of variations and the origins of these variations. Measurements were carried out with the help of GSI, who lent us equipment enabling wavefront measurements up to 200 Hz.

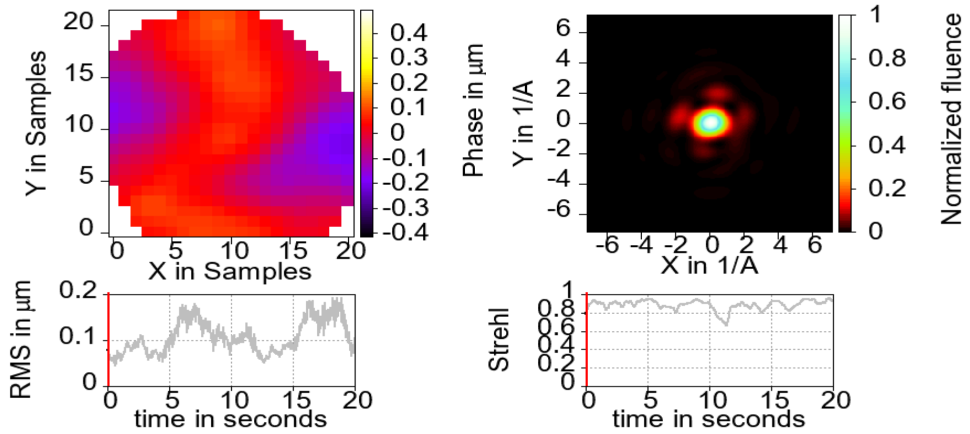

Figure 6 : Measurements made in the LAM zone without passing through the last amplifier.

Figure 6 shows the evolution of the spatial phase and Strehl ratio over a period of 20 seconds without passing through the last amplifier (the condition under which the laser has been used for qualification experiments and for the year 2022). It can be seen that the Strehl ratio varies from 0.6 to 0.9. This measurement was made with a continuous diode in the separation zone, i.e. before transport to the various compressors.

Figure 7 shows the evolution of the spatial phase and Strehl ratio over a 20-second period, but this time passing through the last amplifier. We can see that the Strehl ratio varies from 0.25 to 0.85.

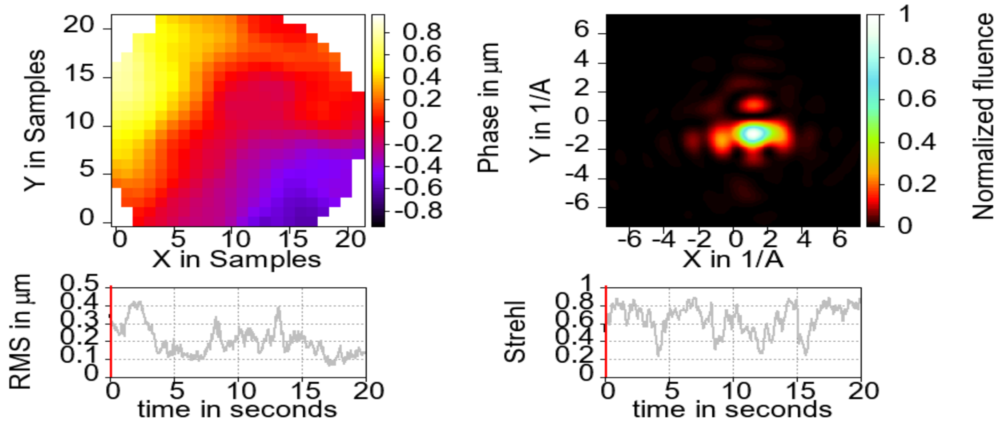

Figure 7 : Measurements taken in the LAM zone via the last amplifier.

Spectral analysis of the measurements shows that above 70 Hz, disturbances are minimal.

Tests were carried out by stopping the airflow in the amplification room, which showed a clear improvement.

We then sought to minimize the sources of airflow disturbance, and thus detected the presence of several heat sources, such as motors for alignment crosses, cameras needed for diagnostics, and vacuum pumps for spatial filters.

Following these measurements, we added covers and tubing as close as possible to the beam, right up to the entrance to the 1 PW compressor, and removed the heat sources represented by the motors and cameras.

