



Deliverable Data	
Deliverable number	D5.2 (D13)
Deliverable name	Blue print of an achromatic, reflective beam transport for ELI-BL, Eu-XFEL and FAIR laser facilities
Work Package	WP5 task (5.1)
Lead WP/deliverable beneficiary	CNRS/CNRS
Type and dissemination level	Report, public
Deliverable status	
Submitting author	Antoine Fréneaux
Verified (WP leader)	Dimitris Papadopoulos, Patrick Audebert
Approved (Coordinator)	Vincent Bagnoud
Due date of deliverable	

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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

As part of WP5 of the European THRILL project, we present the design of an achromatic reflective beam transport telescope for the Apollon F2 ‘1 PW beamline’, together with preliminary design studies for future implementations at the European XFEL and FAIR laser facilities. The primary objective is to improve the near-field spatial quality of high-energy laser beams before compression and focusing, thereby increasing the achievable intensity on target while preserving beam quality.

To eliminate chromatic aberrations associated with refractive optics, the selected solution is based on a 1:1 telescope composed of two large off-axis parabolic (OAP) mirrors. This reflective configuration provides diffraction-limited imaging over a long propagation distance while maintaining excellent spatial and temporal beam quality. The telescope is designed to image the beam from the delay line directly to the entrance of the compressor, minimizing diffraction effects and preserving the super-Gaussian beam profile required for high-intensity laser operation.

The optical design was optimized under several key constraints, including:

- maintaining average fluence below 1 J/cm^2 on all transport optics;
- preserving a 1:1 magnification over a propagation distance of approximately 10 m;
- ensuring compatibility with the existing Apollon layout and synchronization requirements;
- minimizing chromatic, diffraction and nonlinear propagation effects.

A complete optical and mechanical design was developed, including the specification of 200 mm diameter off-axis parabolic mirrors (4.4 m apparent focal length), transport mirrors, vacuum windows, and precision mounts. Beam propagation simulations confirmed that all optical components operate well below their laser-induced damage thresholds while maintaining the required beam diameter throughout the transport line. Detailed technical specifications were established for procurement, including surface quality, wavefront error, reflectivity, dispersion, and laser damage resistance.

The introduction of the AF09 telescope modifies the optical path length of the F2 beamline. A synchronization study demonstrated that adding a simple optical chicane to the F1 beamline restores synchronization while preserving the required **$\pm 5 \text{ ns}$ timing adjustment capability**, and even extends the accessible synchronization range.

A dedicated Class 1 visible alignment source was designed and built to facilitate installation and maintenance of the telescope. Combined with a dedicated alignment procedure based on autocollimation, focal spot optimization, and reference pinholes, this approach enables accurate alignment of the complete afocal system while ensuring that the compressor input axis and beam quality are preserved.

Finally, the experience gained from the Apollon design has been extended to develop blueprints for long-distance reflective beam transport systems for the European XFEL and FAIR laser facilities. These preliminary studies demonstrate that the same reflective telescope concept can be scaled to transport very large (200 – 400 mm) CPA beams over distances of several tens of metres while maintaining excellent spatial quality and avoiding chromatic aberrations.

Overall, this work establishes a practical and scalable solution for high-power laser beam transport based on “off-axis parabolic telescopes”. The proposed architecture significantly improves near-field beam quality before compression, reduces diffraction-induced degradation, and provides a robust foundation for future petawatt-class laser facilities requiring long-distance, high-fidelity beam transport.

Abbreviations

Abbreviation	Definition
WP	Work Package
OAP	Off-Axis Parabola
PW	Peta-Watt
SFA	Short Focal Area
CF2	Compressor of the F2 beam
LAM	Laser Amplification area
F1	Faisceau 1 (Multi-PW Apollon laser beamline)
F2	Faisceau 2 (1PW Apollon laser beamline)
LRO	Ligne à Retard Optique (Delay beamline on F2)
MMLD	Metal Multi Layers Dielectric mirrors
CCTP	Cahier des Clauses Techniques Particulières (Specific Technical Specifications)
AF09	AFocal system 09
LPA	Post Amplification Area

1 Introduction

To reach high intensities about 10^{21} W/cm² on target, it is essential to maintain maximum laser beam spatial quality before focusing. All along the Apollon laser system's beam path, we strive to install very high spatial quality optics and do relay imaging transport to put all the chances on spatial beam quality side.

In order to improve the focal spot spatial quality on the target of the secondary beamline F2 (20 J, 20 fs), it is essential and also challenging to improve the spatial profile quality of the F2 beam prior to focusing. As part of the European THRILL project, specifically within WP5, the installation of a long telescope between the delay line and the 1PW compressor (CF2) should enable a clear improvement in the transport and the spatial quality of the beam reaching the gratings of the compressor (Fig.1).

In order to avoid any chromatic effects caused by lens-based telescopes, we decided to opt for a reflective solution that minimizes both spatial and chromatic aberrations, i.e. a set of two off-axis parabolic mirrors with a low angle of incidence, as they are less costly and less complicated to manufacture as compared to larger off-axis incidence angles (with more manufacturers capable to deliver the required large diameters).

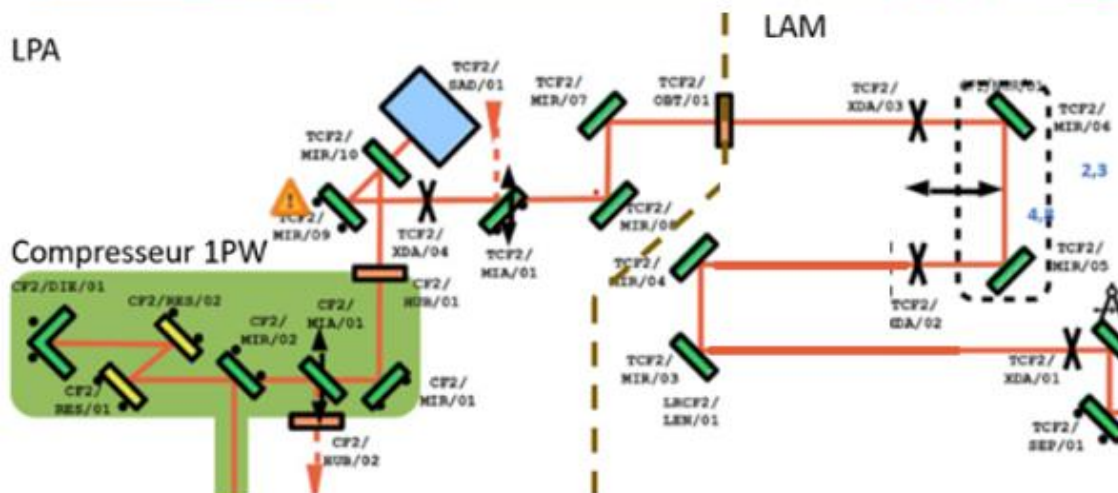
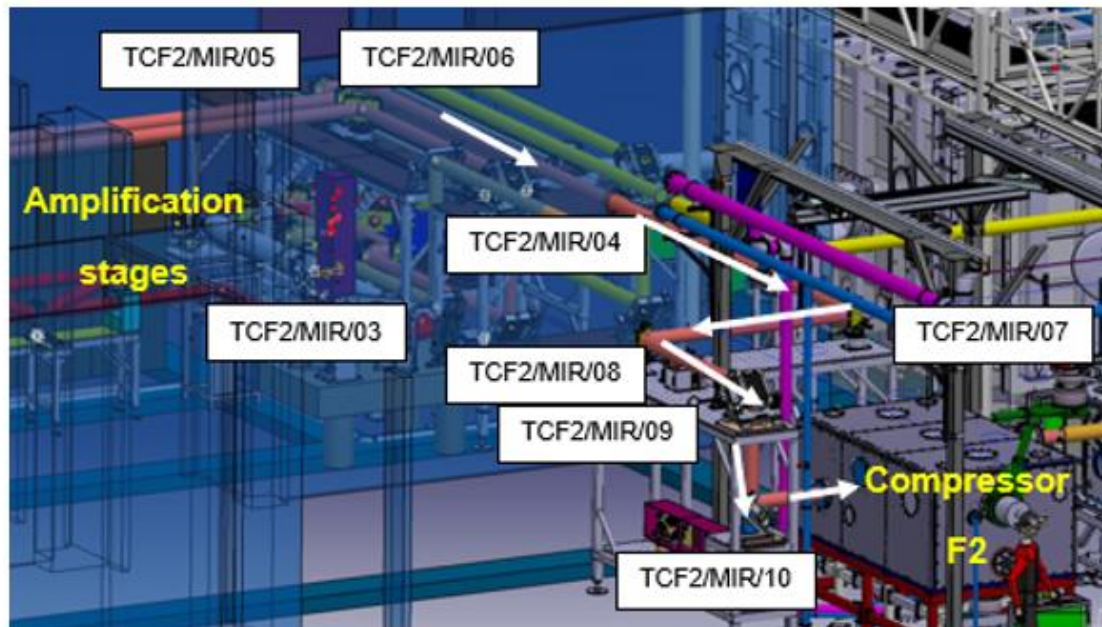
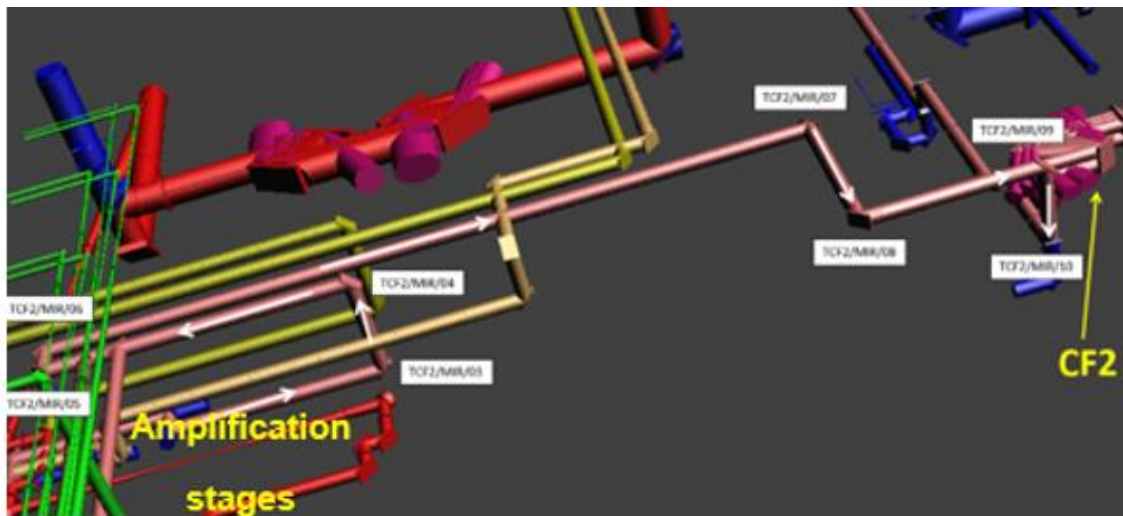


Figure 1: F2 beam actual path (on top) and beam diagram (on the bottom)

2 Objectives and limitations

In order to obtain the greatest possible image transfer distance (minimize the propagation diffraction effects), we need to establish the longest possible telescope, taking into account the possibilities offered by the current layout, the fluences on the optics ($F_m < 1\text{J}/\text{cm}^2$ on the mirrors) and minimize chromatic and non-linear effects, not forgetting the Apollon facility requirements on the synchronization of the two main beamlines of the system, F2 and F1 (10 PW beam line), to within $\pm 5\text{ ns}$, via an existing optical delay line (LRO).

For this reason, we will try to place the first off-axis parabola, named “OAP1”, as close as possible to the output of the LRO, with a focal length that allows an average fluence $< 1\text{J}/\text{cm}^2$ AOI45° on TCF2MIR/07 (MMLD coating specified LIDT $>5\text{J}/\text{cm}^2$ but it's safer to take a factor of 5 as a margin), with the first mirror on the L-shaped chassis.

Concerning the second off-axis parabola, named “OAP2”, we need a magnification of 1, i.e. the focal length $F_2 = F_1 = F$, and it must be placed at a distance of $2F$ from OAP1 to ensure a collimated beam at the CF2 compressor input.

3 Selected configuration

3.1 Principle

The AF09 telescope will consist of two parabolic mirrors with a reasonable off-axis angle $\text{OAA} = 25^\circ$, in order to benefit from manual polishing to avoid the appearance of satellites in the focal plane (Fig.2, 3 and 4). For these two OAPs, we opt for apparent focal lengths $F_1 = F_2 = F = 4400\text{mm}$, because these are the longest focal lengths, to obtain the longest transport distance, compatible with our actual beamline.

This telescope, with a magnification of 1, enables us to project an object plane located 10cm before the first off-axis parabola (OAP1) and 10 metres after the second parabola (OAP2), i.e. in a plane located in the compressor, CPF2, a few centimeters before the second pass on the first grating.

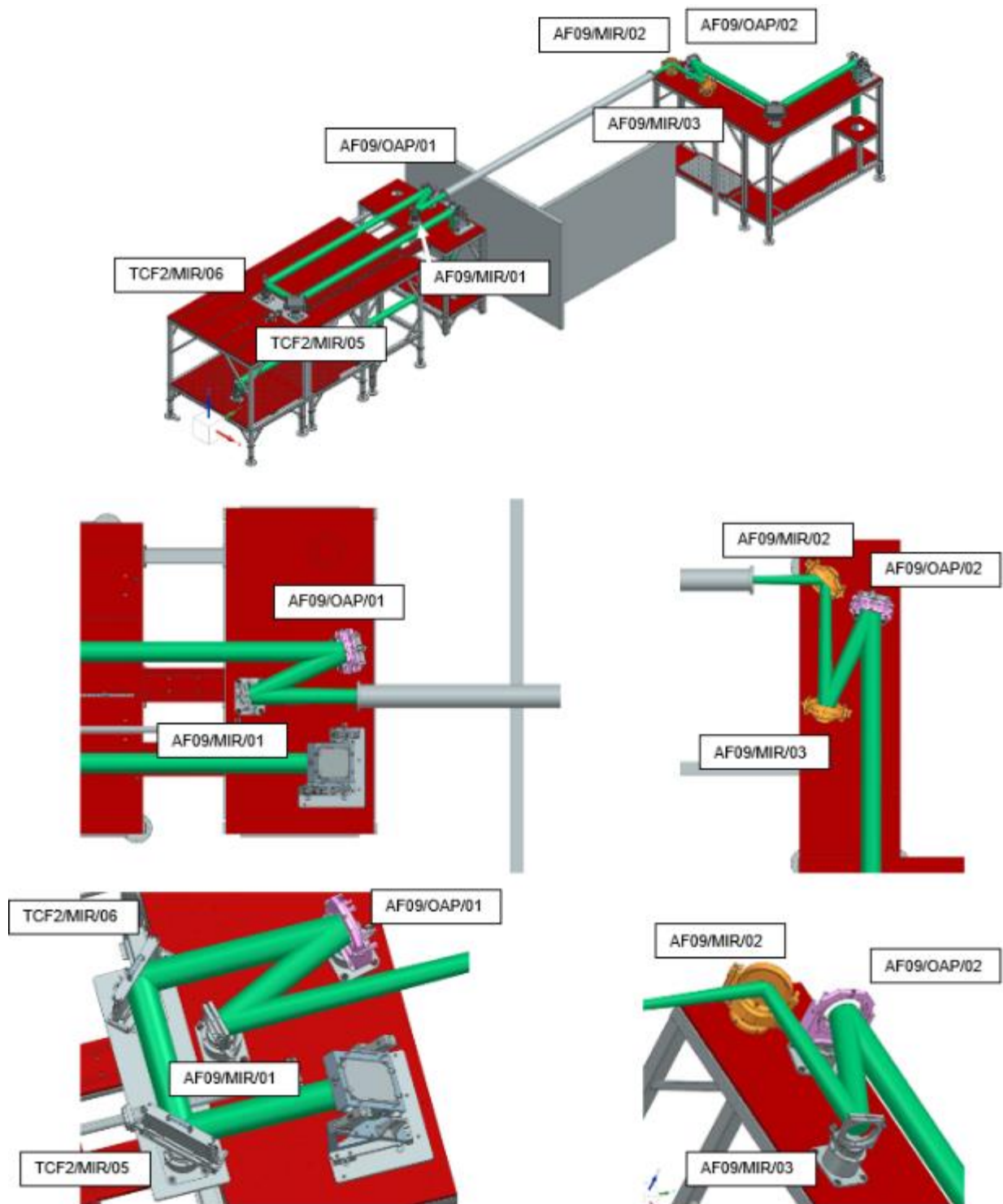


Figure 2: Different 3D views of the F2 line with the AF09 telescope layout

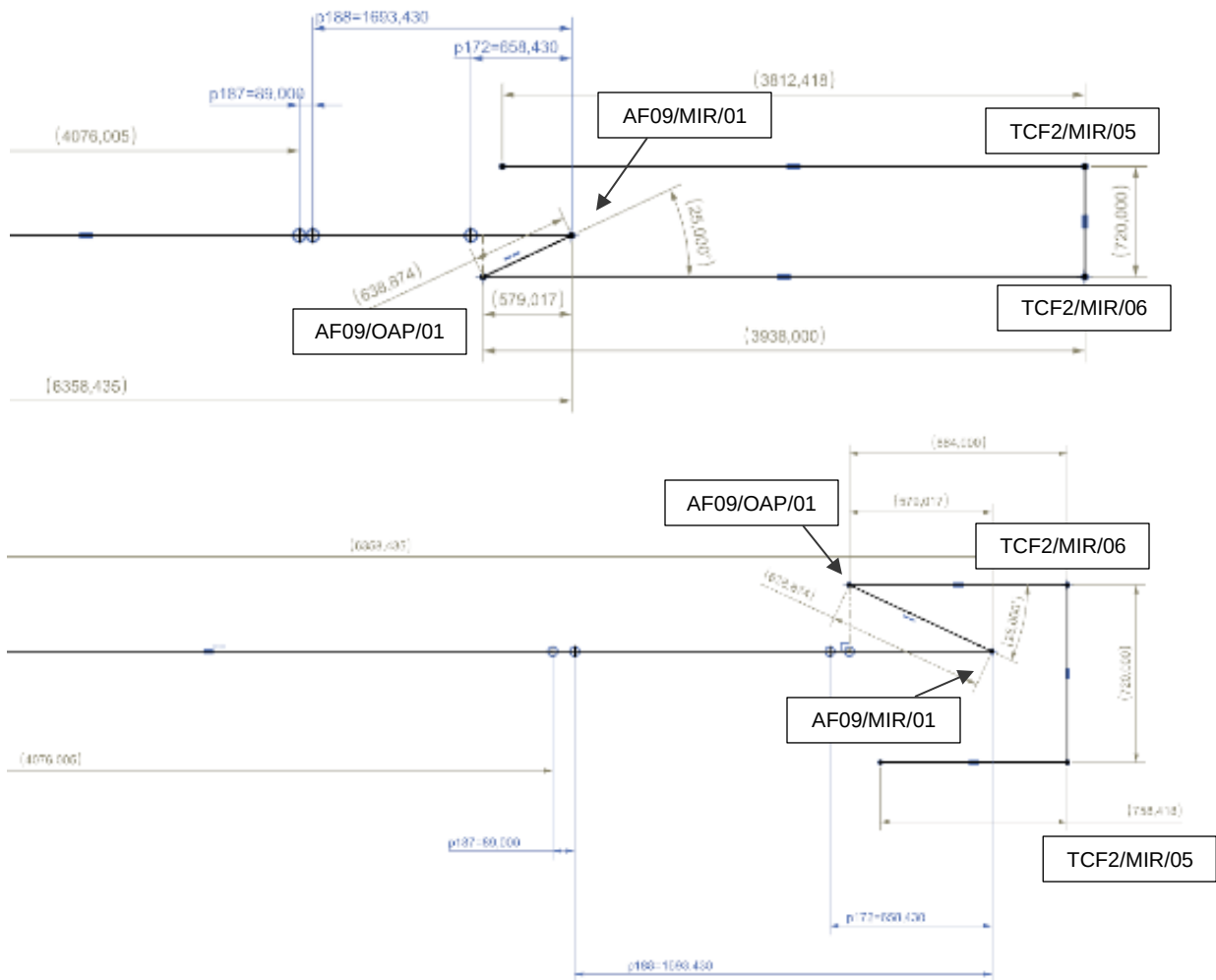


Figure 3: Views and distances between each optic on the beam path, from the entrance to the AF09 telescope, for maximum (on top) and minimum (at the bottom) time delays

3.2.2 Imaging calculations and magnification

For the AF09 telescope, the magnification is 1.

