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MORFEO Calibration Unit: towards the final design

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ABSTRACT

After the Preliminary Design Review, the Calibration Unit of MORFEO, the Multiconjugate adaptive Optics Relay for ELT Observations, underwent a complete design overhaul. This process was aimed at the mitigation of some critical aspects of the manufacturing, both in terms of optics and mechanics. While its optical configuration proved to be the best choice to meet the system requirements, especially on external interfaces, a slightly different layout has been investigated. By changing the displacement of the large beam splitters and applying small changes to a few optical elements, it would be possible to obtain a significant increase in the overall optical quality, for both the NGS and LGS arms. Moreover, some important modification to the mechanics could actually decrease the complexity of the assemblies and adjustments, also allowing a better accessibility to the system from all sides, thus facilitating the MAIT operations. We present an overview of the new layout of the MORFEO CU.

Keywords: MORFEO, ELT, Multi-Conjugate Adaptive Optics, calibration, optomechanics

1. INTRODUCTION

MORFEO (Multi-conjugate adaptive Optics Relay For ELT Observations)[1][2], formerly known as MAORY, is a post-focal adaptive optics module, designed to enable MICADO (Multi-AO Imaging CAmera for Deep Observations) [3] to perform high-angular resolution observations in the near infrared, providing real-time MCAO corrections to the atmospheric wavefront distortions over a FoV of about 1 arcmin.

The Calibration Unit (CU) [4], will allow to run templates for the calibration of the wavefront sensors and the non-common path aberrations (NPCA) within the MORFEO optical system. Moreover, it will be used to train the tomographic reconstructor and to perform system and subsystem functional and health checks, drastically reducing the amount of required night-time for daily, periodic and maintenance operations.

It is a complex opto-mechanical unit installed at the entrance port of MORFEO aimed at projecting artificial sources (both diffraction limited and extended) at visible and infrared wavelengths on the ELT focal planes, thus providing reference light to multiple sensors and instruments, like the NGS and LGS wavefront sensors [2], and focal plane instruments attached to MORFEO exit ports.

Calibration light sources will be different in amount, distribution, size and wavelength, matching the ELT optical interfaces (focal ratio, exit pupil position, field curvature), fully simulating the telescope performance and residual aberrations.

The sources can be grouped in the following three typologies, according to their wavelengths and projected field:

- Extended sources at 589 nm feeding the LGS WFSs at two different conjugated altitudes (104 km and 150 km);
- Extended seeing-limited R-band sources within the ELT technical field of view (FoV), to feed the high-order, reference WFSs;
- Diffraction-limited H-band sources, conjugated at infinity, to feed the low-order WFSs located within the ELT technical FoV and the MICADO science FoV.

This subsystem will play a critical role not only during operations at the ELT, but also during the Assembly, Integration and Verification (AIV) phase in Italy, where it will be used also to ease the alignment of MORFEO and to test and verify its performance, in Test Unit (TU) configuration [2].

MORFEO and hence the CU, successfully passed ESO’s phase B (preliminary design) and are currently in phase C (final design). However, the preliminary design still showed some weaknesses and some possible critical issues that we considered worthy of a subsequent further revision of the optical and mechanical design, before proceeding with development. This revision, here presented, aims primarily to simplify manufacturing and operations during the MAIT phase (reducing costs and risks) and simultaneously optimize the overall performance of the CU.

2. CU PRELIMINARY DESIGN

2.1 Calibration Unit requirements and main aspects of the design

The preliminary design has turned out to be rather challenging, mainly due to the need to transmit high optical quality beams in a large spectral window (from 580 nm to 1800 nm) and projecting a large FoV, especially for the NGS sources (160” diameter). The main optical requirements are shown in Table 1. A further challenging requirement is to provide a small and accessible high quality intermediate pupil, common to the NGS and LGS paths). Finally, the limited available volume and mass budget (max 350 kg) imposed additional stringent constraints to the design.

Table 1. CU main optical requirements. Asterisks indicate the size of the diffraction limited FWHM at 1650 nm.