A new Strehl ratio measurement campaign was carried out, this time in the LFA experimental chamber, under vacuum and with the real beam. Figure 8 shows a clear improvement in coefficient stability, with a variation of ± 7.8%.

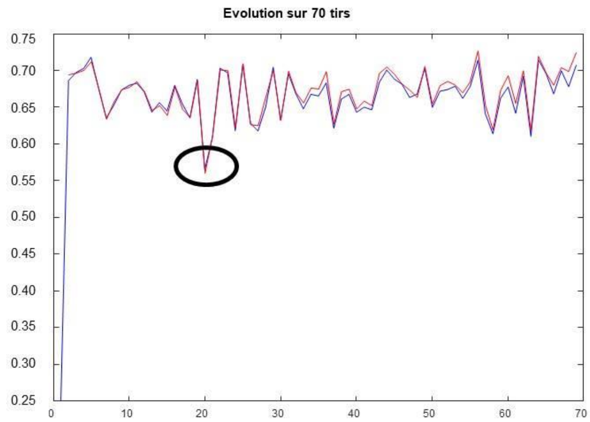

Figure 8 : Variation in Strehl ratio after correction.

Additional operations were carried out in September 2022, adding hoods and tubings. After these operations, the variation is ± 5%.

4 Focal spot stability improvement

4.1 POINTING STABILITY

The initial plan was to implement a passive correction of instabilities. To do this, we needed to know which mechanical structures were causing the instabilities. Unfortunately, we were only able to have access to the installation to carry out these measurements in June 2023 and July 2023. It was therefore impossible to implement this solution in the time available, given that for each structure we had to model the instability and determine the points of the structure on which we wished to act.

However, this subject has not been abandoned and will be pursued, if still necessary, in view of the results obtained following the installation of the active loops described below.

In view of the stability problems encountered with the F1 parabola mount in the short focal area, we re-examined the mount and corrected two problems. We then carried out a new measurement with the device developed at EUPRAXIA in the target chamber, in the 10PW beam, close to the focal spot. Figure 9 shows the measurement results. Points 2, 4, 6 and 7 from Figure 4 are found, but not point 1, which is normal since we did not reuse the TCC diag but sent the beam directly into the device. And we cannot find point 3 in Figure 4 at 9.4 Hz, confirming that the work done on the off-axis F1 parabola mount was effective.

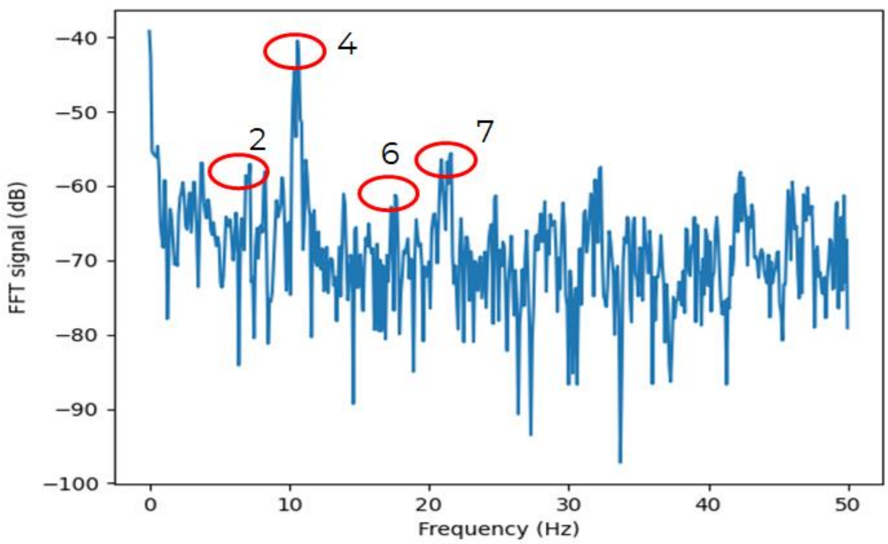

Figure 9 : Basic spectrum of the 10PW in SFA after modification of the off-axis parabola mount.

To mitigate the absence of a passive correction, we tested the implementation of an active beam pointing correction loop. The principle is as follows:

- A pilot beam is injected whose wavelength is compatible with the spectral band of the transport mirrors, but which is also outside the spectral range of two specific mirrors (see Figure 10).