With apparent focal lengths, such as $F1=F2=4400$ mm, we project the Image of an Object located 10 cm before OAP1 at 8.7 m after OAP2, which brings the image in a plane located around the roof mirror position in the CPF2 compressor.

With this afocal system, which will be installed soon, we add an imaging transport distance of 17.6 m on F2 line.

3.2.2.1 Estimating average fluences on each transport optic

A study using ReZonator (Fig.5), a simple optical calculation software package, was carried out to estimate the distances between the optics and the beam diameter on each element, and then to deduce the average fluences, listed in the table below.

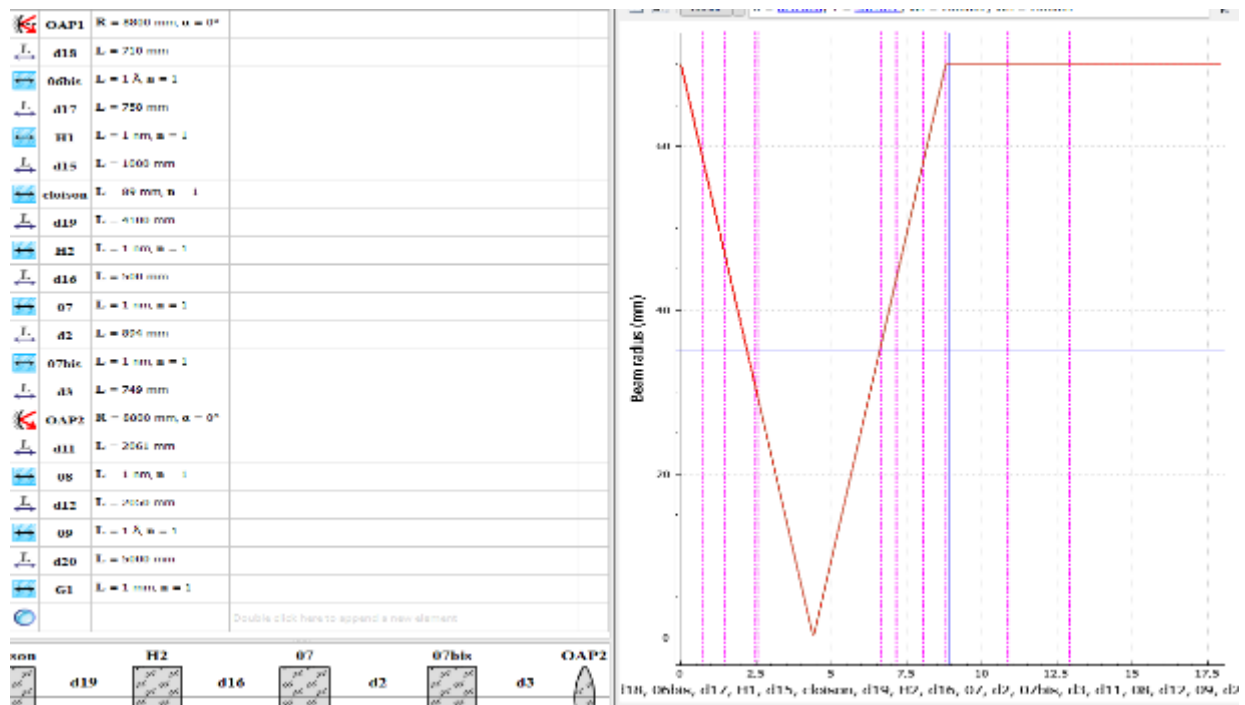


Figure 5: Screenshot of ReZonator software, with the list of all elements on the beam path (left) and the evolution of the beam diameter propagating on the F2 beamline.

From these diameters calculated for each optic, we can deduce the average fluences they experience, for an average input energy of 30J.

Table 1: Table of average fluences on optics at their angle of incidence (AOI)

Optic name	Type	AOI	Diameter at AOI (mm)	Optics dimensions (mm)	Average Fluence on the optic F_{mAOI} (J/cm ²)
TCF2/MIR/05	Mirror	45°	197,4	300x200	0,14
TCF2/MIR/06	Mirror	45°	197,4	300x200	0,14
AF09/OAP/01	Off-Axis Parabola	12,5°	143,4	Ø200	0,19
AF09/MIR/01	Mirror	12,5°	120,2	Ø152,4	0,26
H1	Window AR/AR coating	0°	93,2	Ø120	0,44
wall LAM/MPA	//	0°	61,4	//	//
H2	Window AR/AR coating	0°	71,8	Ø100	0,74
AF09/MIR/02	Mirror	45°	123,5	Ø203,2	0,35
AF09/MIR/03	Mirror	12,5°	119	Ø203,2	0,27
AF09/OAP/02	Off-Axis Parabola	12,5°	143,4	Ø200	0,19
TCF2/MIR/07	Mirror	45°	197,4	300x200	0,14

Remark: The average fluence estimated on the windows at the tube entrance and exit is low enough to set them at normal incidence, and the AR treatment is sufficiently robust (diameter almost twice as small on the window of the tube entrance of another afocal telescope, AF05, before in amplification stages, which has not yet been damaged in any way).

3.2.2.2 List and characteristics of optics

3.2.2.2.1 Off-Axis Parabola

3.2.2.2.1.1 Specifications

Characteristics	Value	Priority
Dimensions	Diameter: 200mm (± 1 mm)	P0
	Thickness: 30mm (± 1 mm)	P0
Minimum dimensions for polished and treated parts	Circular	P0
	Diameter: > 195 mm (± 1 mm)	P0
Dimensions of useful area	Circular	P0
	Diameter: ≥ 180 mm	P0
Position of useful area	Centered on the substrate with a tolerance of ± 1 mm on the input surface	P0
Angle of incidence (AOI)	$12,5 \pm 0,1^\circ$	P0
Off-Axis Angle (OAA)	$25 \pm 0,1^\circ$	P0
Polarisation	S	P0
Reflectivity spectral bandwidth	720 – 920 nm	P0
Minimum frontside reflectivity	$>99.5\%$ in the spectral band [740 nm-900 nm] over the entire useful area	P0
	$>99\%$ on spectral bands [720 nm-740 nm] and [900 nm-920 nm] over the entire useful area	P1
Average frontside reflectivity	$>99\%$ in the [740 nm-900 nm] spectral band over the entire useful area	P0
	$>99\%$ on spectral bands [720 nm-740 nm] and [900 nm-920 nm] over the entire useful area	P1
Group Velocity Dispersion (GVD) induced by the OAP	The dispersion will have a shape similar to that shown in the template in Fig. 8.	
	It will be at most within a peak-to-peak interval of ± 100 fs² over the 740 nm - 900 nm spectral band.	P0
	It will have a maximum peak-to-peak range of ± 200 fs² in the 720 nm - 740	P0

	nm and 900 nm - 920 nm spectral bands. • It will have a maximum peak-to-peak range of ± 100 fs ² in the 720 nm - 740 nm and 900 nm - 920 nm spectral bands.	P1
Roughness after coating	<2 nm	P0
Surface Quality	40/20	P0
Back side Surface finish	Ground polished	P0
Laser Induced Damage Threshold (LIDT)	>1 J/cm ² for the spectrum, pulse duration and firing rate to which the OAP will be under.	P0
Environment	Air - Room ISO7 20.5°C - humidity level 40%-60%.	P0
Apparent focus of the parabola	4400mm (tolerance $\pm 0.5\%$) <u>N.B.:</u> distance g on Fig. 9	P0
Off-Axis Distance (OAD)	392,5mm +/-4mm from the mirror center <u>N.B.:</u> distance h on Fig. 9	P0
Polishing technique	Manual methods. Avoid techniques such as Single Point Diamond Turning resulting in periodic polishing marks.	P0
Front-facing wavefront defect Measured with coating. Flatness values refer to the wave reflected on the useful zone, with the OAP in its specific mounting and working position.	$\lambda/10$ PtV @ 632nm on the useful area	P0

3.2.2.2.1.2 Results

Optical Surfaces, the OAP manufacturer chosen by the supplier Trioptics, obtained excellent results in terms of surface flatness (<40nm PV; <4nm RMS) before coating (Fig. 6).

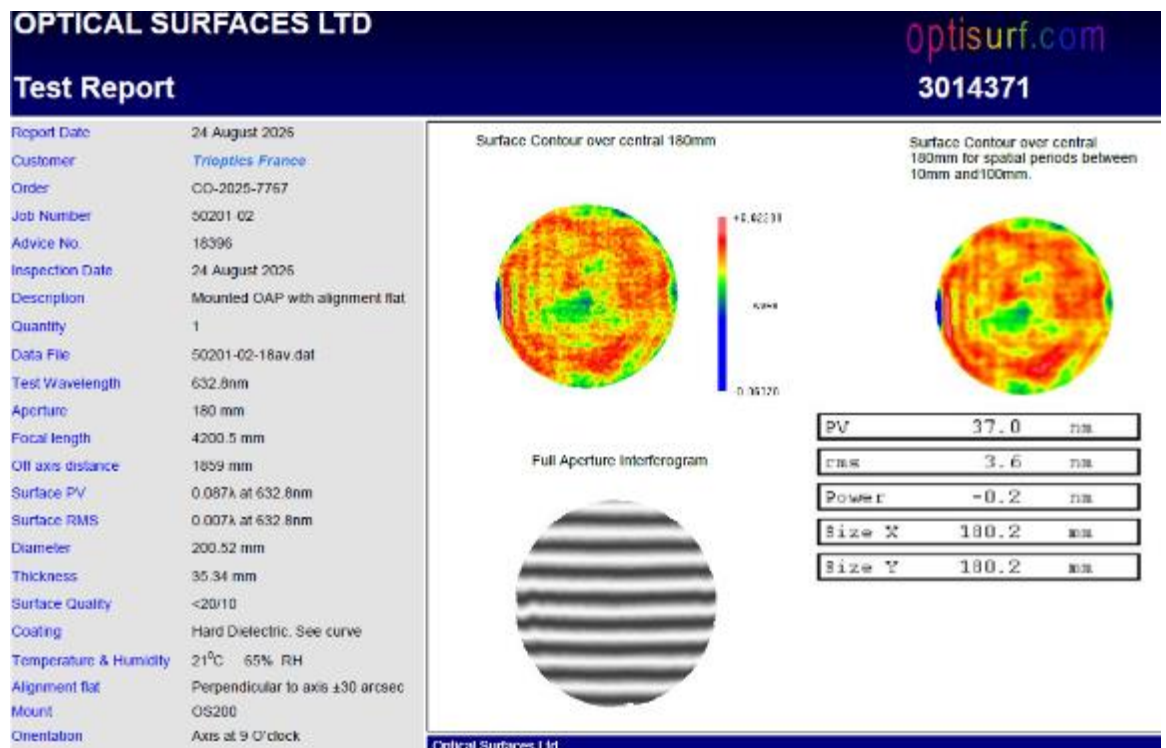
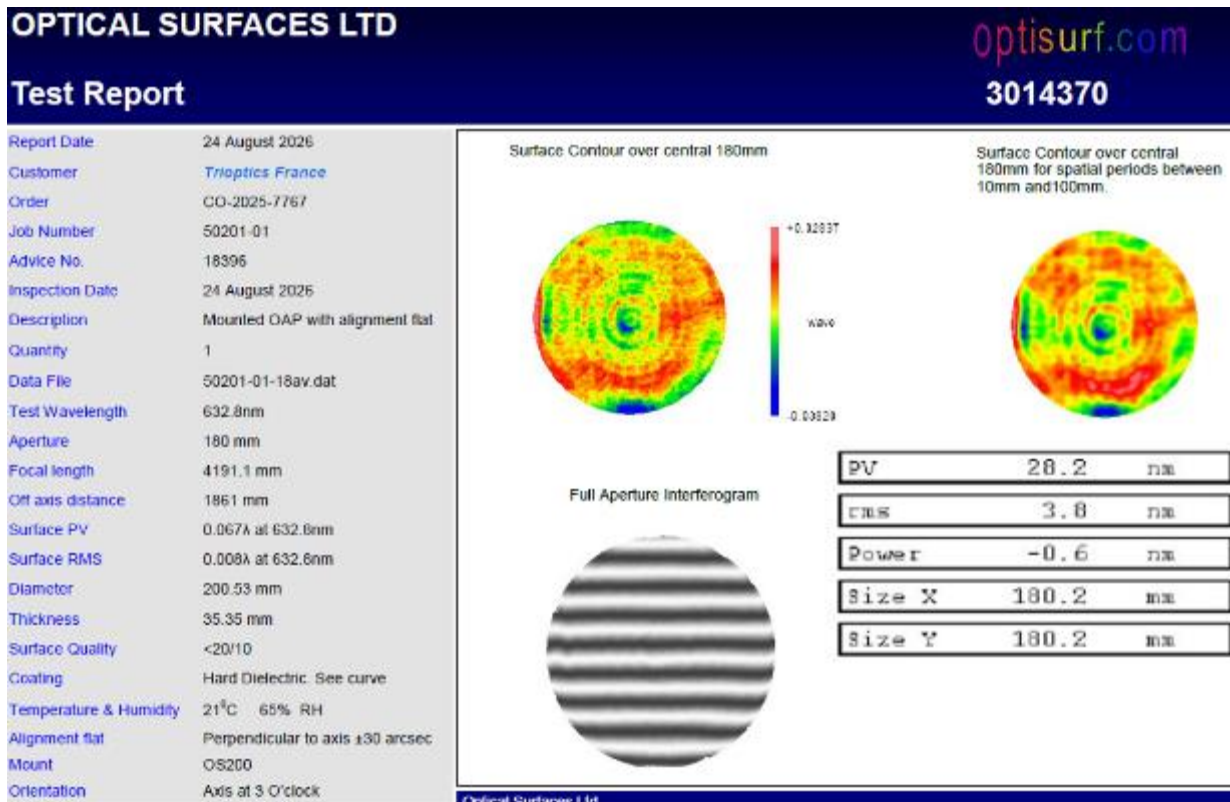


Figure 6: Surface flatness measured of the two parabolic mirrors before coating

After discussing with manufacturers, the best is to buy the 2 parabolas in their tip/tilt mounts (Fig. 7).

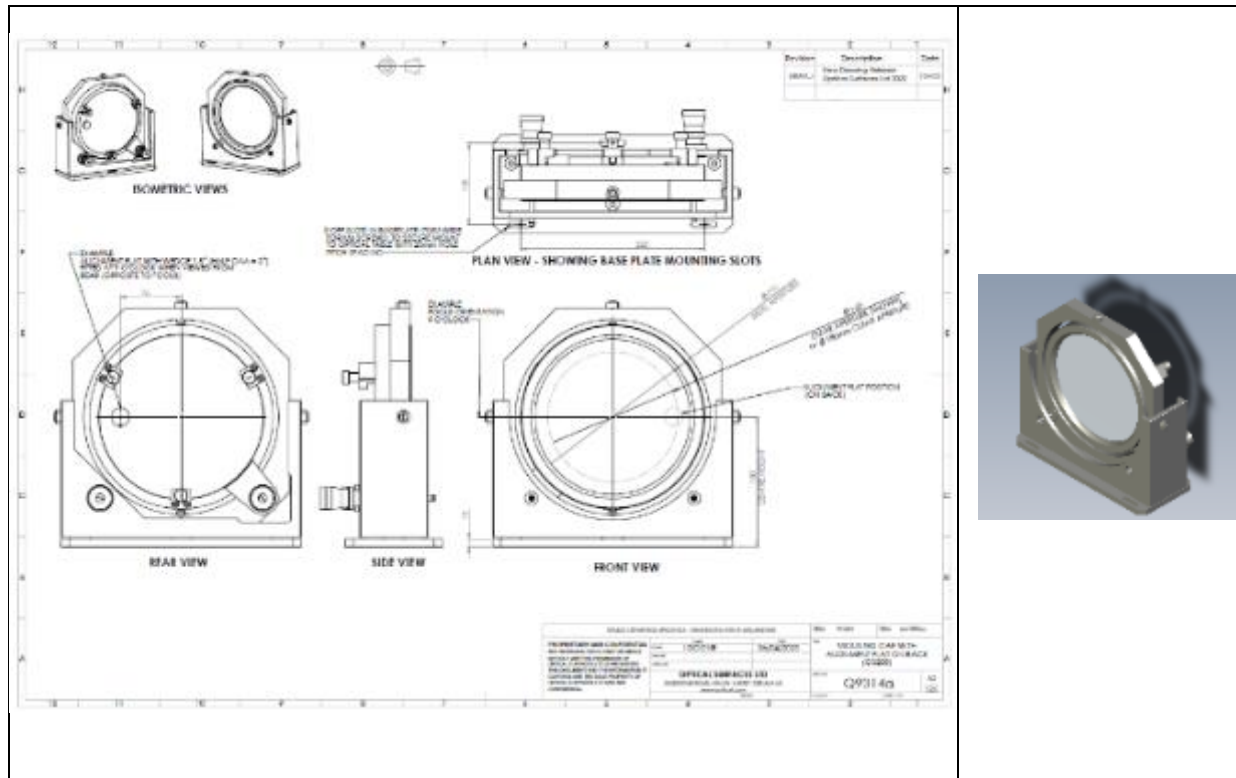


Figure 7: Typical parabola tip/tilt mount

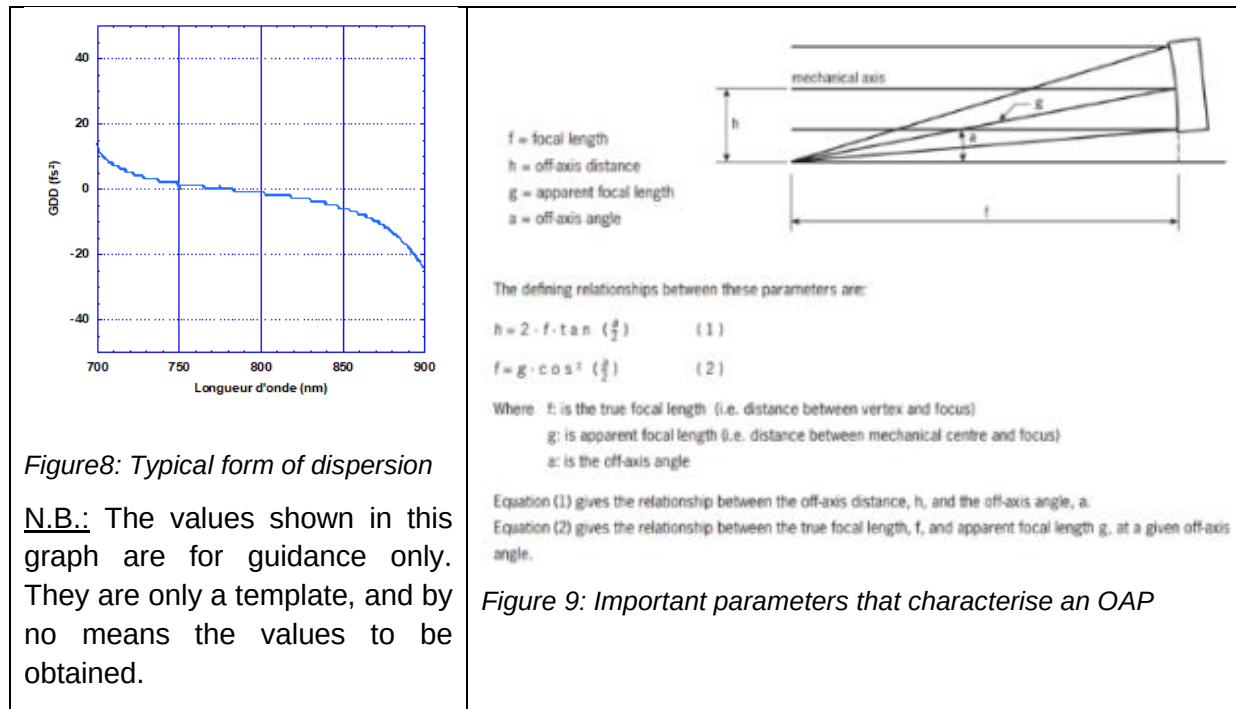


Figure8: Typical form of dispersion

N.B.: The values shown in this graph are for guidance only. They are only a template, and by no means the values to be obtained.