	NGS-REF	NGS-LO	NGS-MIC	LGS
Detector	Reference WFS	Low-Order WFS	MICADO	LGS WFS
Number of sources	≥ 37	≥ 6	≥ 9	6 x 2
Asterism Layout	Grid	Sparse	Grid	Circular
FoV (arcsec)	160	160	51x51	90
Conjugated altitude (km)	Infinity	Infinity	Infinity	104, 150
Wavelength range (nm)	600-1000	1500-1800	1500-1800	584-594
PSF FWHM (arcsec)	0.4	$< 0.009^*$	$< 0.009^*$	3
Intermediary pupil (% of pupil diameter)	shift: $<1\%$; blur $<1\%$; distortion $<1\%$			
Wavefront error (nm, rms)	< 60	< 150	< 60	< 100 (Goal 60)

The CU preliminary optical design [6] is shown in . CU preliminary optical design. The colored arrows indicate the two optical paths: LGS path (red, with the mask planes conjugated to 104 km and 150 km) and NGS path (black). The optical surfaces are marked as “a” for anterior and “p” for posterior interface (reverse direction is used for analysis, from the ELT focal surface to the NGSs or LGSs masks, i.e. the opposite direction of the arrows). Figure 1, consists of three main paths with separated optical systems:

- an LGS arm that allows to select an asterism of 6 LGS between two conjugation altitudes, at 45” off-axis on the corresponding LGS focal plane;

- an NGS arm generating different set of sources across the 160'' technical FoV (R- and H- bands);
- a common catadioptric assembly (Block #2) hosting the largest optics, a spherical Mirror (SM) and a Window (W), both about 600mm diameter, that properly focus the artificial sources to their respective focal planes, according to their conjugation altitudes.

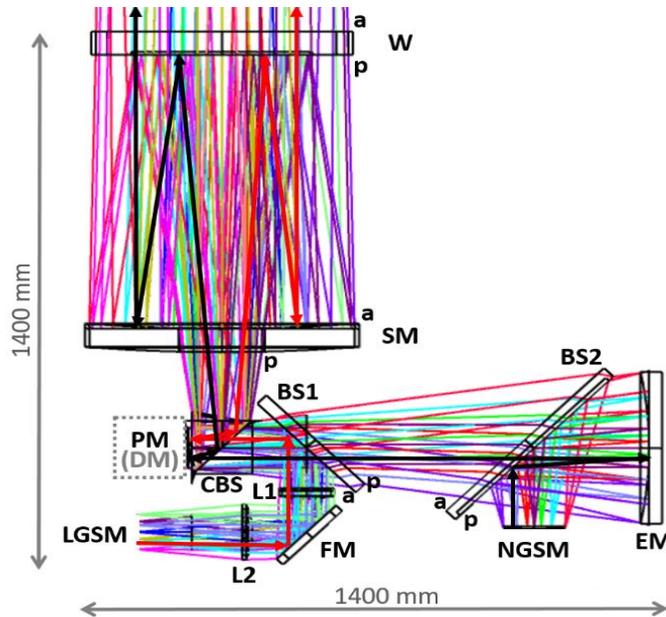


Figure 1. CU preliminary optical design. The colored arrows indicate the two optical paths: LGS path (red, with the mask planes conjugated to 104 km and 150 km) and NGS path (black). The optical surfaces are marked as “a” for anterior and “p” for posterior interface (reverse direction is used for analysis, from the ELT focal surface to the NGSs or LGSs masks, i.e. the opposite direction of the arrows).

The LGS and NGS paths share and illuminate a common intermediate pupil (~100mm diameter). It is required for the calibrations in Chile and to mount a DM - replacing the fixed Pupil Mirror (PM) - when the CU is used in TU configuration, to fully test and verify MORFEO during AIV and Preliminary Acceptance Europe (PAE) in Italy. The peculiarity of this design is the use of a number of semi-reflective (50% transmission and 50% reflection) surfaces, as for the largest optics (W and SM), the Beam Splitters (BS1 and BS2) and a Cube Beam Splitter (CBS).