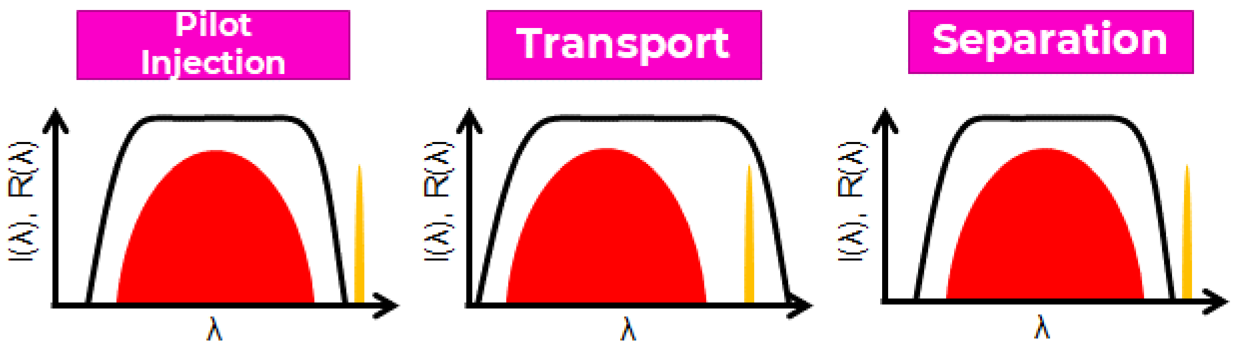

Figure 10 : Pilot-beam injection principle

- As close as possible to the pilot beam injection mirror, we place a piezo-mounted mirror with a frequency of the order of 100 Hz (see Figure 11).
- Behind a separation mirror, placed as far back as possible in the laser chain, we install a 4-quadrants which measures the beam position at a rate of 100 Hz (see Figure 11).
- A loop between the piezo and the 4-quadrant controls the position of the pilot beam, and hence that of the laser beam.

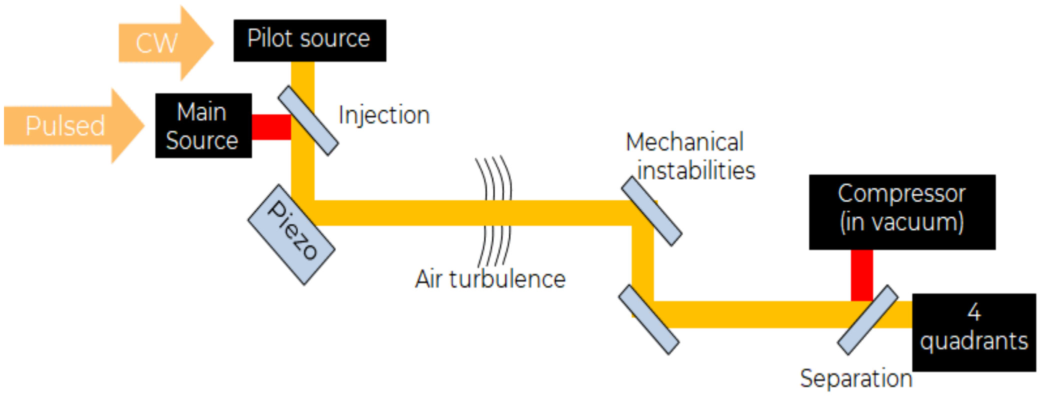

Figure 11 : positioning of the elements making up the active pointing correction loop.

In November 2022, on Apollon, we chose a 905 nm laser diode for the pilot beam.

A loop from MRC company has been installed (see Figure 12). The piezo-mounted mirror was installed at the output of the first Ti-Sa amplifier, where the beam is still only 4.5 mm long.

The 4 quadrants were installed after the amplification stages, before being transported to the compressors. In a final version, we will be thinking about how to install this 4-quadrant in a diagnostic at the end of the chain, which will image the focal spot.