Figure 9: Important parameters that characterise an OAP

3.2.2.2.2 Transport mirrors

For the TCF2/MIR/06bis mirror, we need a 6-inch diameter mirror, with a high reflectivity $> 99,5\%$ at AOI $12,5^\circ$, which will hold an average flux $> 0.8\text{J}/\text{cm}^2$.

For the TCF2/MIR/07 and 07bis mirrors, we anticipate a potential upgrade - to enlarge the beam diameter from $\phi 140$ to $\phi 160$ at the entrance of the compressor, to send more energy, without the risk of damaging the first grating, to potentially increase the energy on the target for the 1PW beam line - and install 8" mirrors directly, with a high reflectivity $> 99,5\%$ at AOI $12,5^\circ$, which should also hold $> 0.8\text{J}/\text{cm}^2$.

High power IAD mirrors from Laser Components, already implemented and tested on the laser line, will be used (Fig. 10).

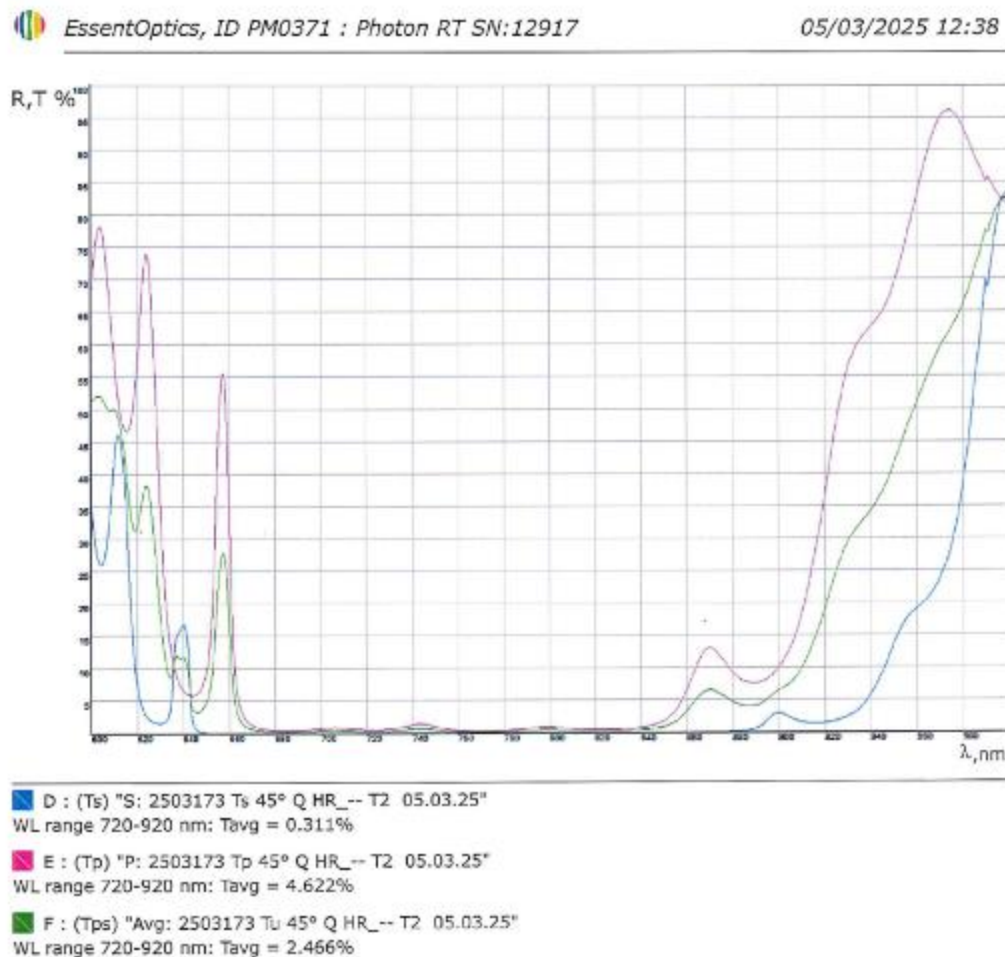


Figure 10: Reflectivity spectral bandwidth measured of the Laser Components IAD mirrors

OWIS 6-inch commercial mounts will be used.



Figure 12: TRANS100 6- inch mirror mount form OWIS

The TCF2/MIR/07bis mirror mount must include a plate along the axis of the reflected beam, with a minimum stroke of 40cm (+ or - 20cm), to compensate for the telescope's tolerances, bearing in mind that the apparent focal lengths of the two OAPs are specified in the CCTP to an accuracy of $\pm 5\text{cm}$ ($\pm 0.5\%$). This means that the angle of incidence on OAP2 remains unchanged.

To re-center the beam on TCF2/MIR/07bis, TCF2/MIR/07 can be tilted slightly to re-center it in relation to the beam.

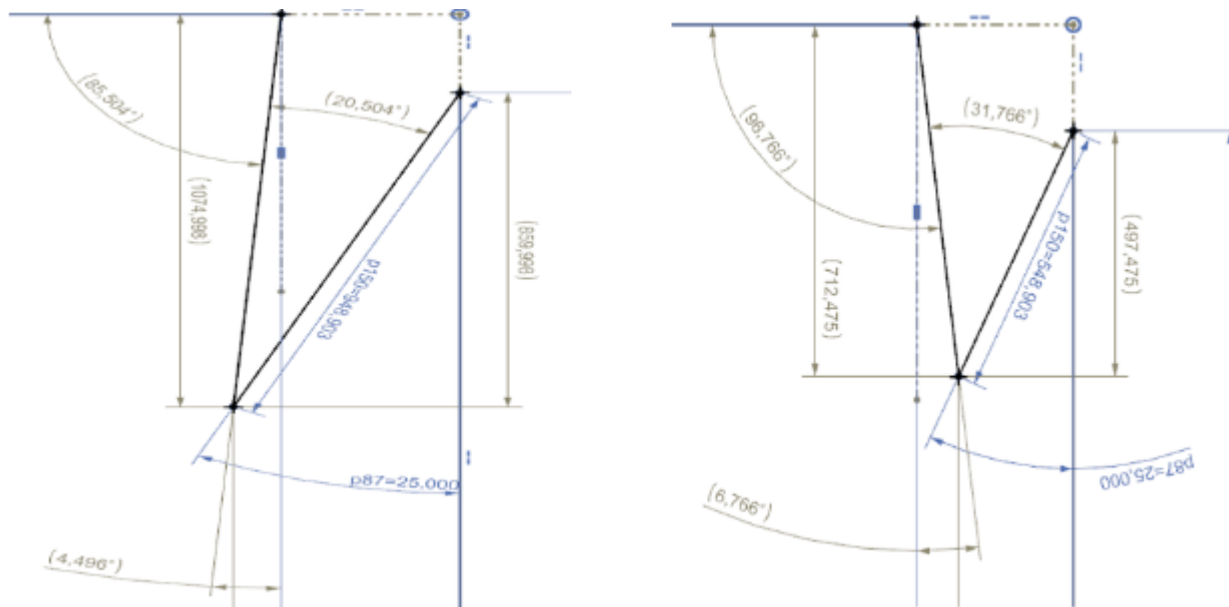


Figure 32: Beam path for a TCF2/MIR/07bis displacement on the stage of + or - 20cm

3.2.2.2.3 Laser windows for the telescope tube

With an average fluence $< 1\text{J}/\text{cm}^2$ at the entrance and the exit of the telescope tube, we need 2 windows with an anti-reflection coating [700-900] nm on both sides for AOI 0° , with a diameter

of 160mm, adapted to the dimensions of the vacuum tube of the telescope that we have already in stock.

3.2.2.3 F1/F2 synchronization management

The experimental users asked for the possibility of having F1 and F2 beams arrive at each of the SFA and LFA targets (config 3, 6 and 9m) with the possibility of desynchronizing them by $\pm 5\text{ns}$. This requirement necessitated the integration of a 3m long delay line (Fig.13) when we designed the F2 line.

A time measurement with a photodiode in SFA room, close to the target position, showed that F2 arrives 3 ns ahead of F1, corresponding to a current F1 optical path 0.9 m longer than F2.

Compared with the current situation, the installation of the AF09 telescope, according to figure 12 below, adds a length of 2600 mm to the path of F2, with the result that F2 becomes 1.7 m longer than F1, under current LRO conditions, in the minimum position as installed.

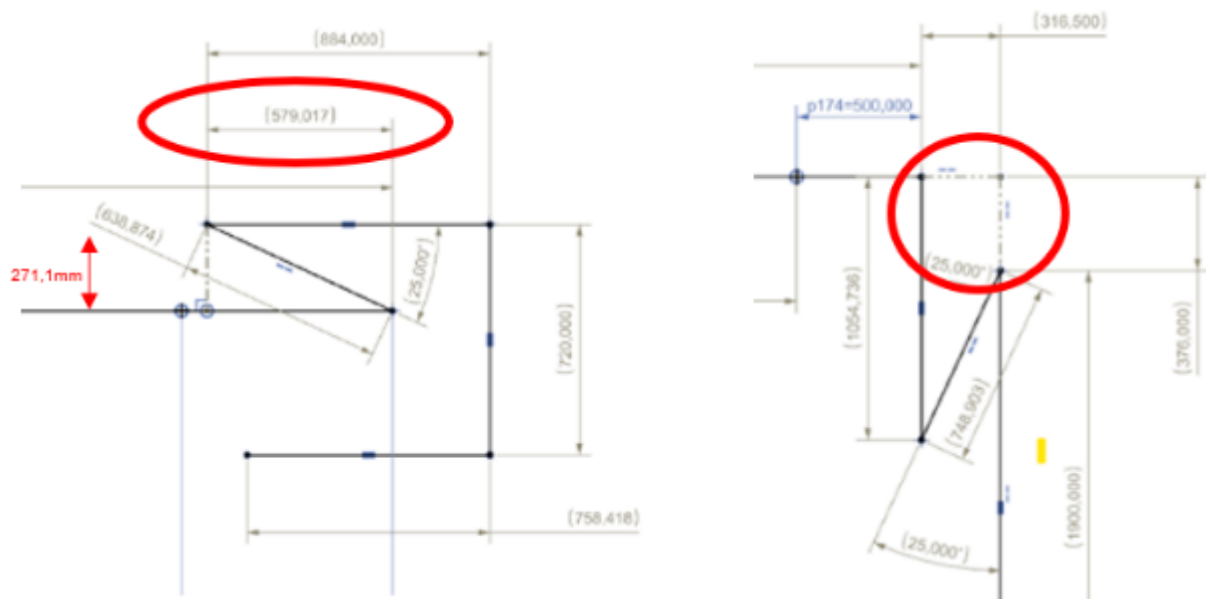


Figure 4: Optical path differences between the current version and the addition of the AF09 telescope

Integrating the AF09 system, the LRO gear has been moved by 760 mm so as to reduce the optical path length of F2 by 1.52 m; in the minimal LRO configuration, F2 arrives 1,15ns before F1, which still poses a problem.

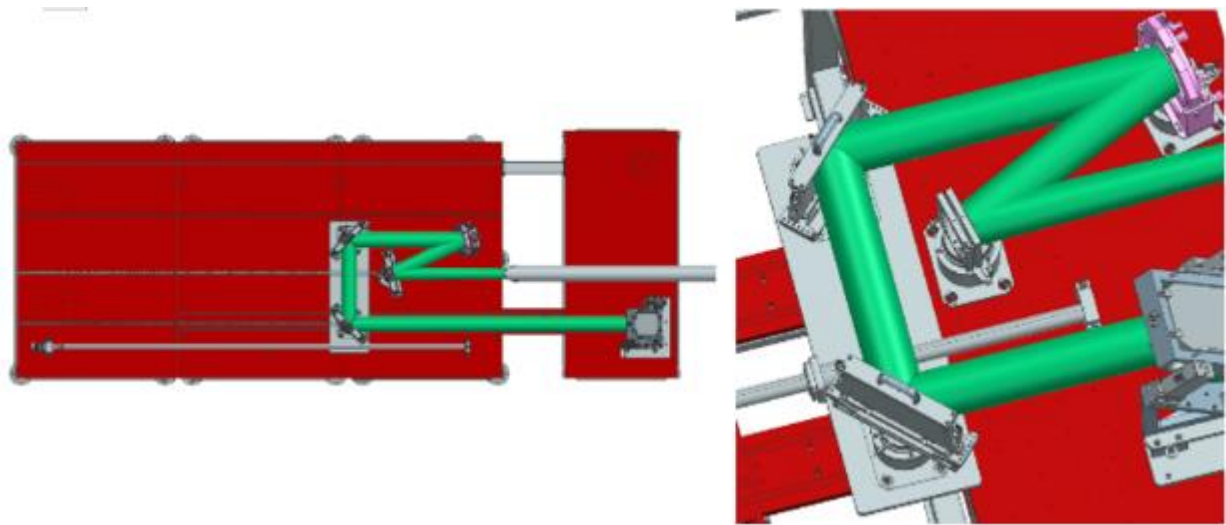


Figure 5: 3D views illustrating the worm screw's offset between its current position (left) and its position once the AF09 afocal has been installed (right).

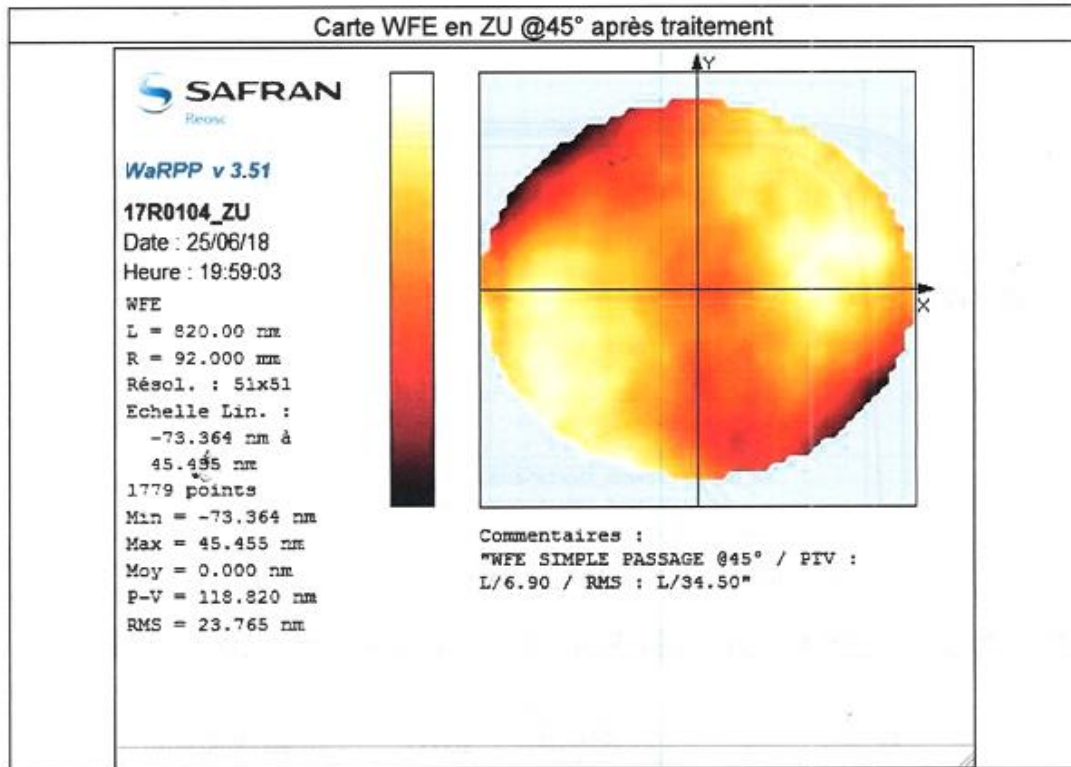
It becomes clear that we need to lengthen F1's optical path to be able to synchronize F1 with F2 to within + or - 5ns.

To achieve this, a chicane can be created by adding 2 mirrors just before the AF08 telescope, which transport the F1 beam from the beam separation area to the compressor CPF1. Here, we could extend F1 by $3144+345 \approx 3500$ mm, so that the intermediate position of the LRO corresponds to synchronization of F2 with F1. In this way, we could desynchronize F2 with

respect to F1 over a range of + or - 10ns.

ARTHEMIS 300x200mm² mirrors from SAFRAN REOSC, already implemented in the Apollon beam transport and supporting the nominal laser fluence of 1J/cm² will be used.