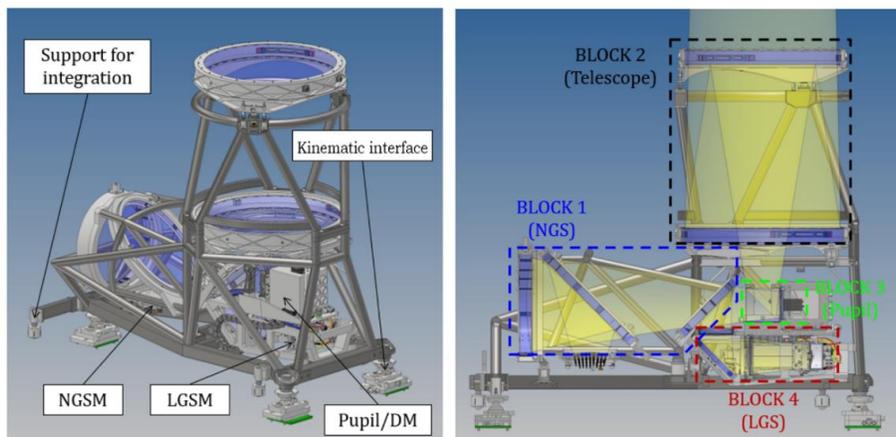


Figure 2. CUMB preliminary design: support structure, opto-mechanical blocks and kinematic interfaces (including adjustments) with the MORFEO MS are shown.

Because of these semi-reflective components, this solution has intrinsic drawbacks (very low throughput, ghost and stray light effects) that need to be extensively analyzed to be sure they will not introduce difficulties in the alignment and limitations to the overall performance.

According to the preliminary design, the CU Main Bench (CUMB, Figure 2) consists of the main support structure integrated with 4 opto-mechanical units (called “blocks”), the latter conceived to ease the alignment process and maintenance operations. They also provide the required DoFs to be aligned each other (after their individual internal alignment) following a well-defined step-by-step procedure. Finally, the CUMB is mounted on the MORFEO Main Structure (MS) through kinematic couplings provided with 6 DoF adjustments.

3. CU DESIGN REVISION

In this chapter we discuss the revision of the preliminary design of the CU. Besides the analysis of the optical performance, the design parameters have been addressed in terms of manufacturability and testability, paying attention to the definition of integration and optical alignment strategies. As outcome of this revision, some changes to the design have been considered, to improve the overall performance and simplify the MAIT phase. All the following concerns guided this revision to seek solution for the improvement of the preliminary design and overcome its weaknesses and critical issues.

3.1 Weak and critical points

Clearance and accessibility

The introduction of a modular architecture allowed to define detailed procedures for the internal and mutual alignment of the opto-mechanical blocks. However, this required to increase the number of internal interfaces (and the overall weight of the subsystem). Furthermore, the reduced accessibility to the individual components of the CU, once the integration on the supporting structure has been completed, is still one of the main weak points of the design.

As shown in Figure 1 and Figure 2, below the SM, many large optical components and subsystems have been packed closely together. Due to the tight overall volume constraints, there is very small margins between optical beams, mechanical components, and, for each optical element, between their mechanical aperture and its clear effective aperture. Other further aspects are related to the difficulty to add baffles and vanes to prevent the visibility of illuminated mechanical surfaces and avoid unwanted stray light sources. Because all of the above, the need for an increased clearance was one of the main reasons to revise the preliminary design, looking for an alternative layout.

Large optics weight and deformations

The exit window W and the spherical mirror SM on Block #2 are the largest and heavy optical components of the CU. They suffer from gravity sag effect and move upwards the center of gravity of the subsystem, being located on top of the CU support structure. Therefore, it is desirable to try to minimize their weight, by making them thinner. However, it is well known that, thinner elements suffer more from gravity sag, therefore a proper opto-mechanical mount is required to ensure that most of deformations are axisymmetric (focus, spherical aberration), so that they can be partially compensated during the alignment of the system and by accounting for them in the optical design. In addition, the limit to the minimum thickness of the optics is also constrained by the manufacturing process: it is usually smaller for the flat ones and larger for the powered ones.

Similar consideration can be done for the large flat beam-splitters, namely BS1 and BS2, oriented at 45° with respect to the gravity vector in the preliminary design. They suffer from asymmetric gravity sag variations, due their elliptical shape and limited thickness, hard to be reduced or compensated.

Cube Beam Splitter

The cube beam-splitter (CBS) is the most complex optical component of the CU and has very tight manufacturing tolerances, including the reflected/transmitted WFE, due to unavoidable inhomogeneity within the glass blank, surface irregularities, thermal gradient and the 50:50 beam-splitter coating. Then, it may be expected that its WFE contribution could dominate the overall WFE budget. The manufacturing of this component is the main critical point of the preliminary design. Possible mitigation strategies have been discussed and presented in [7].