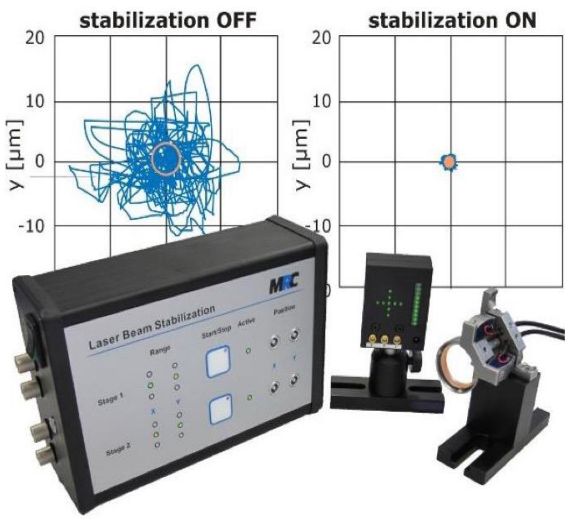

Figure 12 : Photo of the MRC stabilization loop.

We then tested the loop with the pilot-beam only, without checking the impact on the main laser beam. When the loop is not active, we measured a stability of +/- 5 µrad over 5 minutes. When the loop is active, we measure a stability of the order of +/-1.5 µrad PTV. We can therefore see that we are potentially improving stability by a factor of over 3. However, the size of the focal spot on the 4 quadrants was too small, barely covering the useful surface of the sensor. As a result, the measurement was highly sensitive to wavefront variations. It would have been necessary to increase the size of the spot on the sensor to improve measurement stability and, consequently, the efficiency of the stabilization loop.

We have not gone any further with this study to date, as the advisory committees have given priority to working on stabilizing the shape of the focal spot rather than on pointing stability. As we also knew that a focal task shape stabilization loop would have an impact on pointing stability, we decided to give priority to the focal task shape stabilization loop.

In conclusion, we will take a look at how we will be using this pointing stabilization loop in the years to come.

4.2 Shape stability

We tested the implementation of an active loop for beam surface correction. The idea was to transpose to a laser the techniques used on large telescopes. The principle is as follows:

- A pilot beam is injected whose wavelength is compatible with the spectral band of the transport mirrors, but which is also outside the spectral range of two specific mirrors (see Figure 10).
- As close as possible to the pilot beam injection mirror, we place a deformable mirror with a frequency of the order of 100Hz (see Figure 13).
- Behind a separation mirror, placed as far as possible in the laser chain before the compressor, we install a wave front sensor operating at 100Hz (see Figure 13).
- A loop between the deformable mirror and the wavefront sensor controls the shape of the pilot beam's focal spot, and hence that of the laser beam.

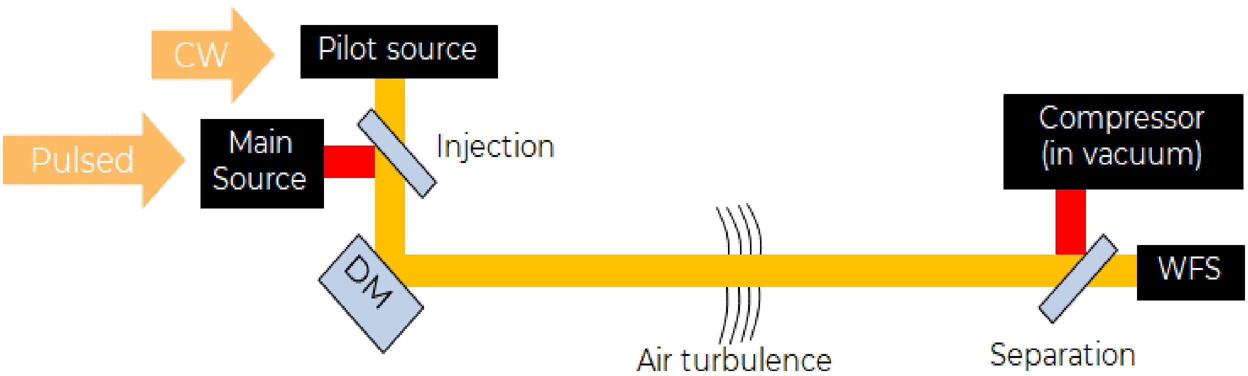

Figure 13 : positioning elements for the active wavefront correction loop.

We used the same 905 nm diode as for the pointing stabilization loop.