Figure 6: Wavefront map of ARTHEMIS mirror



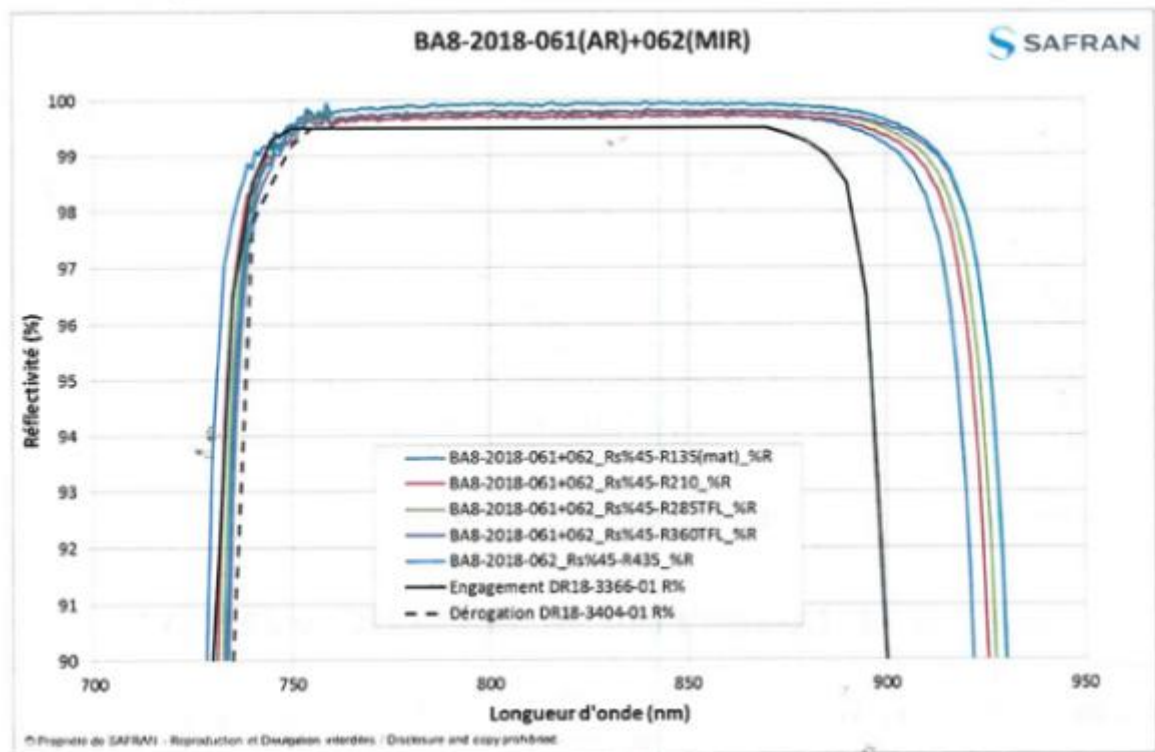


Figure 7: Reflectivity spectral bandwidth of ARTHEMIS mirror

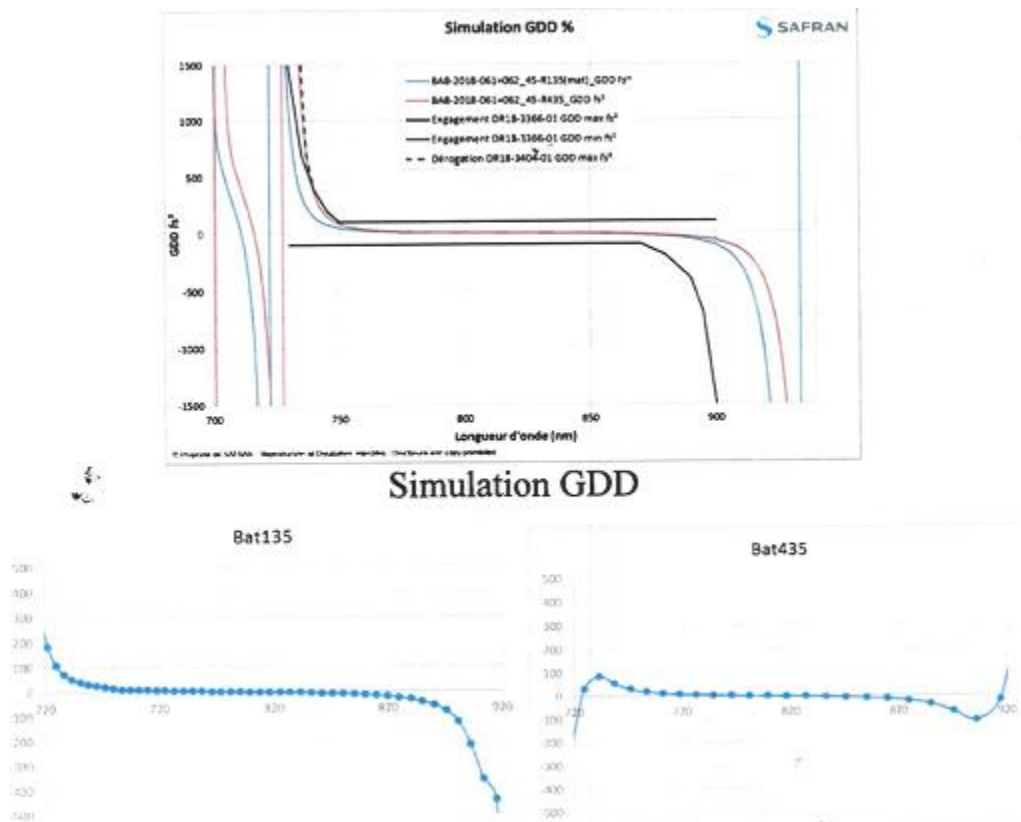


Figure 8: Simulation and measured GDD of ARTHEMIS mirror

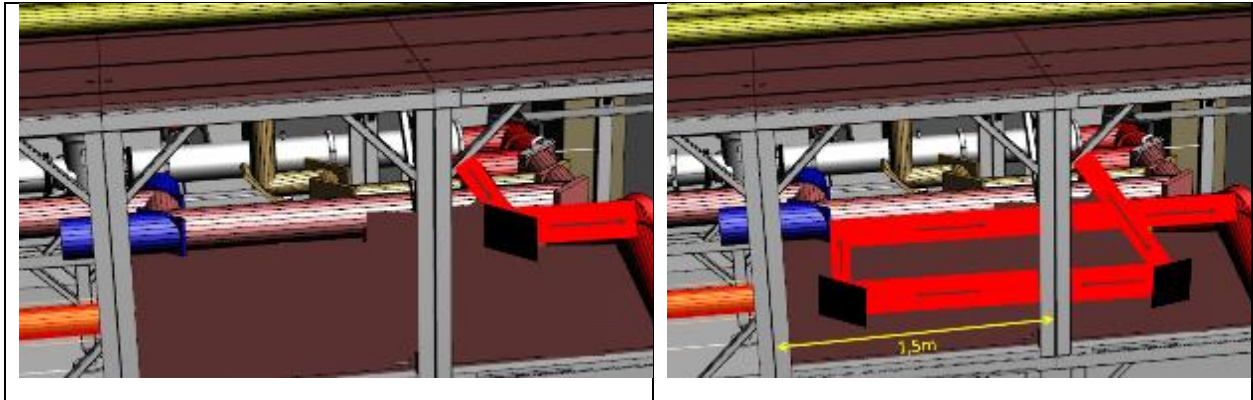


Figure 9: F1 optical path extension: current (left) and planned (right) configurations

3.3 The AF09 telescope alignment

3.3.1 Design of a Compact, Collimated Class 1 Laser Source

We have specifically constructed a compact and collimated Class 1 laser source that delivers 20 mW in the visible spectrum at 705 nm, with a 100 mm diameter beam. The setup consists of a single-mode fiber-coupled laser diode and a 4-inch diameter parabolic mirror (Angle of Incidence (AOI) = 0°) with an effective focal length of 440 mm.

The entire system is contained on a 600 x 300 mm² breadboard, providing a 100 mm diameter visible laser beam for enhanced alignment ease and safety, along with excellent spatial beam quality (Fig. 18).

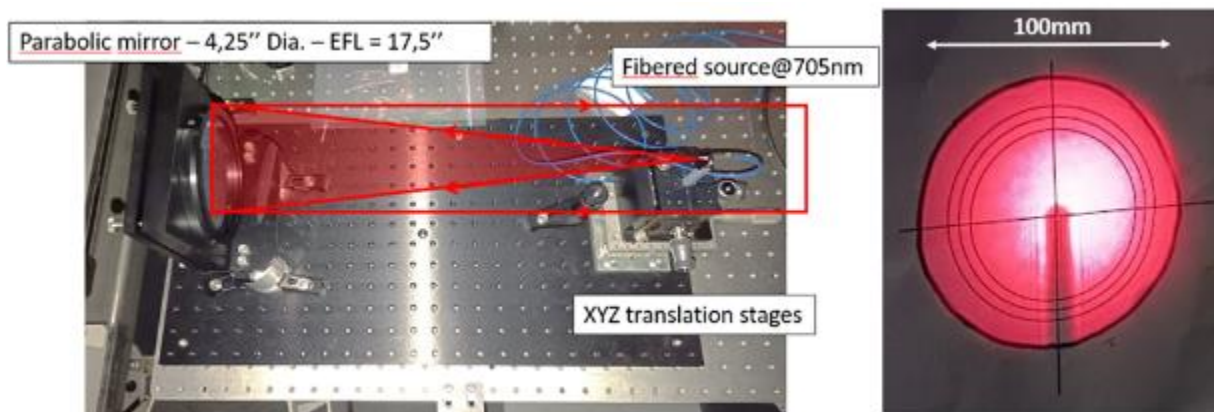


Figure 10: Alignment Class 1 laser source collimated setup (left) and beam profile after 15 m propagation (right).

The parabola was precisely aligned using a spherical mirror with a 9 m focal length to achieve

a well-defined focal spot, approximately 1.2 times the diffraction limit. Remaining wavefront errors are attributed to two low-quality flat mirrors used as turning mirrors during these tests.

These mirrors will be replaced, and further optimization of the setup will bring us closer to an "ideal" reference beam, as required for the alignment of the AF09 telescope.

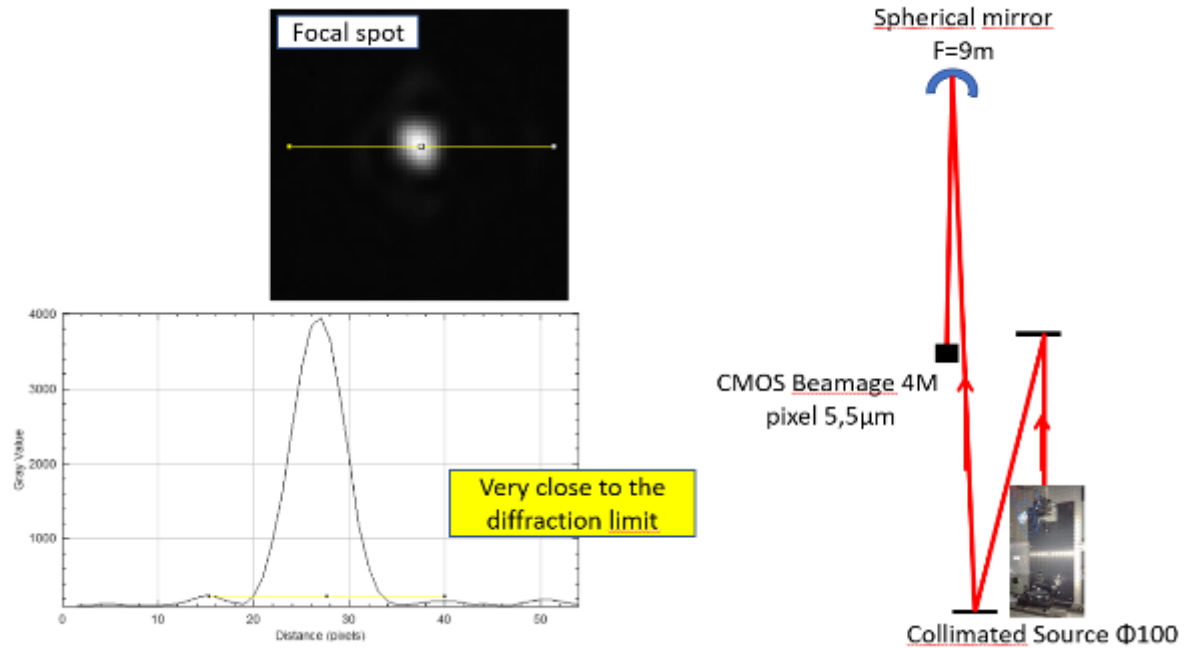


Figure 11: The setup we used to align our collimated alignment source.

3.3.2 Alignment procedure

The alignment procedure addresses two primary objectives. First, a perfectly aligned afocal system is necessary to produce a collimated output beam with minimal induced aberrations, thus preserving optimal spatial beam quality. Second, the beam must enter the 1 PW F2 compressor at the correct angle to ensure efficient pulse compression without requiring re-optimization of the compression.

Initially, the compressor input axis will be materialized using two widely spaced mechanical crosses.

Firstly, the laser source will be injected in the beam separation area (Fig. 20) and the beam will be directed to the first OAP. We will start with obtaining the autocollimation adjusting the tip/tilt actuators of the parabola mount and determining the corresponding angle indicated on the turntable scale. Once this step is done, we will turn the parabola mount to its working angle ($12,5^\circ$). The focal spot will then be optimized by adjusting the tip/tilt actuators of the parabola mount, correctly passing through the two crosses. Once this step is complete, a pinhole, with a

hole diameter of $75\ \mu\text{m}$ well-adapted to the focal spot size we expect to be close to the diffraction limit ($\approx 100\ \mu\text{m}$ for $1,2 \times \text{LIDT}$), will be positioned at the focal spot as an axis reference. A camera with an objective ($\times 20$) will be placed immediately after the focal spot at the appropriate position, so that the pinhole is imaged onto it.

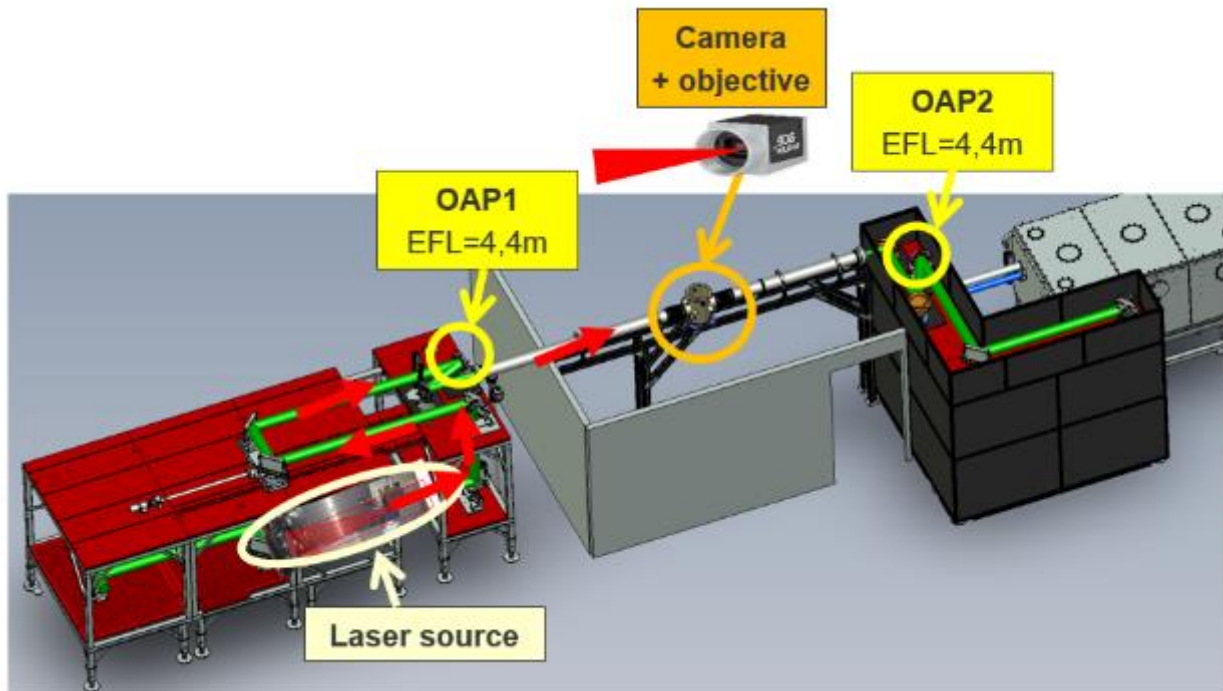


Figure 12: Scheme for the first steps of the AF09 alignment procedure with the laser source injected at the entrance of the F2 line

Subsequently, the alignment laser source will be relocated just at the entrance of the compressor (Fig. 21) and the beam will be directed back to the afocal system. We will follow the same steps to tune the second parabola.

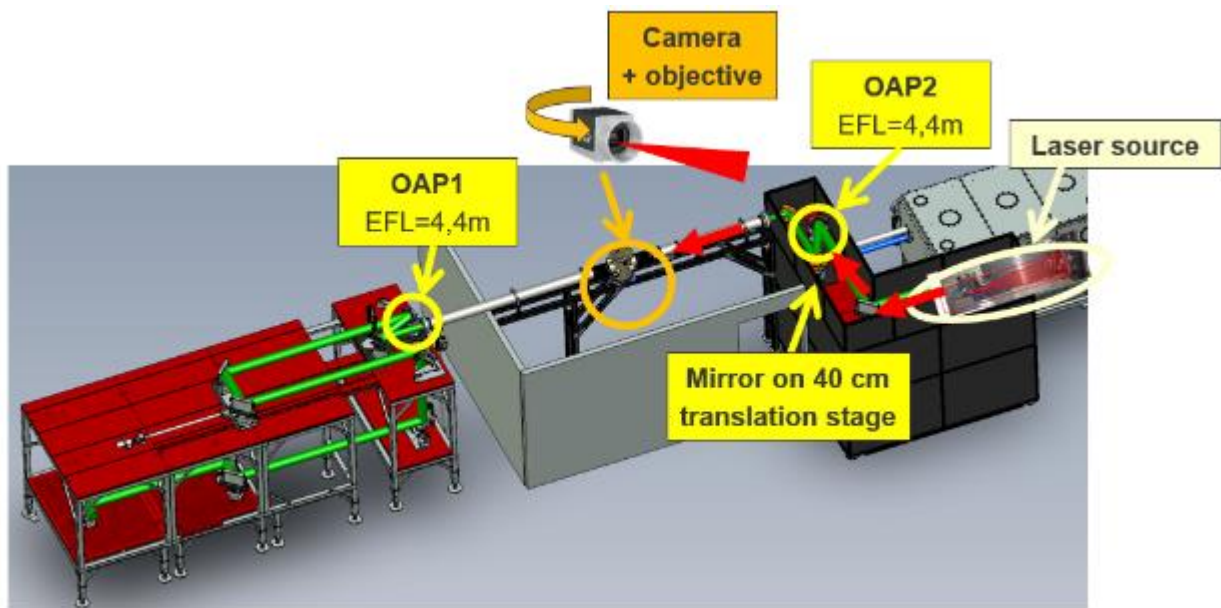


Figure 13: Scheme for the second steps of the AF09 alignment procedure with the laser source injected back to the afocal system

At the end, we will overlay the two focal spots on the pinhole, adjusting the distance between the two parabolas acting on the translation stage, in the direction of the reflected beam axis, of the mirror before the second parabola.

Following these steps, we can be sure that the afocal system is perfectly aligned and we must not modify the OAPs and/or mounts tuning with the Apollon beam passing through our alignment mechanical references, even if beam aberrations are detected at the afocal system output. If this particular case happens, it signifies that one or several optics on beam transport have bad spatial quality.

4 Blueprint for the Partner Laser Facilities

Based on the experience gained during the design and development of the Apollon beam transport system, we have developed preliminary beam transport concepts for our partner facilities. These proposals were established using the technical requirements and constraints provided by each partner for their future laser infrastructures.

4.1 Blueprint of an achromatic reflective beam transport for ELI Beamline

4.1.1 ELI Beamline Facility

For the ELI Beamlines L4 beamline, no achromatic reflective beam transport has been proposed because the current facility layout leaves virtually no margin for implementing such a system. The L4 beam has a very large cross-section ($650 \times 650 \text{ mm}^2$), and recent installations along the beam transport have occupied the remaining available space, making the integration of additional optics impossible. Furthermore, the existing 90° steering mirrors, with a 1200 mm diagonal, already operate close to their maximum usable aperture, leaving no possibility to increase the beam diameter. Reducing the beam size is also not an option, as operational experience has demonstrated that the laser-induced damage threshold (LIDT) safety margin is already very limited on the transport optics. Similarly, the existing 1 m diameter vacuum beam pipes constitute a hard geometrical constraint that cannot accommodate larger optical components.

Considering these optical, mechanical, and operational constraints, no alternative achromatic reflective beam transport design was developed for the ELI Beamlines facility.

4.2 Blueprint of an achromatic reflective beam transport for EuXFEL laser facility

4.2.1 Introduction

The present study deals with achromatic transport solutions we propose for the future EuXFEL fusion project. They need several telescopes for the transport and beam size matching for the compressor of a square beam of $200 \times 200 \text{ m}^2$, such as:

- Beam parameters:
 - Energy: up to 2 kJ
 - Wavelength: 1053 nm, up to 20 nm bandwidth
 - Pulse duration: 2-20 ns (2kJ at $\sim 5 \text{ ns}$)

- First telescope:
 - Magnification: 1
 - Transport distance: around 60m
 - Spatial filtering at the focus
- Second telescope:
 - Magnification: 1,75
 - Transport distance: around 10m
 - No spatial filtering

Furthermore, we have to take into account the laser lines and the facility constraints, as illustrated by Figure 24 below.

At this stage in the system design, several parameters have not yet been finally determined, which explains why we weren't able to go into more detail.

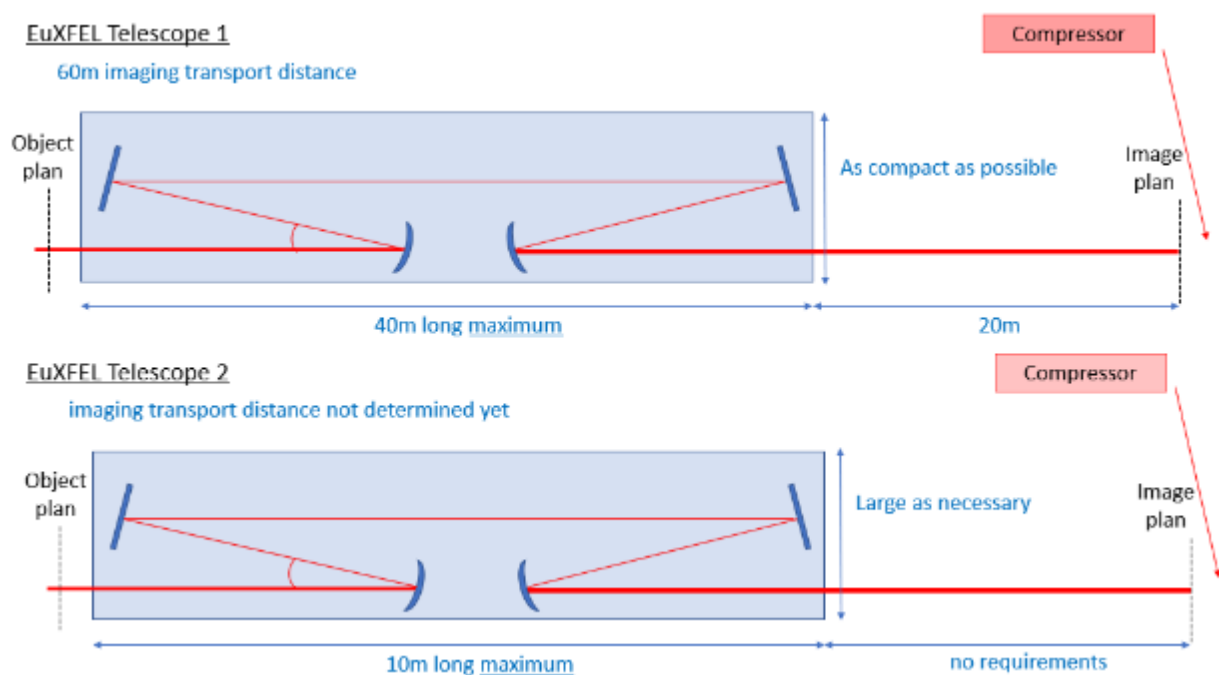


Figure 14: Requirements and facility constraints for the two telescopes design

4.2.2 Proposals

4.2.2.1 Telescope 1

We are looking for an achromatic solution to transport an uncompressed laser beam (5ns pulse duration), with a 20nm bandwidth, that means that it wouldn't be necessary a reflective solution.