LGS arm bandwidth and WFE

Since the on-sky LGS beacons are created by using a sodium laser tuned to 589 nanometers, the CU LGS optical path has been initially optimized for the same wavelength. Nevertheless, monochromatic sources injected at the LGS mask could introduce unwanted fringe patterns. To avoid this, and allow for the use of simpler electronic devices, quasi-monochromatic sources (LEDs) are foreseen to be used in the CU. Then, to maximize the photons flux, and prevent chromatic aberrations, the LGS lenses have to be redesigned to make them achromatic, changing from singlets to achromatic doublets. The revised design should also take into account the size of the LGS sources and reduce the large variation in WFE as a function of conjugate altitude, thus helping to meet the required WFE budget.

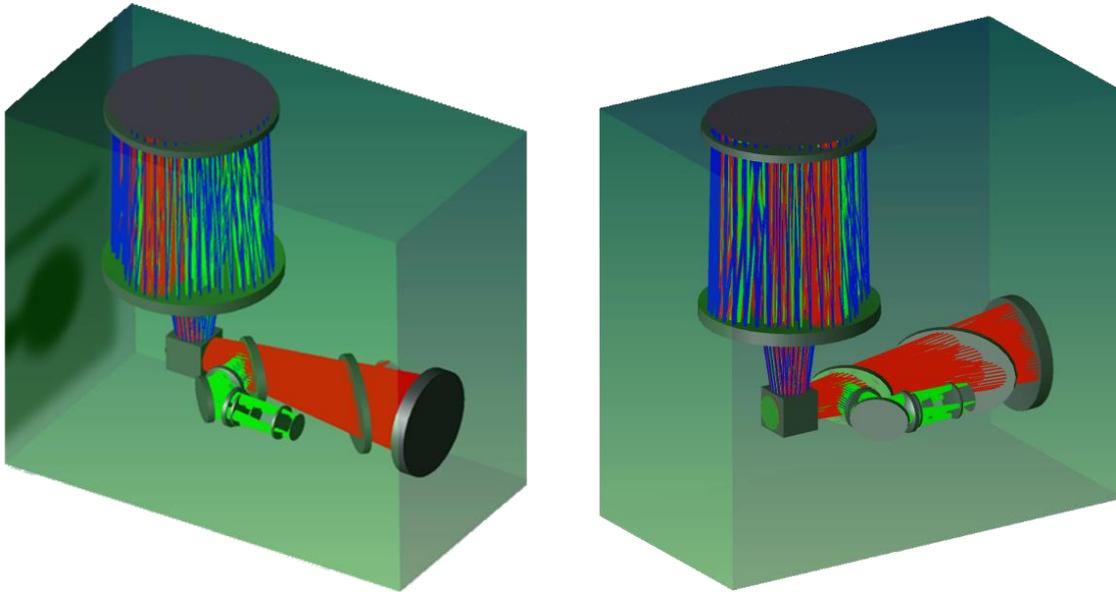


Figure 3. Overall view of the new optical layout within the allocated volume for the CUMB on the MORFEO Main Structure.

3.2 The new optical layout

The revision of the CU optical design has taken into account the results of all the analyses and considerations carried out on the preliminary design, eliminating weak points, minimizing the critical issues, and improving the final performance of the subsystem. While keeping the same optical configuration (already confirmed in the previous project phase as the only one that meet the requirements on the assigned volume), the revision led to a different arrangement of several optical components, and therefore required a substantial change to the mechanical design. Although it maintains the separation between the “telescope” (TEL) assembly on the top (formerly Block #2) and the support structure on the bottom, it showily differs from the previous design (see Figure 3 and Figure 4). Changes mainly concerned the orientation of the two large beam splitters (BS1 and BS2), now parallel and mounted on their edges, with the consequent change in the position of the NGS mask, and the displacement of the LGS arm (now folded towards the elliptical mirror, EM).

Being rotated 90° along the horizontal axis, the two elliptical beam splitters are no longer subject to gravity effects. They have been also wedged by $\sim 1^\circ$ to improve the optical performance off-axis and to reduce double-bounce ghosts coming from the more collimated NGS beam. Moreover, the different location of the two source masks has effectively increased their accessibility and the clearance below the SM, ideally allowing the displacement of all the components belonging to the LGS and NGS arm on the same optical bench (OB, see Figure 4).