We created a loop with the following components:

- Camera from XIMEA: PCIe 3.0 x8 interface, Shack-Hartmann Sensor with custom MLA, WaveFront acquisition up to 7 kHz,
- Real Time Computer (RTC): Consumer grade hardware, OS: Ubuntu, AO control based on open source framework “cacao“, Graphics Processing Unit (GPU)-based SHS evaluation in < 100 µs
- Deformable Mirror from Dynamic Optics: Bimorph Piezoelectric, 55 mm active area, 96 actuators, 2.5 ms latency.

This loop was tested in the development room in November and December 2023 (see Figure 14). We made a technical reception of the mirror and validation of the complete closed loop architecture: detection, communication, correction. We simulated air turbulence and assessed the system's stabilization capabilities.

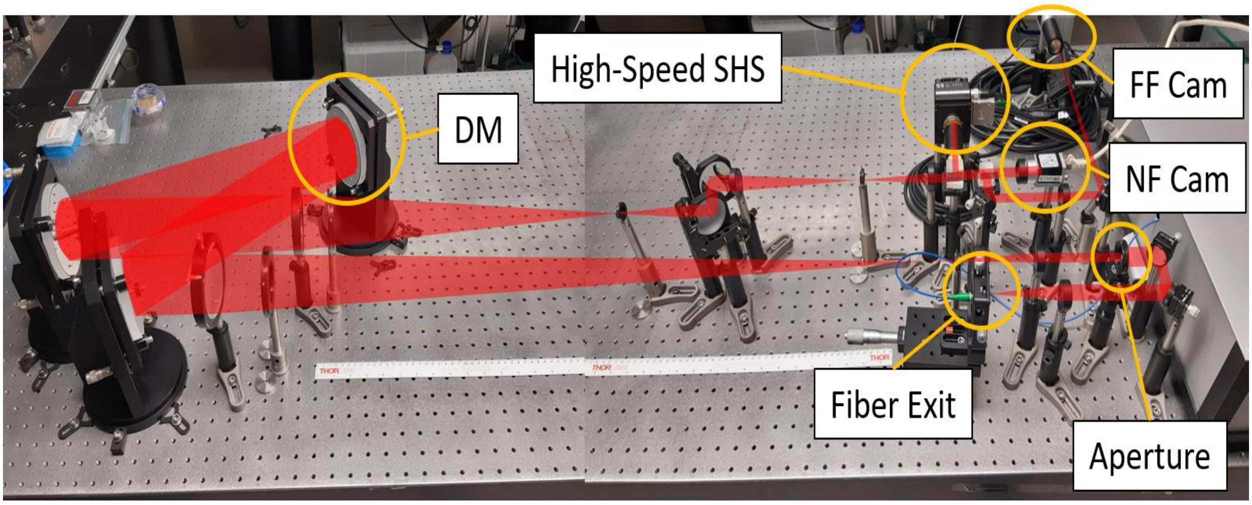

Figure 14 : Test bench at LULI: the setup.

Figure 15 shows that, on the test bench, stabilization was very good, and the operation of all components was robust and repeatable. We can see that the wavefront is 0,18 µm +/- 0,13 µm with the loop off and is 0,01 µm +/- 0,04 µm (here we are at the limit of the precision of the wavefront sensor used on the test bench.

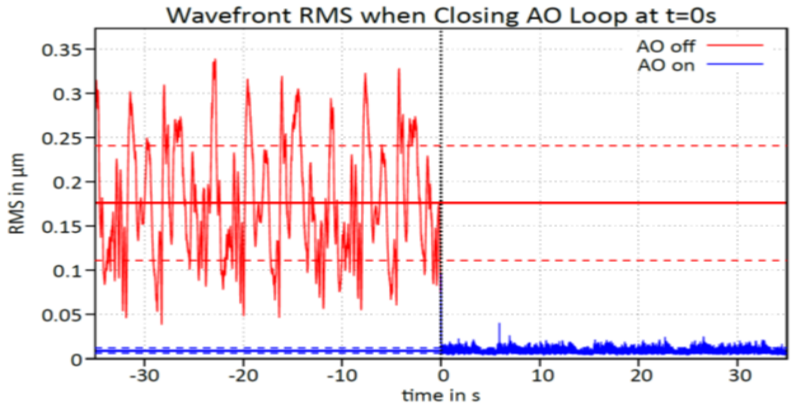

Figure 15 : Results of the loop on the test bench.