Indeed, the easiest and cheapest achromatic solution could be an achromatic lenses afocal system.

4.2.2.2 Study for an achromatic lenses afocal system

We want to design a couple of singlets to get a focal length of 15 m without chromatism.

We choose N-BK7/SF11 as couple Crown/Flint to design our achromatic doublet, materials employed usually and compatible with the wavelength (1020nm) and we calculate the different radius of curvature, opting for the simplest configuration, it means bi-convex / plan-convex.

We use the Zemax software (Fig. 16) for the design of the two identical achromatic doublets (Fig. 15) to get the desired afocal system, respecting the parameters we calculated previously, then we start an optimization to reduce achromatism and aberrations.

We get the following design for the couple of singlets, assembled with a 2-mm gap.

RADIUS	RAD TOL	IRR TOL	C.A. DIA	EDGE DIA	MATERIAL	THICK	THI TOL
9167.3400 CX	1830.74	0.0	200	400.0000	N-BK7	10.0000	10
9167.3400	-2312.415	0.0	200	400.0000		2.0000	2
17512.006	-2749.696	0.0	200	400.0000	SF11	5.0000	8
102591.64 CC	6611.557	0.0	200				

1. All dimensions in Millimeters
2. Material per MIL-G-174
3. Pitch polish to test plate within power and irregularity indicated.
4. Manufacture per MIL-O-13830
5. Bevel Edges at 45 DEG to 1 mm max face width



TITLE			
DATE	SCALE	DRAWN	APPROV
20/03/26	1:5	Fréneaux, A	
PROJECT			
Temporary AF09 - Apollon - LULI			
DESIGNER		REVISION	
Doublet 1			

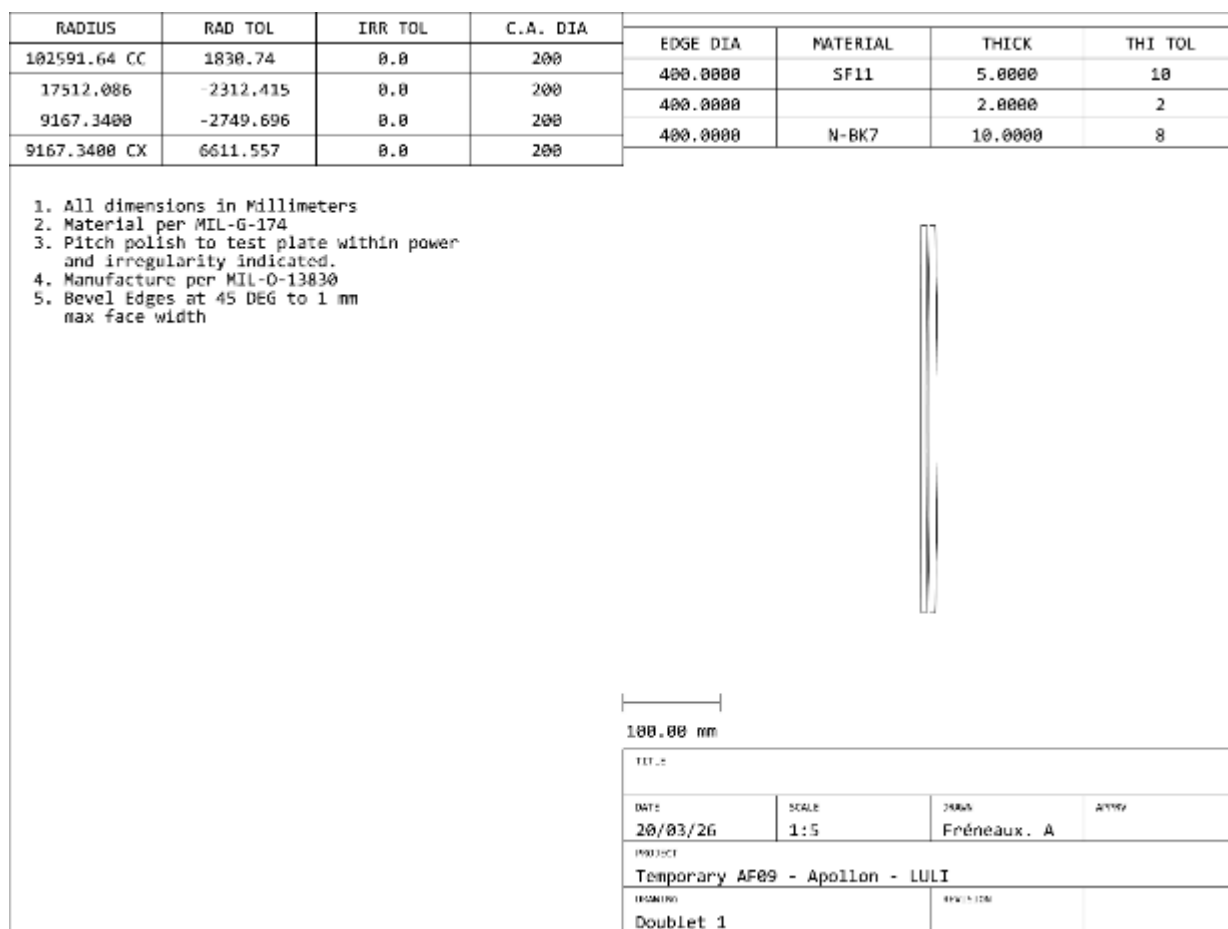


Figure 15: Technical Drawings of the first (on top) and second (on the bottom) doublet of the telescope 1

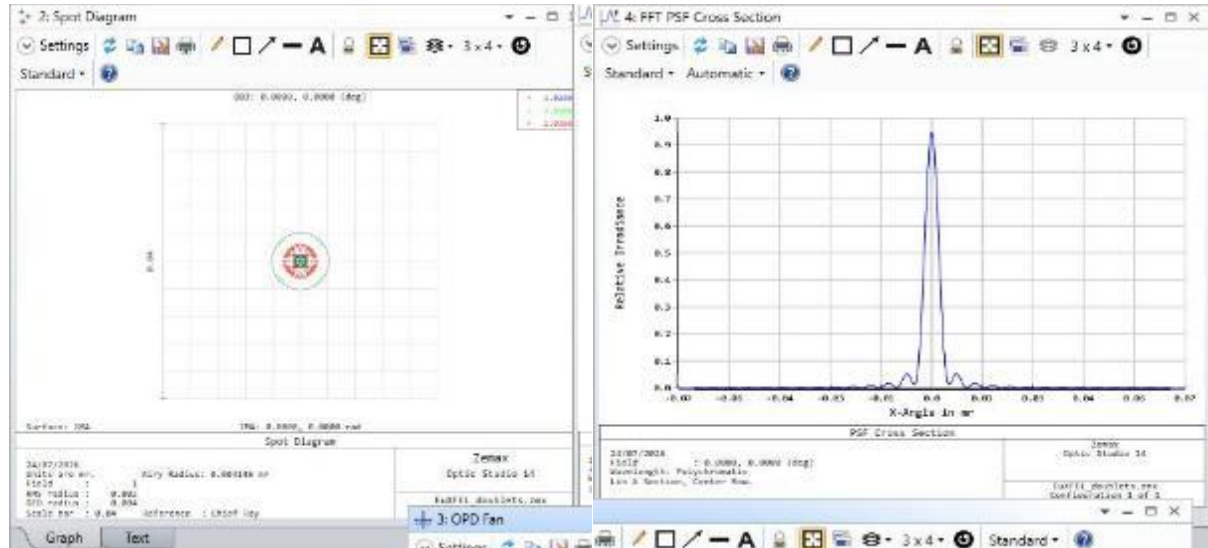
In the table below, the complete Zemax design of the achromatic lenses for the afocal system is shown. The obtained results in terms of spatial beam quality, we will compare with alternative proposals.

Lens Data

Surface 6 Properties Configuration 1/1

	Surf.Type	Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Conic	TCE x 1E-6
0	OBJECT Standard		Infinity	Infinity			0.000	0.000	0.000
1	STOP Standard		Infinity	300.000			150.000	0.000	0.000
2	(aper) Standard		Infinity	200.000			100.000 U	0.000	0.000
3	(aper) Standard	L1	9167.340	10.000	N-BK7		200.000 U	0.000	-
4	(aper) Standard	L1 (2mm air)	-9167.340	2.000			200.000 U	0.000	0.000
5	(aper) Standard	L2	-1.751E+004	5.000	SF11		200.000 U	0.000	-
6	(aper) Standard	L2	1.026E+005	1.465E+004			200.000 U	0.000	0.000
7	Standard		Infinity	3917.202 V			17.673	0.000	0.000
8	Standard		Infinity	1.465E+004			17.736	0.000	0.000
9	(aper) Standard	L1	-1.026E+005 P	5.000	SF11		200.000 U	0.000	-
10	(aper) Standard	L1 (2mm air)	1.751E+004 P	2.000			200.000 U	0.000	0.000
11	(aper) Standard	L2	9167.340 P	10.000	N-BK7		200.000 U	0.000	-
12	(aper) Standard	L2	-9167.340 P	1464.836			200.000 U	0.000	0.000
13	Standard		Infinity	1.000E+004			150.095	0.000	0.000
14	IMAGE Standard		Infinity	-			150.032	0.000	0.000

Figure 16: Lens data table used to simulate the telescope 1 in ZEMAX software



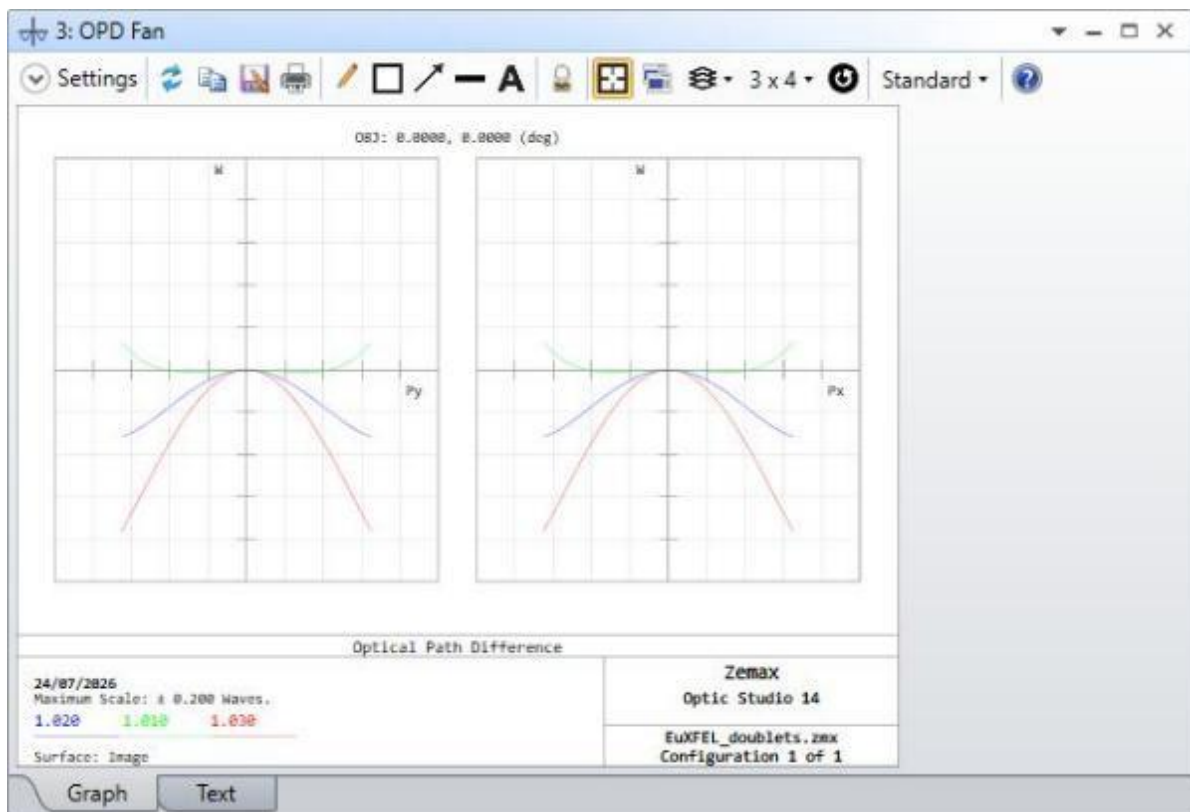


Figure 17: Different analyses on ZEMAX software: Spot Diagram and FFT PSF Cross section (on the top), OPD Fan (on the bottom)

The Spot Diagram simulation we obtained shows excellent results with the totality of rays of all wavelengths contained in the Airy spot at focal plan. We got a nice FFT PSF Cross Section with a central peak containing ~94% of the total energy (Fig.17).

The OPD Fan diagram shows that the afocal system we designed is achromatic because the curves of the three different wavelengths intersect at the center, are symmetrical about the central axis and because the vertical spacing between these curves is $< \lambda/4$, where λ is the center wavelength (Fig.17).

We could improve these results, using triplets but this study hasn't been done.

4.2.2.3 Study for using spherical mirrors in the afocal system

As a next step, we investigate if we can improve the lens-based results by using spherical mirrors in the afocal system, taking into account an angle of incidence as small as laser beam parameters and facility constraints make it possible.

For these two spherical mirrors (SM), we could opt for a focal length $F_1=F_2=F= 35\text{m}$.

Considering the available distance of 40 m, we could imagine a configuration like in the figure 18 below, using two spherical mirrors (SM) with a focal length $F_1=F_2=F=35\text{m}$ and an angle of total reflection on SM of 2° , the minimal angle compatible with optics dimensions.

This afocal telescope makes a transport distance of about 140 m possible, compared to 60 m for the solution using achromatic lenses.

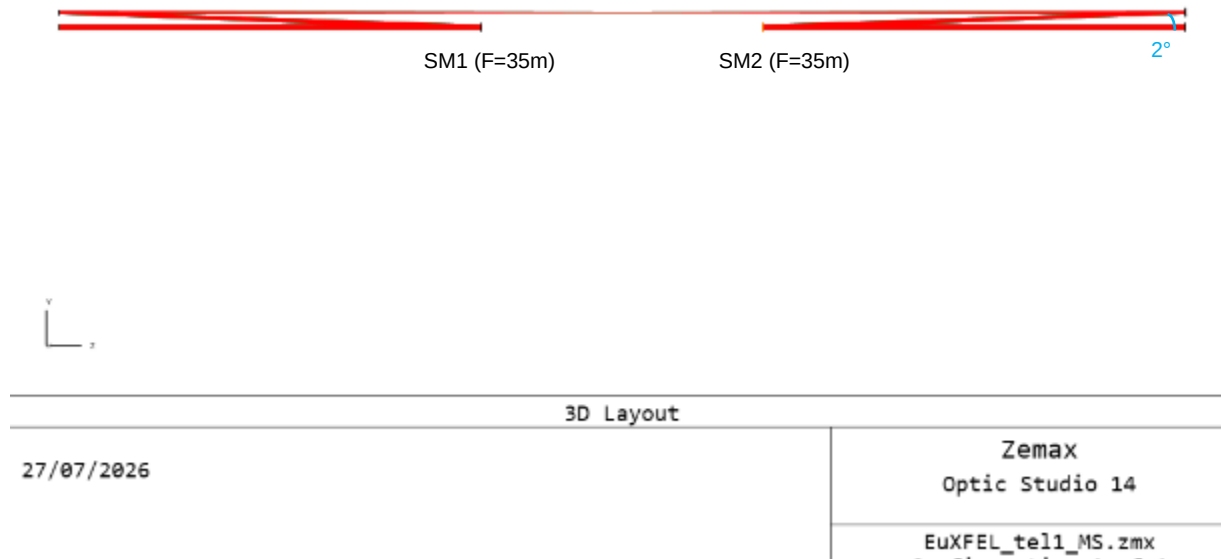


Figure 18: Folded afocal system proposition for the telescope 1 with spherical mirrors

In the table below (Fig. 19), the complete Zemax design of the spherical mirrors for the afocal system is shown together with obtained results in terms of spatial beam quality.

SurfType	Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Conic	TCE x 1E-6	Par 1(used)	Par 2(used)	Par 3(used)	Par 4(used)	Par 5(used)	Par 6(used)
0	OBJ/ELI	Infinity	Infinity			0.000	0.000	0.000						
1	Input	Infinity	1.500E-004			150.000	0.000	0.000						
2	Input mirror	-1.000E+000	-1.500E+000	MR802		150.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	Coordinate Break	0.000				0.000			0.000	0.000	0.000	0.000	0.000	0.000
4	Input	Infinity	2.000E-004	MR802		80.719	0.000	0.000						
5	Input	Infinity	1.000E-004			100.000	0.000	0.000						
6	Coordinate Break	0.000				0.000			0.000	0.000	0.000	0.000	0.000	0.000
7	Input	Infinity	1.500E+000	MR802		150.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	Coordinate Break	0.000				0.000			0.000	0.000	0.000	0.000	0.000	0.000
9	Input	Infinity	1.500E-004	MR802		150.000	0.000	0.000						
10	Coordinate Break	0.000				0.000			0.000	0.000	0.000	0.000	0.000	0.000
11	Output	Infinity				150.000	0.000	0.000						

Figure 19: Lens data of the telescope 1 with spherical mirrors in ZEMAX software

We have estimated, with an input average energy of 2kJ, a reasonable laser fluence of about $0,6\text{J}/\text{cm}^2$ on the two mirrors inside the afocal telescope.

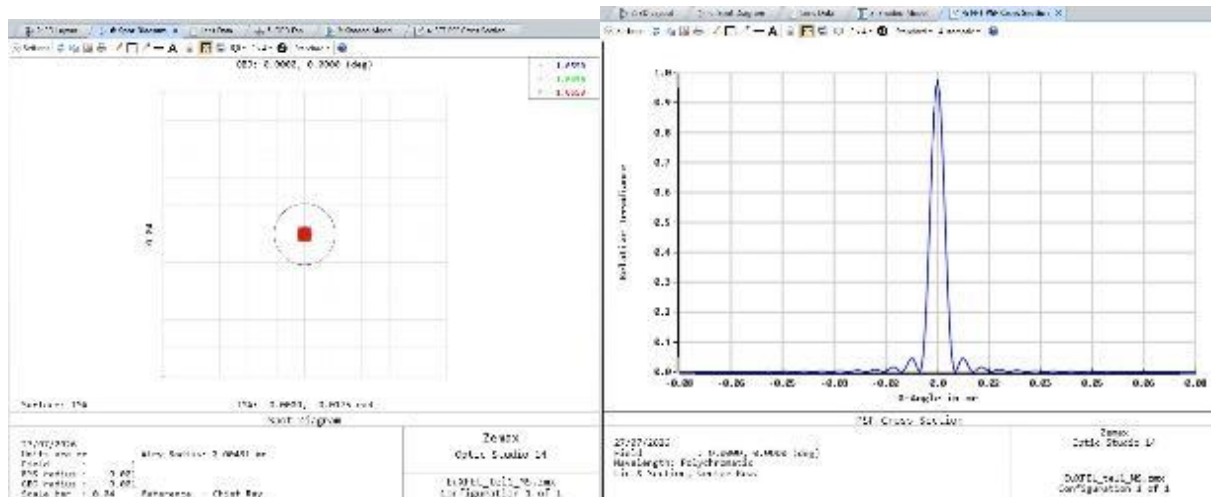


Figure 20: Zemax data and results for the telescope 1 with the spherical mirrors solution: Spot Diagram (on the left) FFT PST Cross Section (on the right)

With the spherical mirrors solution, we significantly improved the laser beam quality and obtained nice results, notably by decreasing the size of the focal spot by a factor of 2 (Fig. 20, left), which could be very interesting if we want to do spatial filtering.