The LGS lenses have been redesigned to be achromatic within a 584-594 nm band and improve their nominal image quality (smaller WFE) for both conjugated altitudes (104 and 150 km).

Further changes have been done to the thickness of the optical components of the TEL: W and SM have been reduced to 30 mm and 50 mm, respectively and the CBS side dimension has been increased to 150 mm to widen the clear aperture and allow chamfering of the sharp edges.

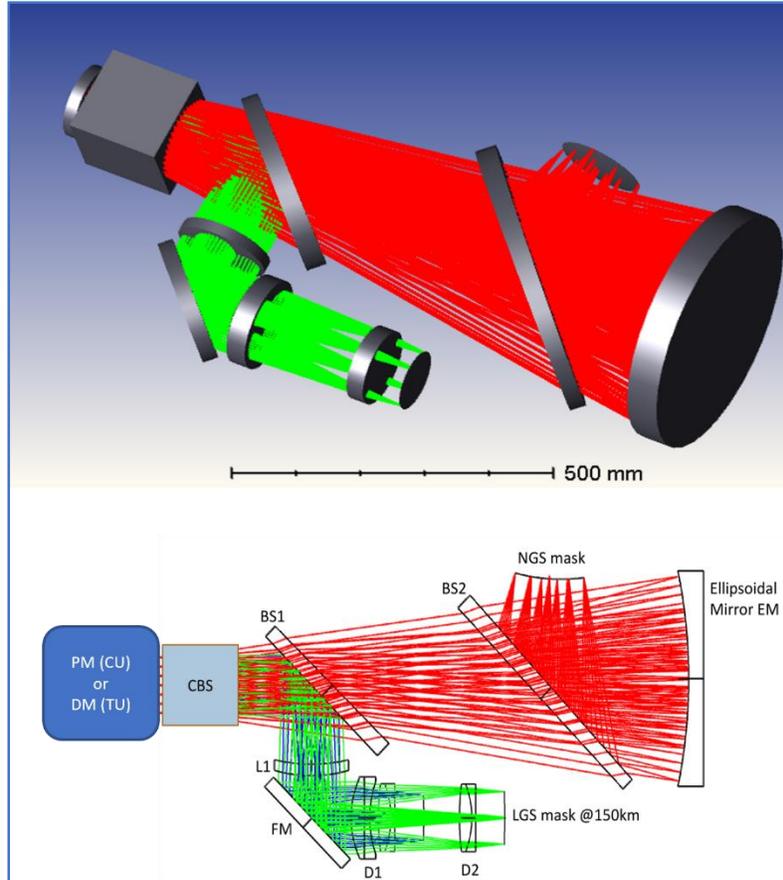


Figure 4. The CU Optical Bench (OB). The NGS (red) and LGS (green) optical path from the corresponding source mask to the CU intermediate pupil are shown (TEL optics above the CBS are not shown in this picture).

3.3 Mechanical Design

The CU mechanical design has been modified in order to accommodate the new optical layout (Figure 5) and then it has been verified by new FEA analyses [7]. Similarly to what was foreseen in the previous design, two main assemblies can be identified, namely the OB and the TEL. The split is functional not only from the mechanical point of view. This separation, in fact, is enabled by the nearly collimated beam at the pupil mirror that provides an easy optical interface between the two assemblies, that can be aligned as standalone optical systems. However, this is strictly true only for the NGS path while a different procedure is required for the LGS arm (see below).

The OB (and hence the whole CUMB) is mounted on the MS through the same interface that has been presented for the preliminary design, consisting in three kinematic couplings (see Figure 2) each mounted on a leg provided with 6 DoF adjustments, required to align the CU with the MORFEO optical axis.