A closer analysis of the latency times shows that there is some residual "ringing" of the wavefront evolution depending on the spatial frequency and the amplitude (see Figure 16).

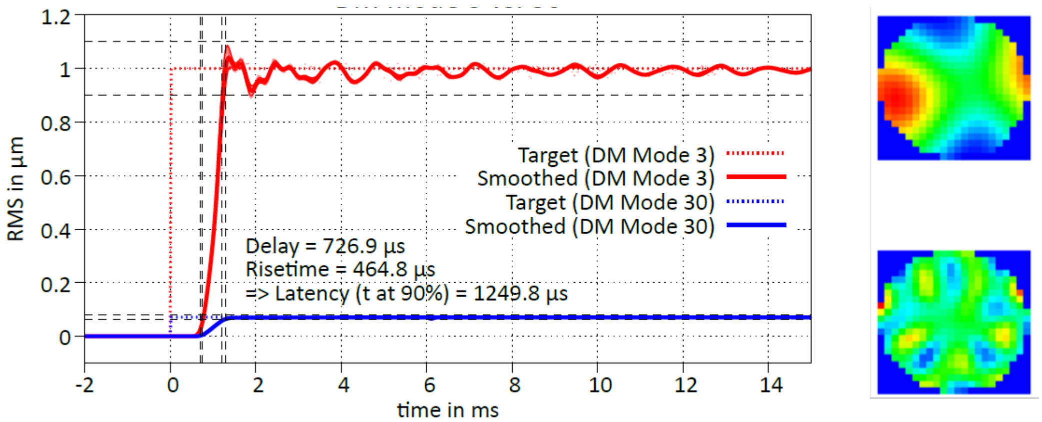

Figure 16 : Residual variation of the wavefront with the active loop on the test bench.

Between January and March 2024, this loop was tested on the Apollon installation using only the pilot beam. We acquire the focal spot at the entrance of the 1 PW compressor (see Figure 17). With the loop off we can see a lot of aberration in the focal spot (come and astigmatism) while with the loop on we can see a focal with only high order aberration.

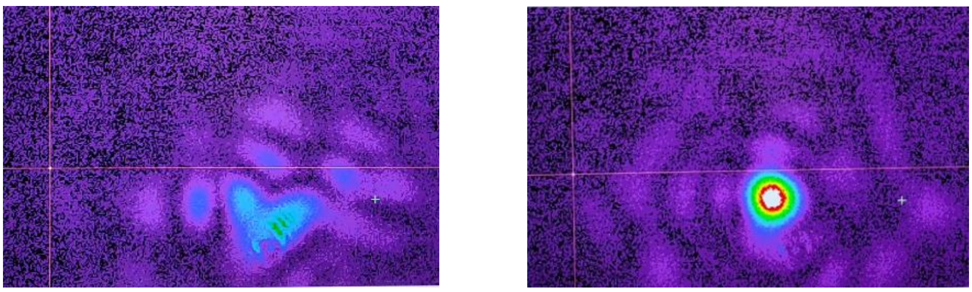

Figure 17 : focal spot without loop (left), focal spot with loop (right)

The results on Strehl ratio stabilization are very satisfactory. In Figure 18, we are able to measure a Strehl between 0.65 and 0.97 with the loop off and a Strehl between 0.96 and 1 with the loop on.