We improved slightly the FFT PSF Cross Section with a central peak containing almost all of the energy.

4.2.2.4 Study for an Off-axis parabolas afocal system

We now investigate the use of two off-axis parabolas to realize such a beam transport system.

Drawing on the previous proposal, we choose off-axis parabola with a focal length of $f = 35\text{m}$ and an angle of total reflection of 2° , compatible with optics dimensions.

In the figure and table below, the complete Zemax design of the afocal system using OAPs is shown together with the obtained results in terms of spatial beam quality.

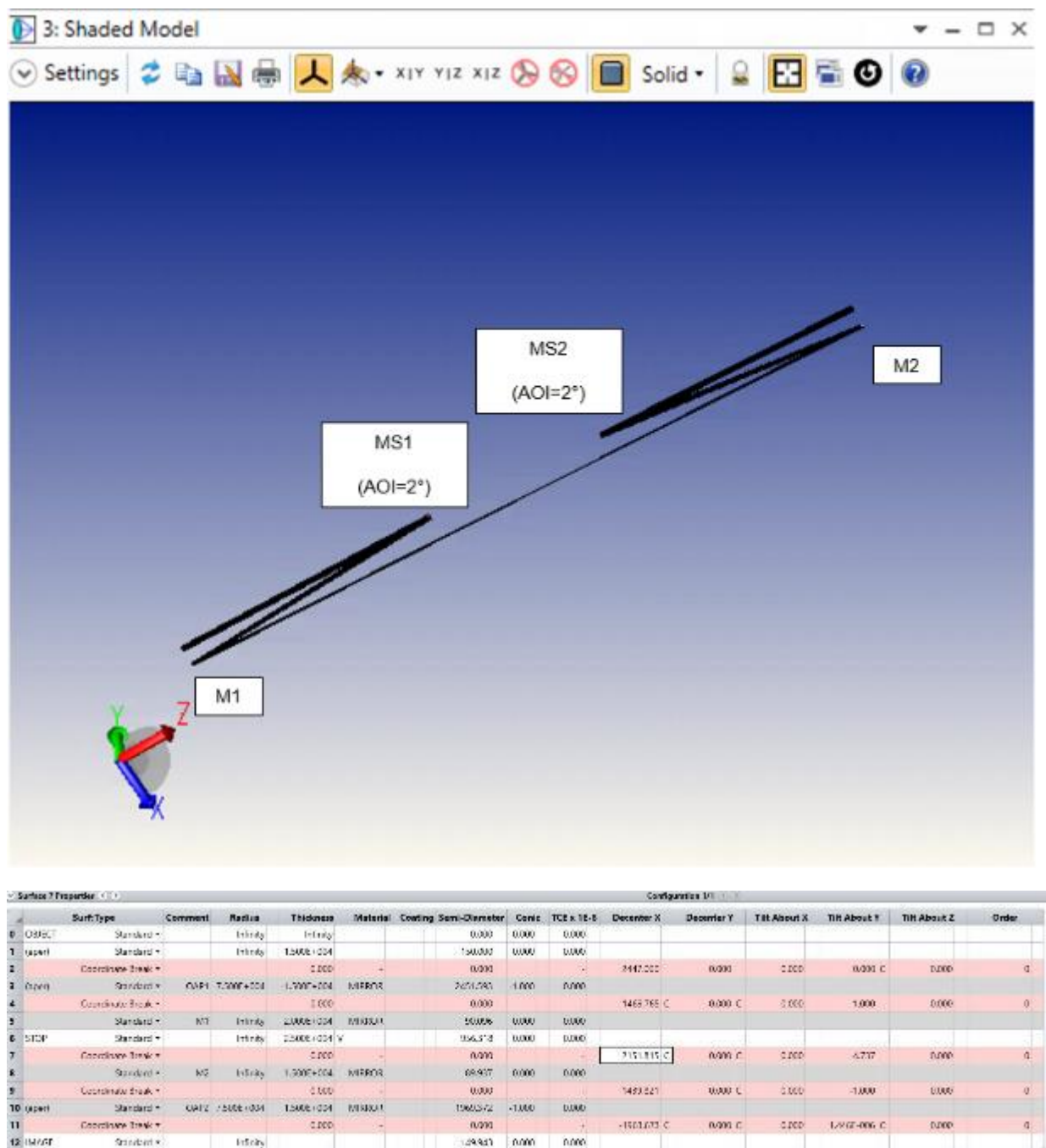
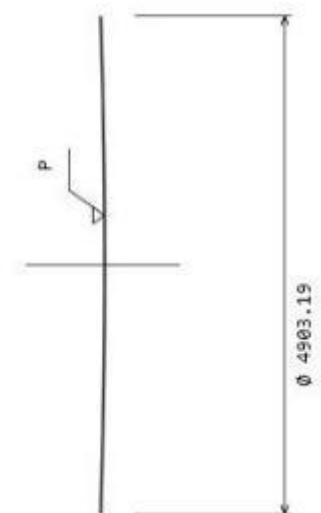
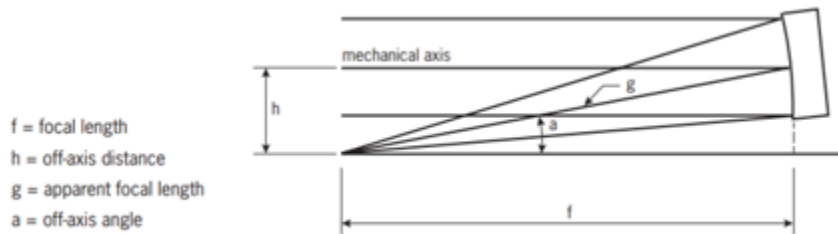


Figure 21: 2D scheme (on top) and Lens data table (on the bottom) of the folded telescope 1 with OAPs

Characteristics of the OAPs:

- off-axis angle: $a = 2^\circ$
- focal length: $f = 15000\text{mm}$
- off-axis distance: $h = 1047,62\text{mm}$
- apparent focal length: $g = 15004,57\text{mm}$



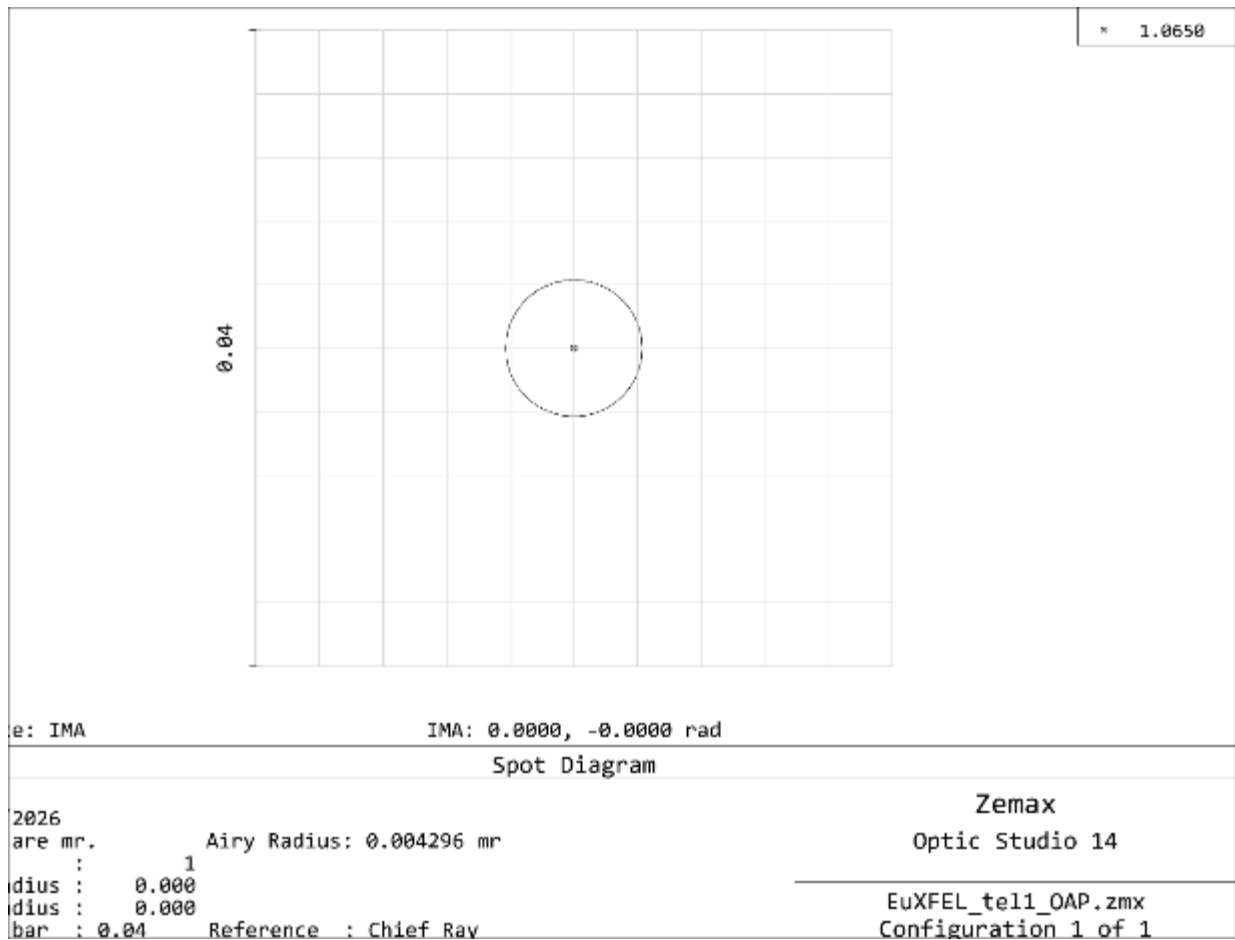
Dimensions in Millimeters

R 75000
K -1
Ø 4903.19

Left Surface

Figure 22: Technical drawing of the OAP surface, with $\varnothing_e$ the diameter of the parent parabola with a focal length of 7,5m

As we might expect with OAPs, we obtain perfect beam quality results (Fig. 23) as the previous OAPs system we studied.



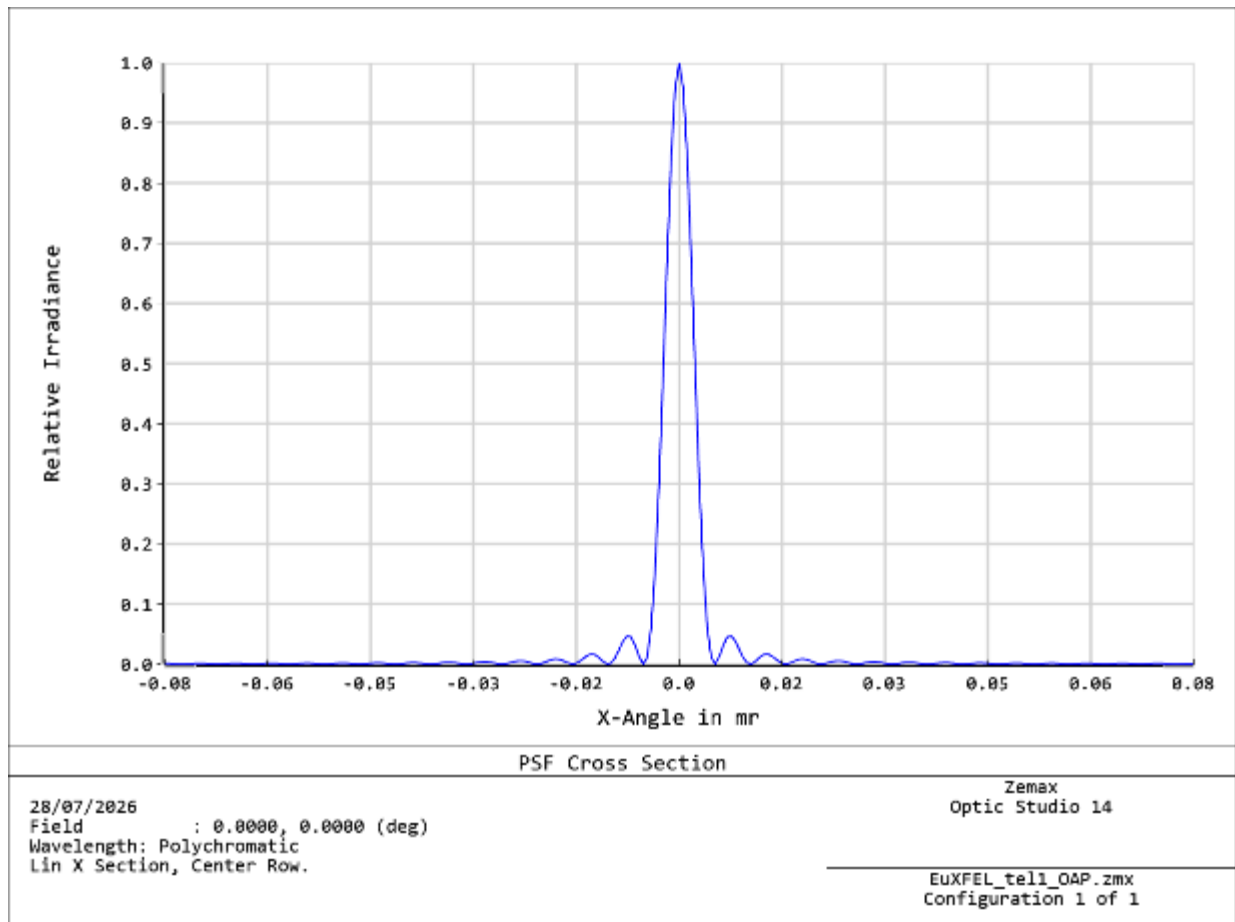


Figure 23: Checking of the afocal system 1 alignment with Spot Diagram (on top) and PSF Cross Section (on the bottom)

4.2.2.5 Telescope 2

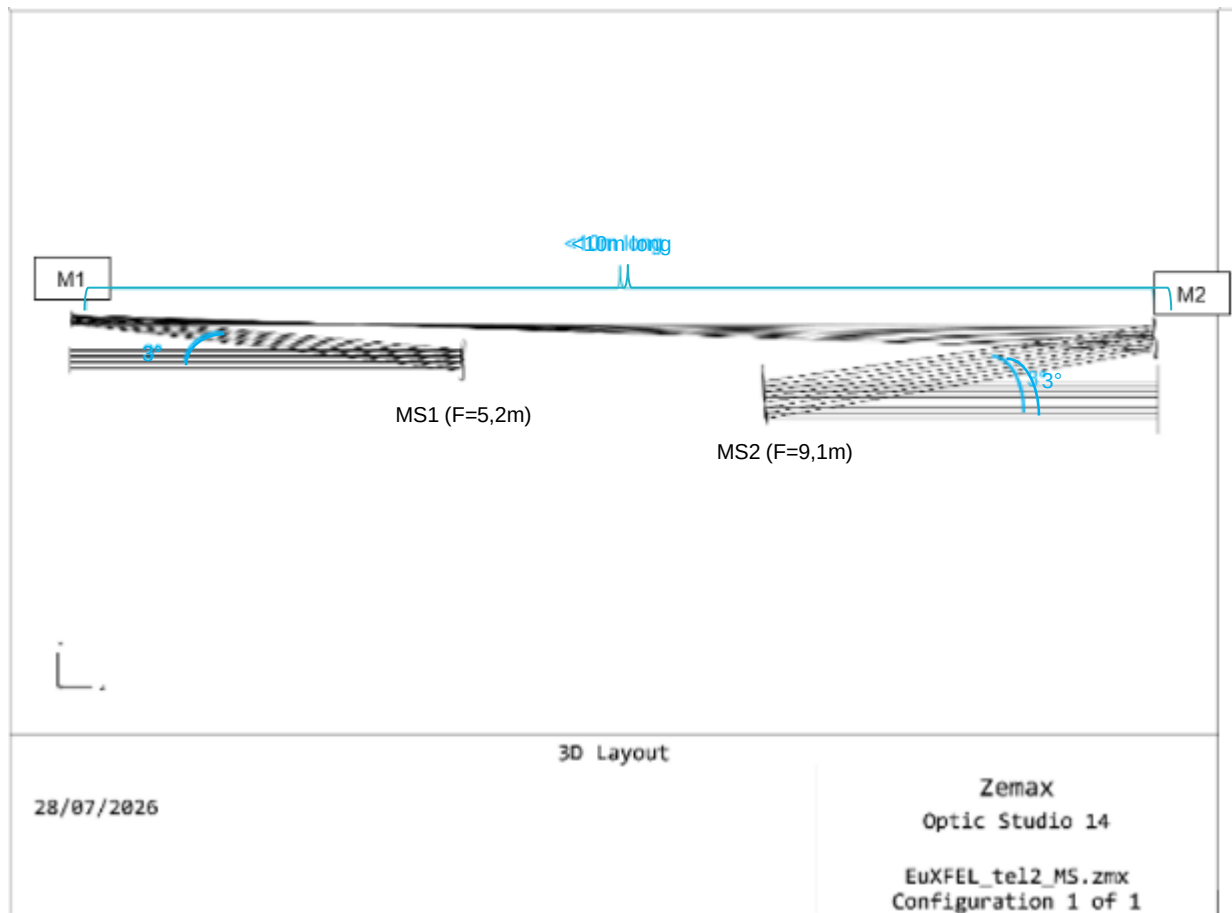
We did not study a transmissive solution because the afocal system is not long enough to avoid important aberrations notably with the laser beam passing through too much material.

4.2.2.6 Study for using spherical mirrors for the afocal system

We have designed two spherical mirrors with the focal lengths $F1 = 5,2\text{m}$ (MS1) and $F2=9,1\text{m}$ (MS2) to obtain an afocal system with less than 10 meters in length with a magnification of 1,75.

We have determined the minimal angles of incidence of the two spherical mirrors, considering the laser beam diameter and the optics dimensions, resulting in 3° (Fig. 24).

The transport distance is about 39 m.



Configuration 1/1													
	Surf.Type	Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Conic	TCE x 1E-6	Par 1(unused)	Par 2(unused)	Par 3(unused)	Par 4(unused)
0	OBJECT	Standard	Infinity	Infinity			0.000	0.000	0.000				
1	(apert)	Standard	Infinity	3000.000			150.000	0.000	0.000				
2	(aper and tilt)	Standard	-1.040E+004	-3000.000	MIRROR		120.000	0.000	0.000				
3	Coordinate Break		0.000				0.000			0.000 C	15.7223 C	1.500 V	0.000 C
4	(tilt/dec)	Standard	Infinity	7000.000	MIRROR		63.466	0.000	0.000				
5	SLIP	Standard	-3.077E+006	1205.776 V			445.505	0.000	0.000				
6	Coordinate Break		0.000				0.000			0.000	361.805 C	-2.500 C	0.000
7	(aper and tilt)	Standard	Infinity	-1000.000	MIRROR		120.000	0.000	0.000				
8	Coordinate Break		0.000				0.000			0.000 C	-262.666 C	-1.500 P	0.000
9	(tilt/dec)	Standard	1.2170E+004	3000.000	MIRROR		267.169	0.000	0.000				
10	Coordinate Break		0.000				0.000			0.000	-216.305 C	6.500 C	0.000
11	IMAGE	Standard	Infinity				267.098	0.000	0.000				

Figure 24: Folded spherical mirrors system afocal proposal for telescope 2

Below, the results in terms of focal spot calculations show that we would be at 20 times the Airy radius, due to astigmatism (Fig. 25).