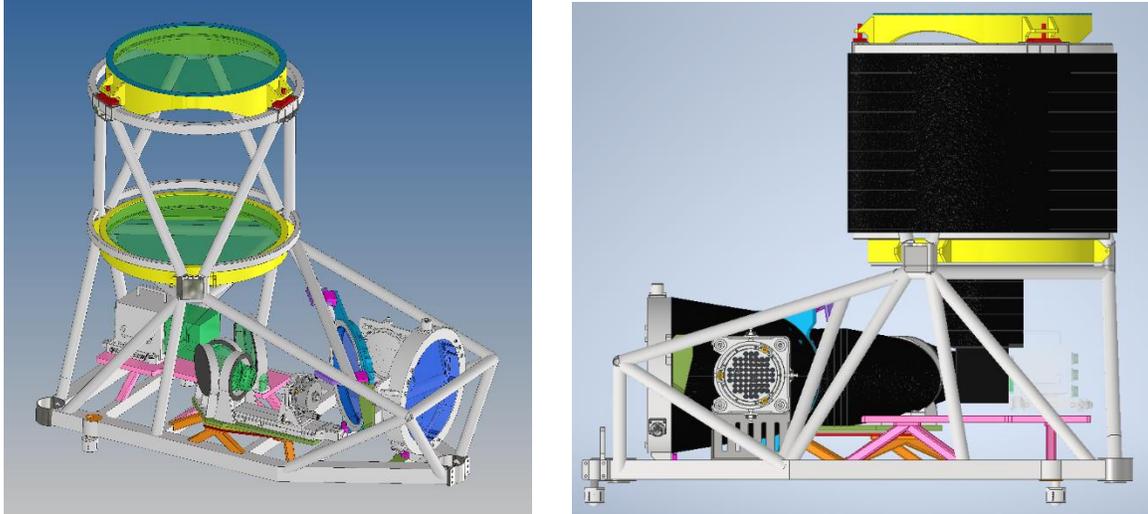


Figure 5. Overall view of the opto-mechanical components in the CUMB: *(left)* the TEL is interfaced on the OB just below the SM mount; the LGS subsystem is mounted on a removable bench (colored in green) provided with adjustments. All other components have single-component mounts. *(Right)* Side view of the CUMB showing the improved accessibility to the NGS mask; the increased clearance also facilitates the design of baffles and vanes, here shown in black. The CU external cover and the interfaces with the MORFEO MS are not shown here.

The TEL can be pre-aligned as a functional subassembly, and then mechanically interfaced to the OB. It is provided with 3 lateral displacements and tip & tilt adjustments for the alignment with the optical axis defined by the CBS. Finally, the LGS subassembly can be mounted and pre-aligned in a common removable bench (the green one on Figure 5). All other components (PM/DM, CBS, BS1, BS2, EM, NGS mask) have their own mounts.

4. NEW DESIGN PERFORMANCE

One of the outcomes of the revision of the preliminary design is an increase of the CU performance in terms of nominal WFE reduction. New analyses [7], in fact, showed that the nominal WFE is significantly improved for NGS sources across the full tech FoV, as well as for the LGS extended sources (see Table 2). The tolerance analysis and the definition of the WFE breakdown are still ongoing, but the first results make us confident that more margin can be gained to meet the stringent requirements indicated in Table 2.

Table 2. Nominal WFE (nm, rms) of the revised design compared to the ones of the preliminary design. All values have been calculated for the central wavelength of each source band (see Table 1).

DESIGN	WFE (nm, rms)				
	NGS-REF	NGS-LO	NGS-MIC	LGS@104km	LGS@150km
Central wavelength (λ_c)	800nm	1650nm	1650nm	589nm	589nm
Preliminary	16	26	28	37	40
Revised	10	11	11	20	23

Given the thickness of some optics and in particular the bulky CBS, it is necessary to consider large uncertainties for the homogeneity of the material, which could lead to a considerable increase in the WFE. In this case it is necessary to consider some compensation strategies to remove residual errors.

In fact, to mitigate this risk, as we expect that a large fraction of the field-invariant aberrations could come from the CBS, we plan to derive the shape of the correction map to be applied to the pupil mirror (by reworking it) to significantly compensate the measured WFE.

5. CONCLUSION

The revision of the optical design of the CU, started after the Preliminary Design Review, led to significant changes to the layout of the subsystem, while maintaining the same catadioptric configuration. Many weaknesses and critical issues have been overcome, as for the limited clearance around optical components and their accessibility, the asymmetric gravity sag variations of large flat beam splitters, and the chromatic aberrations, in particular in the LGS path. Some criticalities can still arise from the manufacturing of the CBS and from the homogeneity of its blanks, therefore a compensation strategy for residual errors has been investigated. The alignment plan has been completed and is currently under verification, as for the definition of the overall WFE breakdown. We are confident that the results of this revision will contribute effectively to speed up the final design phase of the CU, having already allowed to identify and address possible risks that could arise during the MAIT phase.

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