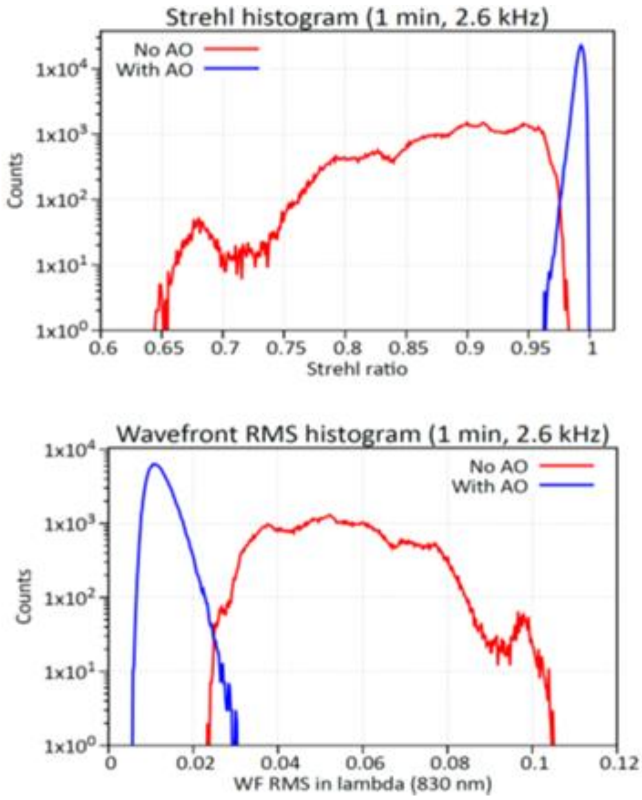

Figure 18 : variation in Strehl ratio and wavefront with and without the active loop

But as you would expect, stabilization of the focal spot shape is also accompanied by stabilization of the pointing (see Figure 19). We estimate that this test improves pointing stability by a factor close to 3.

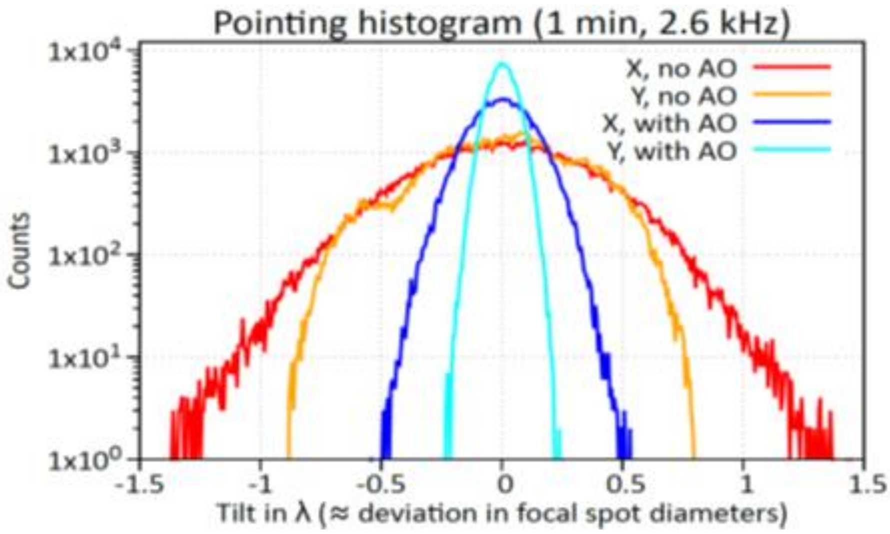

Figure 19 : evolution of the focal spot position with and without the active loop

5 Future plans / Conclusion

During this study, we were able to demonstrate that the device we had developed to characterize mechanical structures gave highly reliable measurements.

We were able to demonstrate that we could gain a factor of 3 on pointing stability with an active pointing stabilization loop. We believe that with a larger spot on the four quadrants, we could achieve a factor of 5.

We were also able to demonstrate that we could gain a factor of 3 on pointing stability with an active wavefront stabilization loop.

With these results, we hope to achieve a factor of 10 in pointing stability. This would give Apollon a stability of the order of +/- 0.3 µrad PTV. This would exceed the desired 0.1 µrad RMS.

However, access to the Apollon facility was very limited over the duration of the project, more so than we had envisaged. As a result, there are a number of limitations to our study:

- our results were obtained only on a part of the laser chain, so a loop must be performed on the entire chain.
- our results were only obtained with the pilot beam, so we still need to check the correlation of the real and witness beam.

Finally, we still have to check that we are capable of driving a pointing control loop and a wavefront control loop in parallel on the same laser chain.

Depending on the results we will obtain, we may pursue a study of passive correction, which we have not carried out here, but which would be very costly as it would have to be applied to each structure presenting nano vibrations.

6 Annex: Glossary

Acronym	**Definition**
Diag TCC	Laser Diagnostic installed at the Center of the Target Chamber
DM	Deformable Mirror
FFT	Fast Fourier Transform
LFA	Long Focal Area
LAM	Room where are installed the amplification stages
PTV	Peak To Valley
RMS	Root Mean Square
SFA	Short Focal Area
WFS	Wave Front Sensor