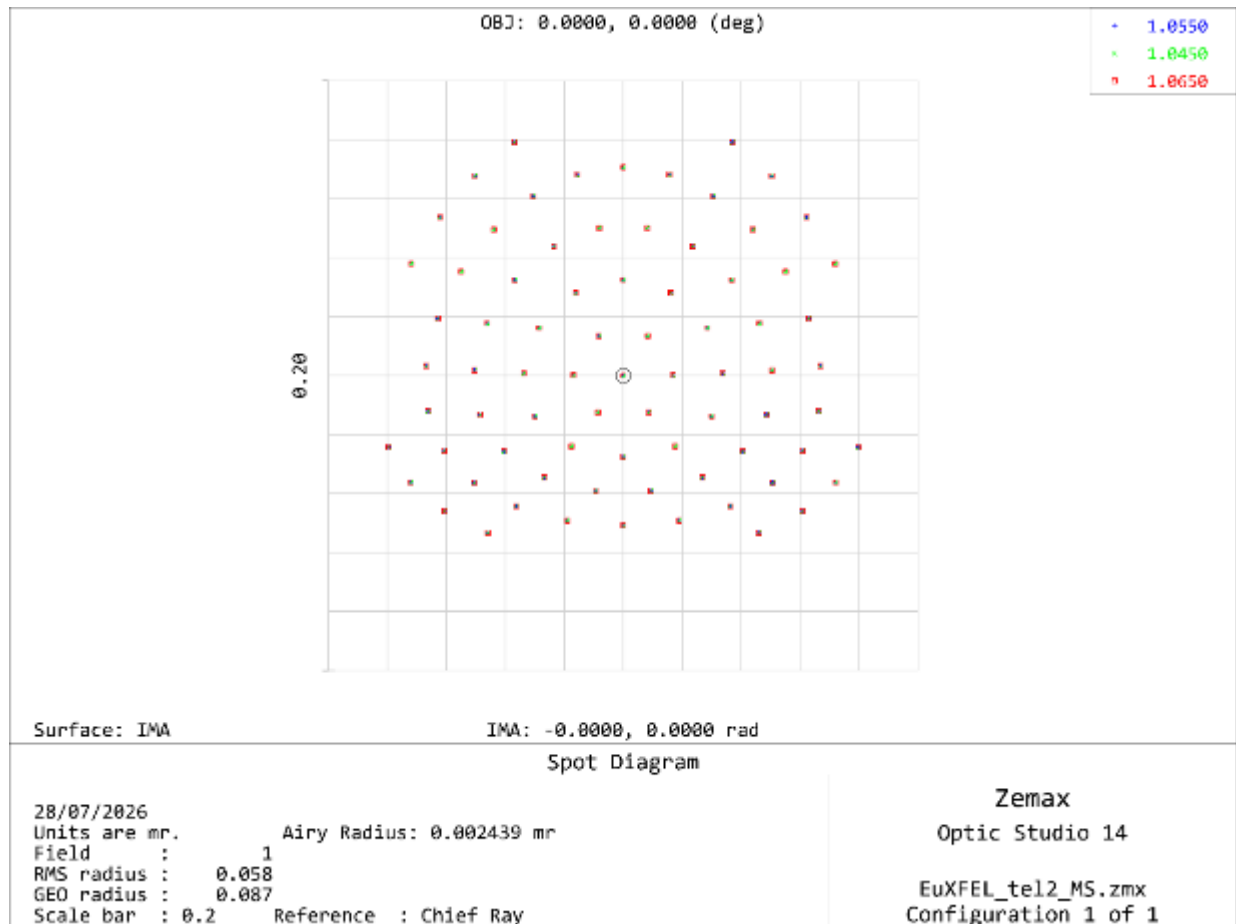


Figure 25: Spot Diagram we obtained in ZEMAX software in the telescope 2 with spherical mirrors case. Spatial filtering is not possible but not required so, this configuration could be a solution.

4.2.2.7 Study of an afocal system based on OAPs

Furthermore, we review what would be the parameters of the two off-axis parabolas to realize an afocal system respecting the beamline scheme and the output beam parameters.

Drawing on the previous proposal, we choose off-axis parabolas with focal lengths $F1 = 5200$ mm and $F2 = 9100$ mm and an angle of total reflection of 4° , compatible with optics dimensions. We choose the same angle of incidence for the two OAPs for practical reasons, so that the input and output beams are parallel.

Below, the complete design of the OAP afocal system in Zemax is shown, together with the characteristics (Fig. 26).

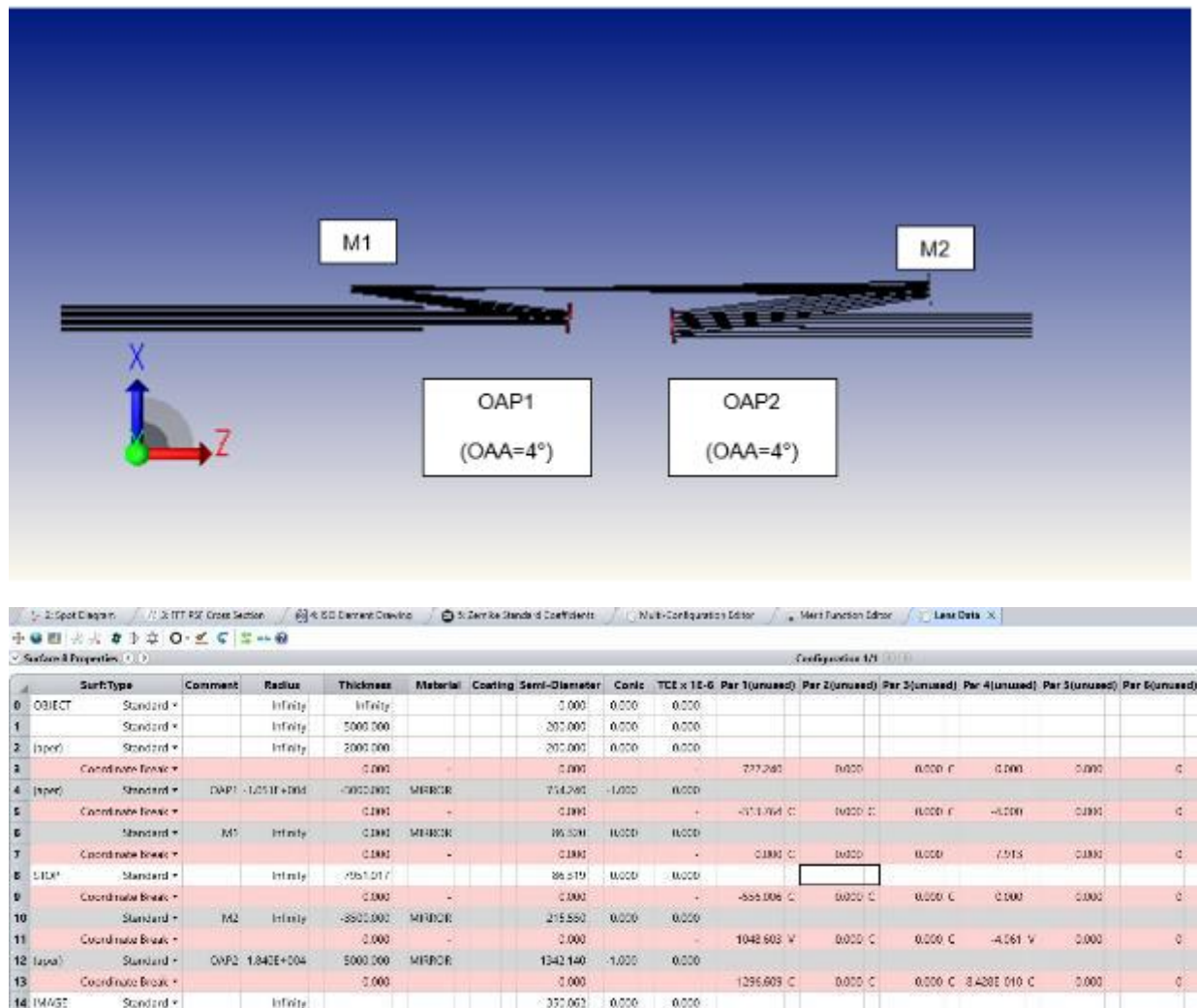
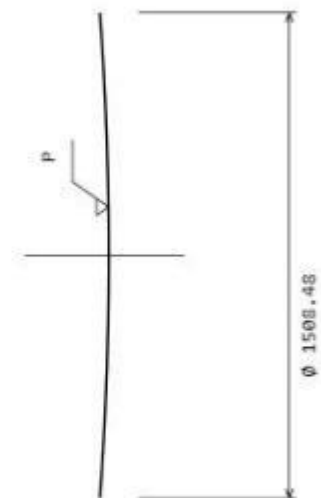
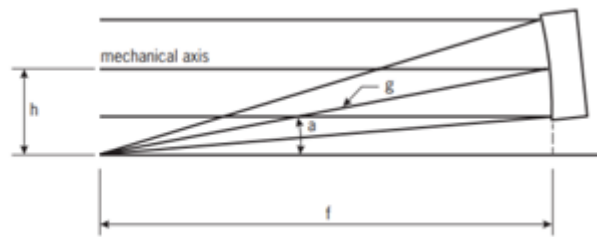


Figure 26: Zemax design of the telescope 2

Characteristics of the OAPs:

OAP1	OAP2
- off-axis angle: $\alpha = 4^\circ$ - off-axis distance: $h = 727,24\text{mm}$ - apparent focal length: $g = 5225,42\text{mm}$	- off-axis angle: $\alpha = 4^\circ$ - off-axis distance: $h = 1272,67\text{mm}$ - apparent focal length: $g = 9144,5\text{mm}$

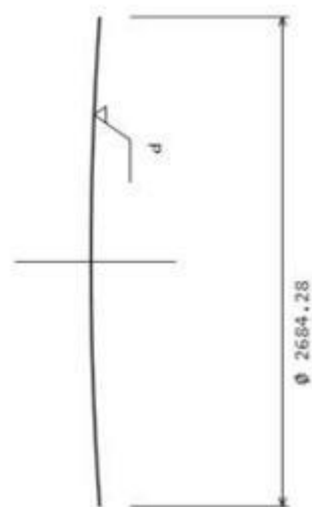
f = focal length
h = off-axis distance
g = apparent focal length
a = off-axis angle



Dimensions in Millimeters

Left Surface

R 10514.9
K -1
Ø 1508.48



Dimensions in Millimeters

Left Surface

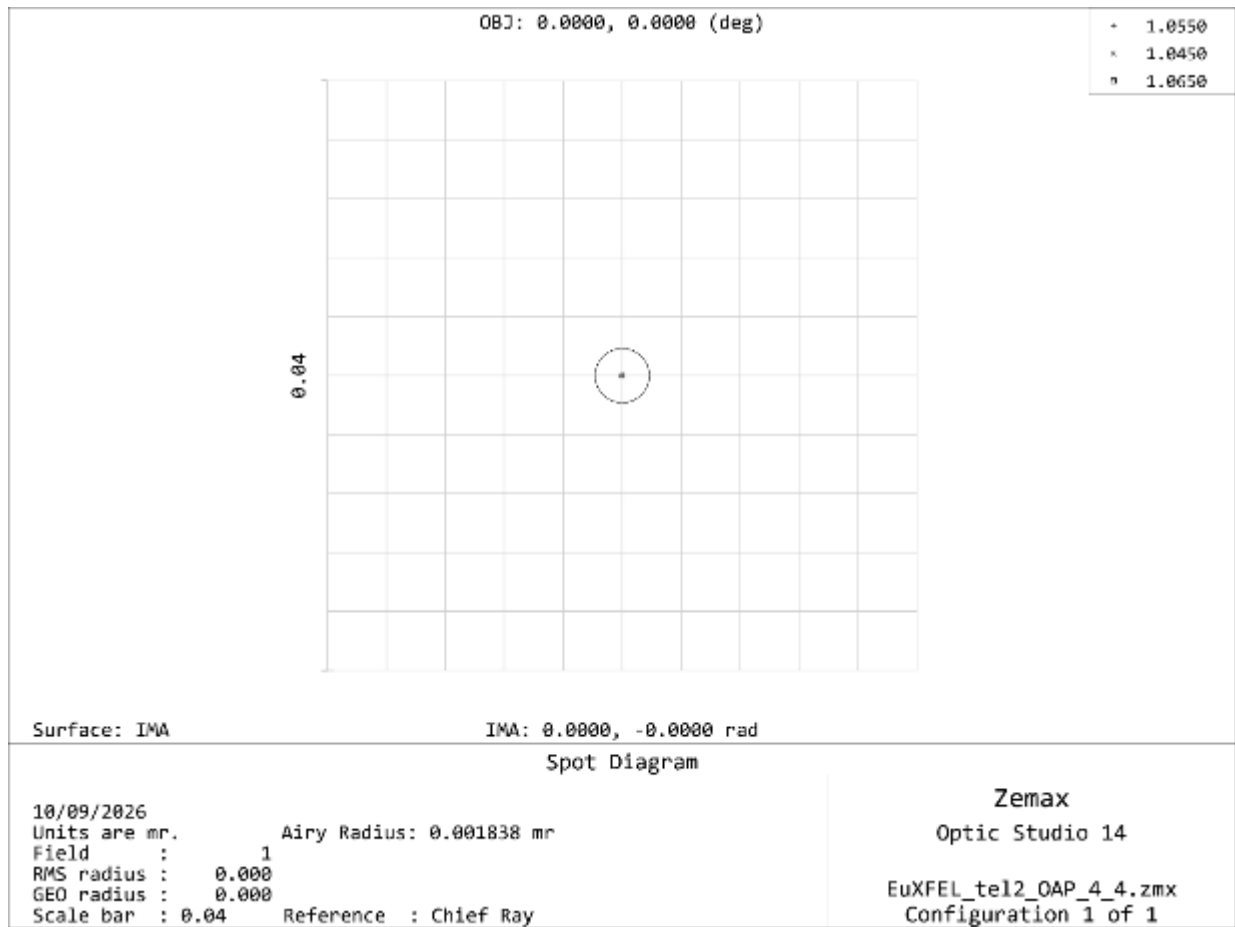
R 18401.1

K -1

Ø_s 2684.28

Figure 27: Technical drawings of the OAP1 (on top) and OAP2 (on the bottom) with Øe the diameters of the parent parabolas

As expected, the results are excellent.



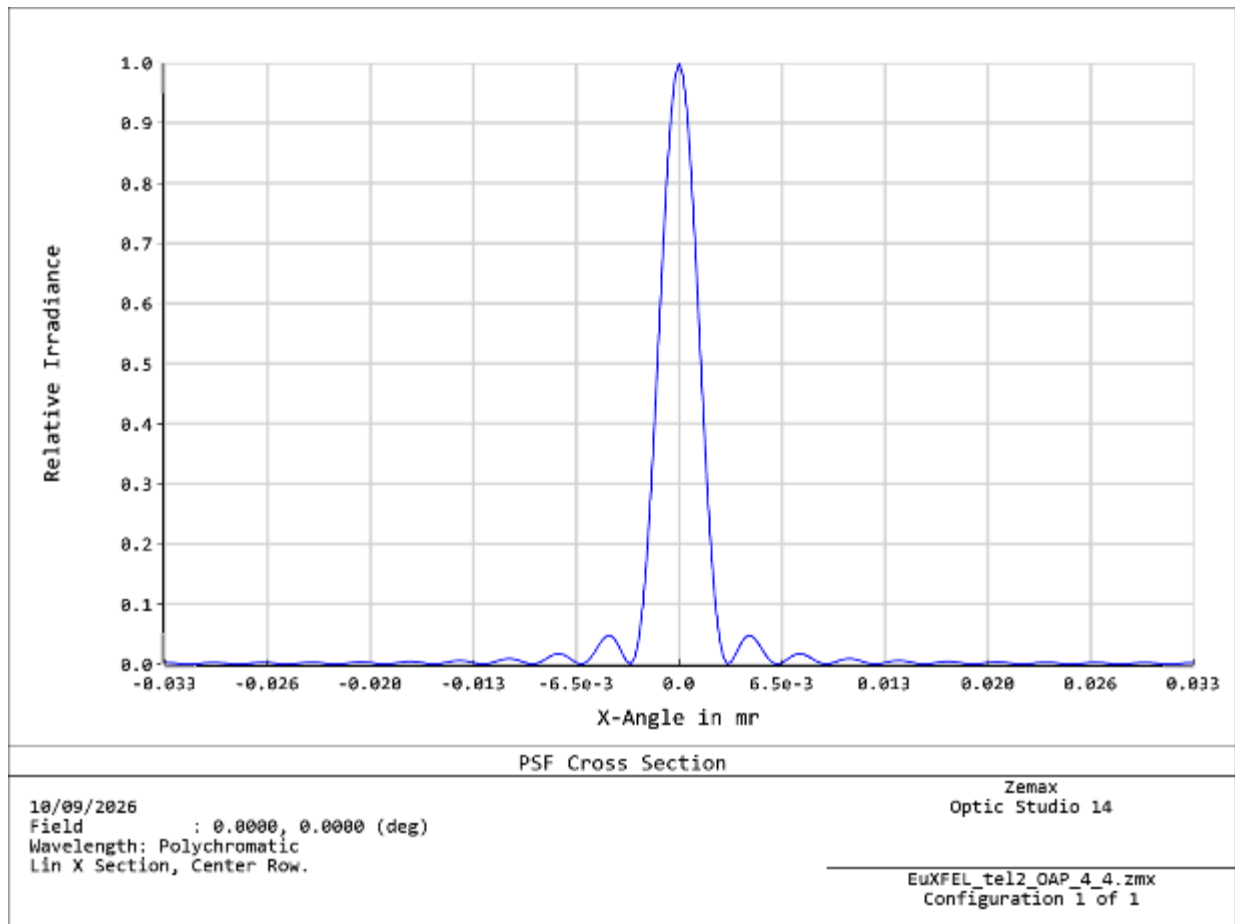


Figure 28: Checking of the afocal system 2 alignment with Spot Diagram (on top) and PSF Cross Section (on the bottom)

As expected, the best solution for the EuXFEL transport telescopes, but the most expensive is to use OAPs. With large beam dimensions and long transport distances, which require to design folded telescopes with fairly large angles of incidence, it seems mandatory to choose OAPs if we want to conserve the beam spatial quality.

4.3 Blueprint of an achromatic reflective beam transport for the future laser at the FAIR facility

4.3.1 Introduction

Currently the international accelerator facility FAIR (Facility for Antiproton and Ion Research in Europe), one of the largest research projects worldwide (150,000 m², 25 buildings), is being built in Darmstadt, Germany. At FAIR, matter that usually only exists in the depth of space will be produced in a lab for research. Scientists from all over the world will be able to gain new insights into the structure of matter and the evolution of the universe from the Big Bang to the present.

FAIR will generate particle beams of a previously unparalleled intensity and quality. The variety of these particles will be unique: Ions of all the natural elements in the periodic table, as well as antiprotons, can be accelerated.

The FAIR facility consists of a superconducting ring accelerator with a circumference of 1,100 meters, storage rings and experiment sites with several kilometres of beam line in total. The existing GSI accelerators will serve as the first acceleration stage. Research into a large variety of topics will be carried out at different experiment caves. One of the is the APPA cave, focusing on Atomic, Plasma Physics and Applications. Research here at will range from the investigation of fundamental processes in atoms and macroscopic effects in materials or tissues all the way to engineering and medical applications. In order to exploit the full potential of the new heavy-ion infrastructure a multi-kJ, multi beam laser facility is planned to be located adjacent to the APPA cave (Fig.29).

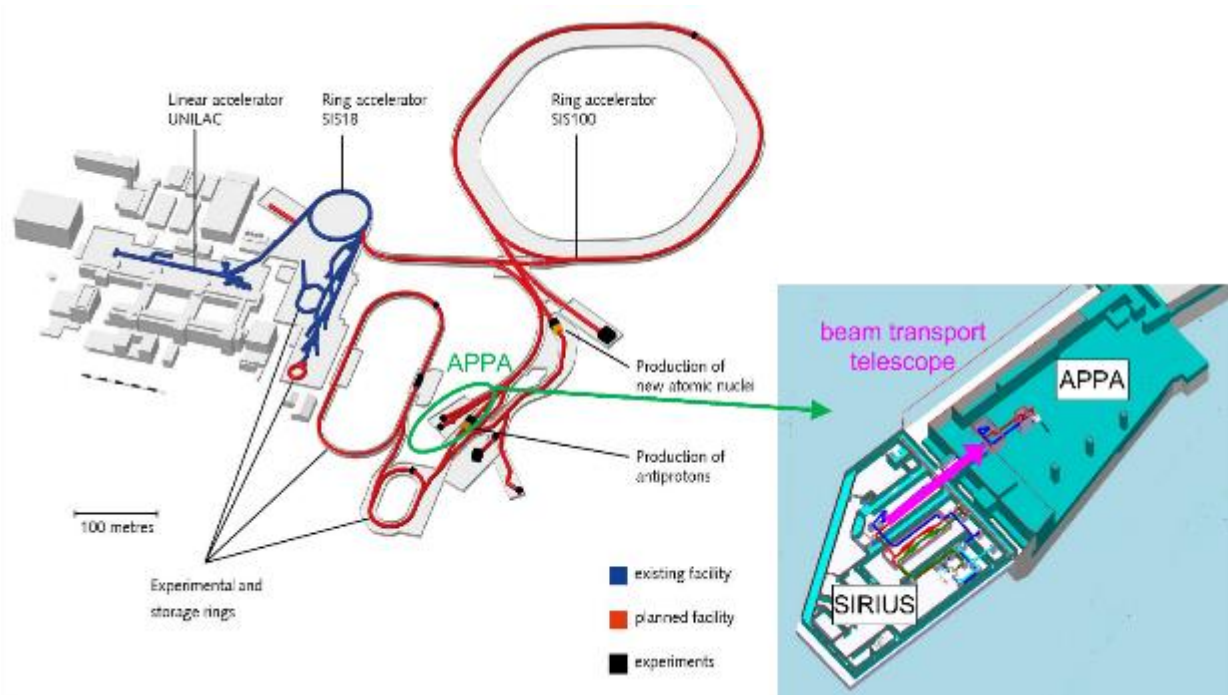


Figure 29: View of the FAIR facility with a zoom on APPA cave where the multi beam laser facility would be implanted (on right)

Here we study the feasibility of an achromatic reflective beam transport telescope from the laser area to the APPA cave. The transport system to be designed, consists of a 1:1 OAP transport telescope to transport a $400 \times 400 \text{ mm}^2$ CPA beam (the blue beam path on figure 31, below) from a room to another, passing through a $1 \times 2 \text{ m}^2$ tunnel.



Figure 30: APPA Cave, visualization

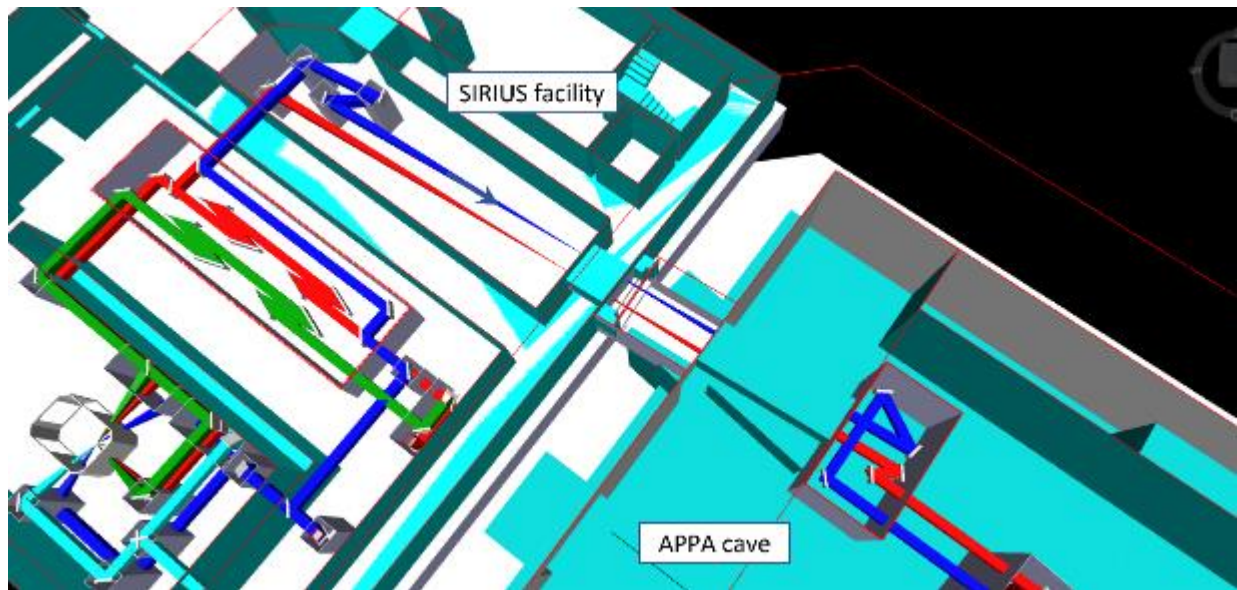


Figure 31: 3D view of the 1:1 OAP afocal

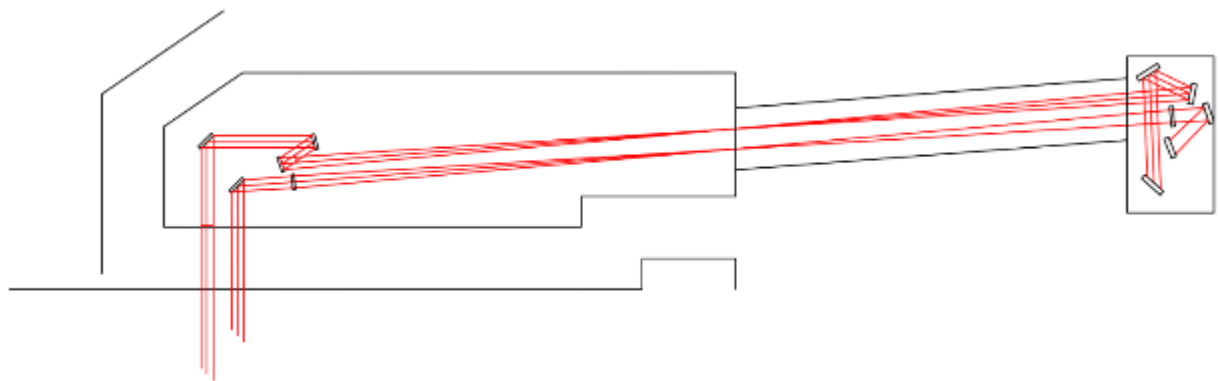


Figure 32: 2D drawing of the 1:1 OAP afocal

4.3.2 Proposal

The FAIR beam parameters we are designing an afocal solution are:

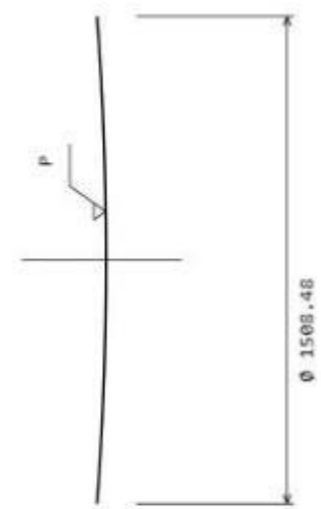
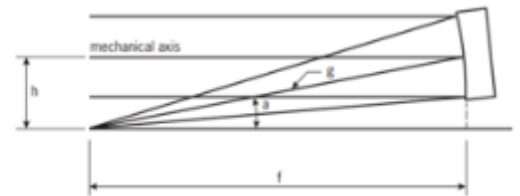
- Energy: either up to 2 kJ (at 0,5ps pulse duration) or 4kJ (at 1ns pulse duration)
- Wavelength: 1053 nm, up to 20 nm bandwidth

For this case, we investigate the possibility to use two off-axis parabolas to realize an afocal system taking into account the beamline scheme and the output beam parameters.

Drawing on the 2D scheme (Fig.32) of the beamline design, we choose the two OAPs with following parameters:

- off-axis angle: $\alpha = 30^\circ$
- focal length: $f = 15000\text{mm}$
- off-axis distance: $h = 8038.47\text{mm}$
- apparent focal length:
 $g = 16076,95\text{mm}$

f = focal length
 h = off-axis distance
 g = apparent focal length
 α = off-axis angle



Dimensions in Millimeters

Left Surface

R 10514.9

K -1

$\varnothing_i$ 1508.48

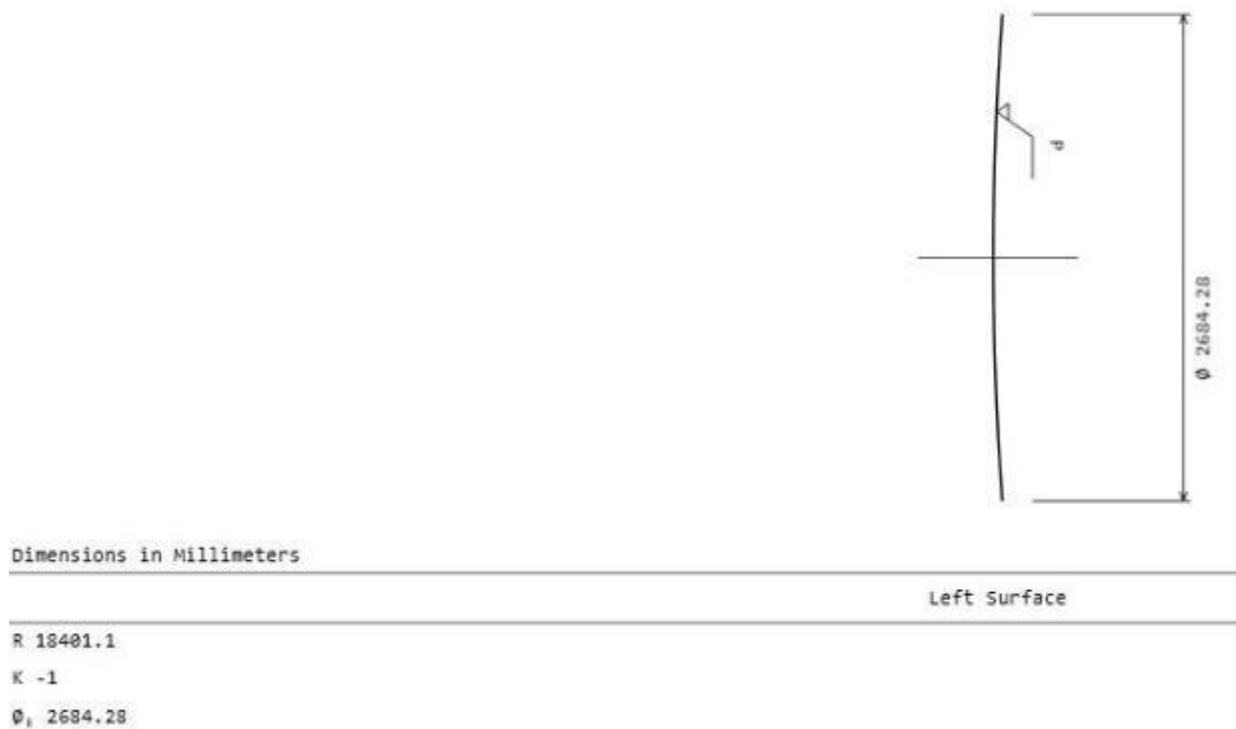


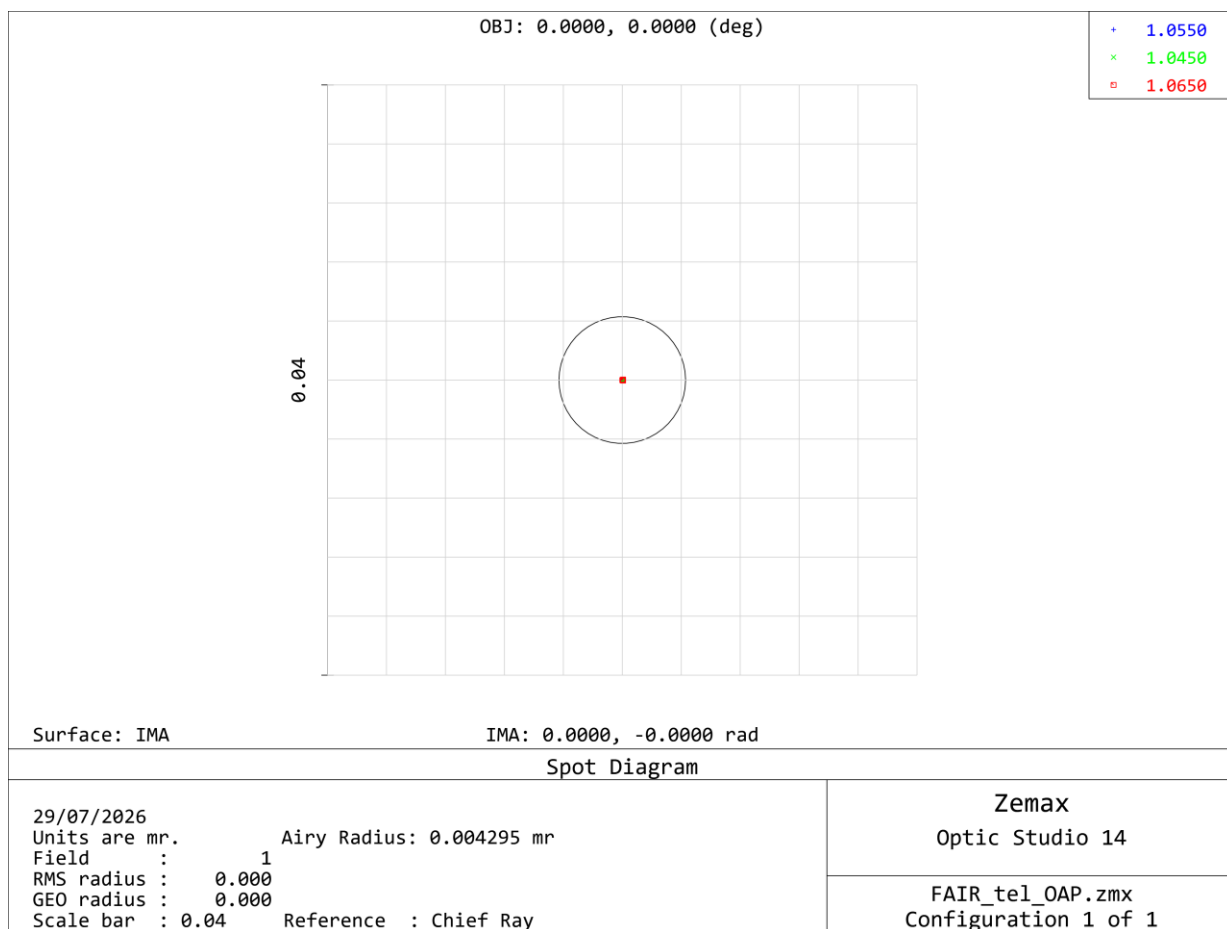
Figure 33: Technical drawings of the two OAPs designed for the FAIR telescope

Below, it shows the complete design of the OAP afocal system in Zemax (Fig. 34).

Configuration 1/1													
Surf.	Type	Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Conic	TCE x 1E-3	Par 1(used)	Par 2(used)	Par 3(used)	Par 4(used)
0	OBJECT	Standard	Infinity	Infinity			0.000	0.000	0.000				
1	STOP	Standard	Infinity	1000.000			350.000	0.000	0.000				
2	Input	Standard	Infinity	1240.000			350.000	0.000	0.000				
3	Coordinate Break			0.000	-		0.000			1130.000	0.000	0.000	-0.109
4	Input	Standard	0.000	-1.000	MIRROR		1157.611	-1.000	0.000				
5	Coordinate Break			0.000	-		0.000			1096.000	0.000	0.000	0.000
6	Standard		Infinity	-1156.000			0.000	0.000	0.000				
7	Standard		Infinity	-1.440			1096.000	0.000	0.000				
8	Coordinate Break			0.000	-		0.000			1230.147	0.000	0.000	-0.157
9	Coordinate Break			0.000	-		0.000			-1150.000	0.000	0.000	0.000
10	Input	Standard	0.000	1450.000	MIRROR		1156.000	-1.000	0.000				
11	Coordinate Break			0.000	-		0.000			1116.856	0.000	0.000	-0.485
12	IMAGE	Standard	Infinity	-			249.712	0.000	0.000				

Figure 34: Lens data table of the FAIR telescope in Zemax software

As we might expect with OAPs, we obtain excellent beam quality results with optimal diagram spot and FFT PSF Cross Section (Fig. 35), as we explained previously, which ensures a system perfectly achromatic.



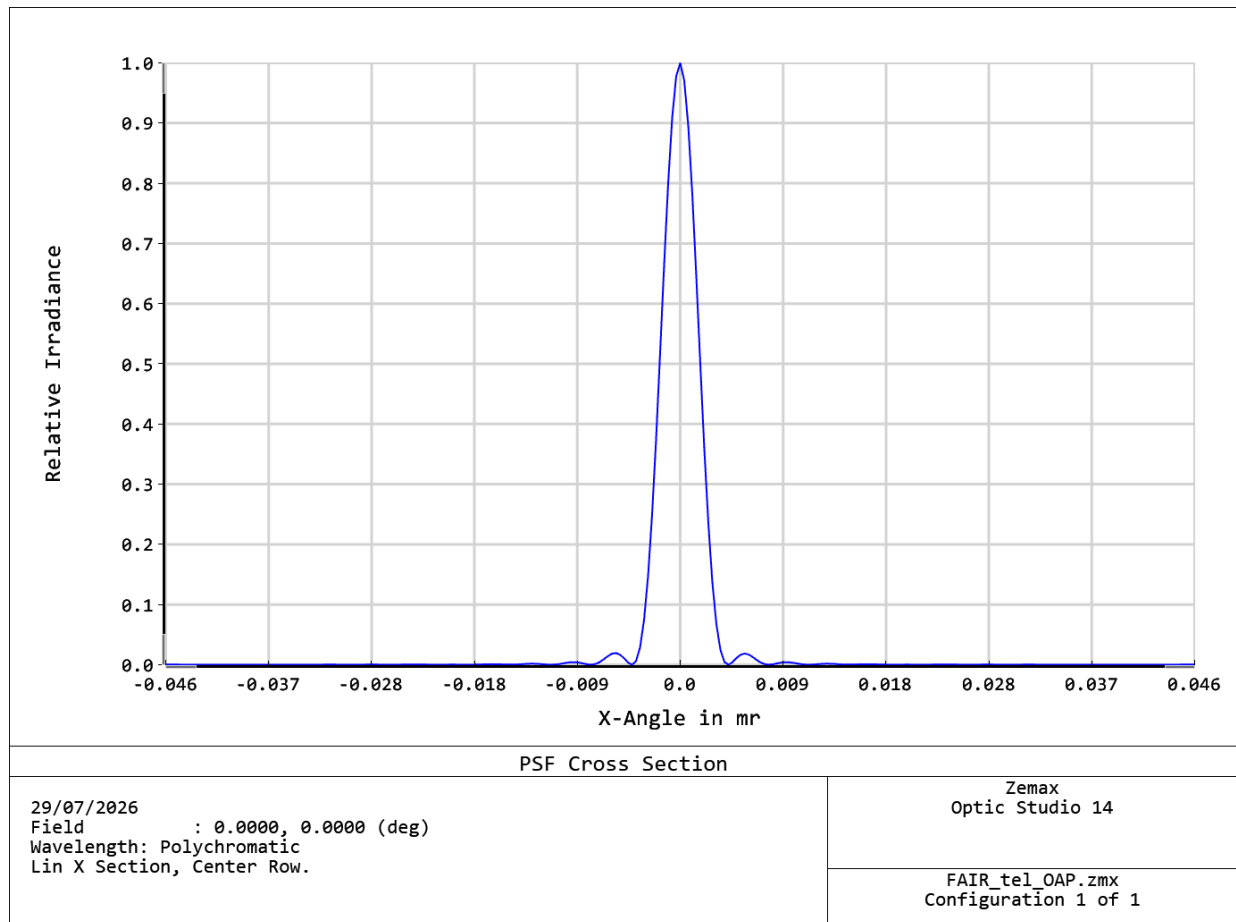


Figure 35: Checking of the afocal system alignment with Spot Diagram (on top) and PSF Cross Section (on the bottom)

If it is necessary, these results allow to install a spatial filter at the imaging transport focal plan.

5 Conclusion

We have determined a new configuration for the transport of the Apollon F2 beam from the exit of the amplification stages to the entrance of the compressor, respecting imaging constraints with the integration of 8,8m long focal length off-axis parabolic mirrors, in order to maintain the quality of the spatial beam profile all the way to the target chamber.

We have realized studies for two telescopes of EuXFEL facility and proposed different afocal system solutions we designed with Zemax. The configurations which offer the best results are, without surprise, afocal systems using two off-axis parabolas. However, using spherical mirrors for the long telescope with a magnification of 1 also seems to be an interesting possibility for a cheaper solution, which would also be easier to align.

According a 2D scheme provided on the future high-energy laser facility at FAIR, we have

determined the specific parameters of the two OAPs for a beam transport telescope from the laser area to the experiment cave, as requested. This solution offers excellent results and would maintain a good beam quality despite the long distances.