C2 - Restricted

FINAL REVIEW – TDE
LOW DISTORTION THICK DISK AMPLIFIER AT > 400 mJ

ESA Contract No. 4000129323/19/NL/AR/idb

Noordwijk, 2022, July the 12th

TDE - ORDER OF THE DAY

Contract Review TDE

Technical synthesis TDE

WP1 Improvement of Multizone Mirror

WP2 Decrease of thick disks OPD

WP3 Production of CAD drawings for the amplifier

WP4 Space compatibility and link to future space missions

WP5 Elaborate Preliminary Design

Conclusions

Approval TDE + Approval GSTP BB

PARTICIPANTS

For ESA

Pol.Ribes@esa.int	ESA technical officer
Alessandra.Ciapponi@esa.int	ESA technical officer

For CILAS

Rapaport@cilas.com	Technical manager, Project leader
Becerril@cilas.com	Mechanical engineer
Meyer.externe@cilas.com	Mechanical engineer
Aubry@cilas.com	Process engineer
Leval@cilas.com	Head of DE laser
Jegousse@cilas.com	Head of DP
Dufour@cilas.com	PLM
Porta@cilas.com	DQP

TDE – APPLICABLE AND REF DOCUMENTS

Applicable documents:

Reference	Title	Révision	Origin
4000129323/19/NL/AR/idb	Low distortion thick disk laser amplifier at > 400 mJ	1 / 0	ESA
DDC-19-244	MoM Negotiation meeting	0000	CILAS
M219-151	Contractor's Detailed Proposal	0000	CILAS
4000129323 CCN 1	CCN1_(COVID19)		ESA
CCN 2 to 4000129323	CCN2		ESA

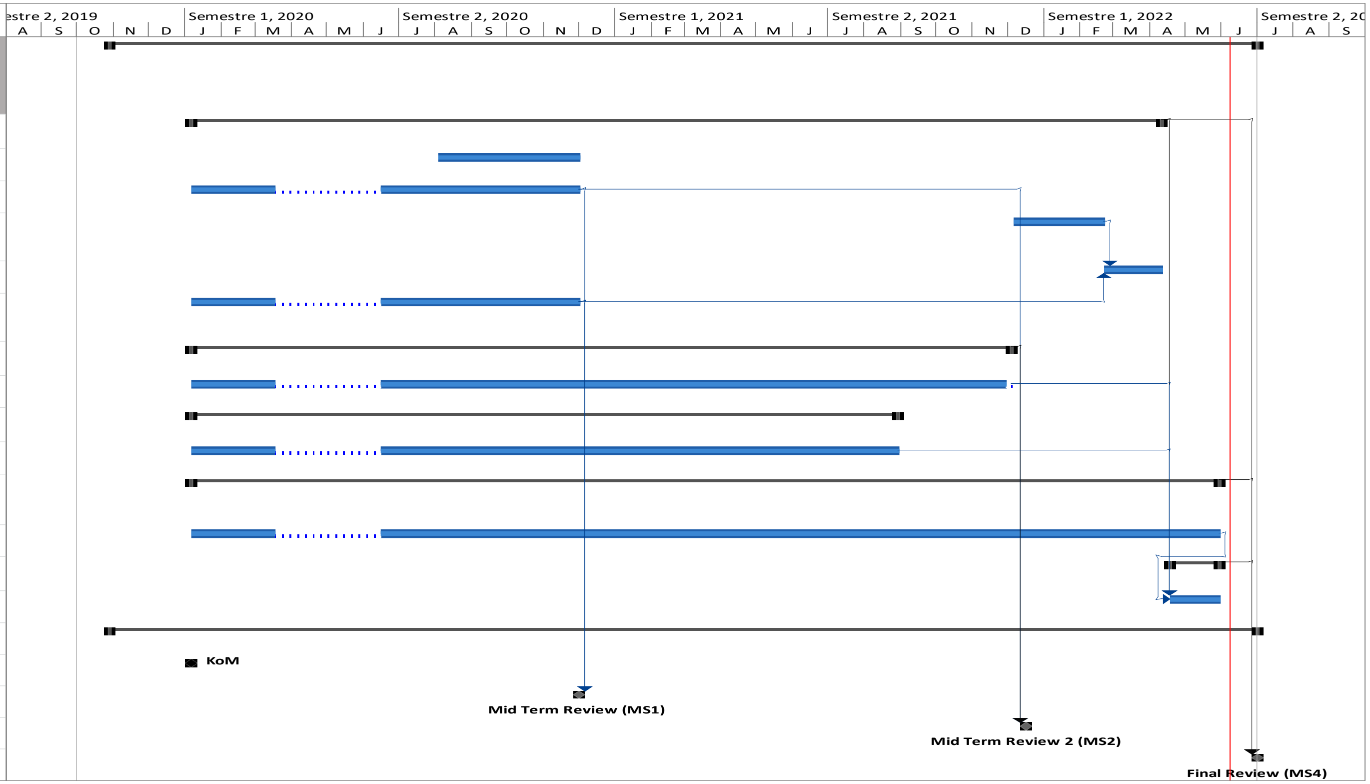
Reference documents:

Reference	Title	Reference	Title
ET-P-4070042-Rev0000	TN1.1 Review of multizone mirror design, testing and failure analysis	ET-P-2132082-Rev0000	ESA-CILAS-WP8.1-Oct 2016-DLR.pdf
ET-P-4070096-Rev0000	TN1.2 LIDT testing of new multizone mirrors	ET-P-2132173-Rev0000	FR_TRP 400 mJ
ET-P-4070097-Rev0000	TN1.3 Endurance test and space qualification of novel multizone mirrors	ET-P-4172006-Rev0000	FR_GSTP BB 400 mJ
ET-O-4070032-Rev0000	TN1.4 Report on potential new pump optics interface design	ET-O-2132177-Rev0000	WP4.1_BB integration & analysis of sensitivity of 400mJ amplifier_signed
ET-O-4070012-Rev0003	TN2.1 Improvement of thick disks OPD and comparison of models with experimental data	patent US9887512B2	Thick disc laser amplification system and uses thereof
ET-M-4070050-Rev0001	400mJ amplifier CAD model.stp	EP-P-2132195-Rev000	KoM Low distortion thick disk.pdf
ET-M-4070062-Rev0001	TN3.1 Thermomechanical analysis of Engineering Qualification model	ET-P-4070001-Rev0000	MoM of the KoM
ET-M-4070060-Rev0001	CAD Model 400 mJ amplifier	ET-P-4070077-Rev0000	TN4.1 Space Qualification
ET-P-4070076-Rev0000	TN3.2 Detailed Design Justification document for Engineering Qualification Model	ET-P-2132082-Rev0000	ESA-CILAS-WP8.1-Oct 2016-DLR.pdf
ET-P-4070043 Rev0000	MS1 EXPRO Low distortion thick disk.pdf	ET-P-4070044-Rev0000	ET-P-4070044-rev0000_EXPRO_MS1_MoM signed.pdf
ET-P-4070072-Rev0000	Presentation MS2 EXPRO + MS1 GSTP BB	ET-P-4070073-Rev0000	Minutes of Meeting MS2 meeting EXPRO

TDE - PLANNING

Gantt diagram

N°	Task Name	% achieved
1	**1 EXPRO : Low Distortion Thick Disk Amplifier at >400mJ**	**100%**
2	**1.1 WP1 Improvement of Multizone Mirror**	**100%**
3	1.1.1 Review of the laser beam characteristics	100%
4	1.1.2 Procurement of a new Multizone Mirror batch	100%
5	1.1.3 Testing and comparison of performance for 2 types of multizone mirrors	100%
6	1.1.4 Testing of the new mirror integrated in the laser	100%
7	1.1.5 Investigation of a different mirror design in order to avoid the masking	100%
8	**1.2 WP2 Decrease of thick disks OPD**	**100%**
9	1.2.1 Improvement of the OPD and models validation	100%
10	**1.3 WP3 Production of CAD drawings for the**	**100%**
11	1.3.1 Thermomechanical design and analysis of	100%
12	**1.4 WP4 Space compatibility and link to future space missions**	**100%**
13	1.4.1 Input from an end user of the amplifier	100%
14	**1.5 WP5 Elaborate Preliminary Design**	**100%**
15	1.5.1 Recommendations for follow-up activities	100%
16	**1.6 Management**	**100%**
17	1.6.1 KoM	100%
18	1.6.2 Mid Term Review (MS1)	100%
19	1.6.3 Mid Term Review 2 (MS2)	100%
20	1.6.4 Final Review (MS4)	100%



TDE - DELIVERABLES

Deliverable	Title	Deliverables Contractual Due Date	Delivered Date	Due date	Ref N°
TN1.1	Review of the 100Hz laser beam characteristics and its possible spatial and temporal modulations	End of task 1	23/11/2020	Nov. 2020	ET-0-4070042-Rev0000
TN1.2	Laser damage testing of the new multizone mirror	End of task 1	24/06/2022	June 2022	ET-0-4070096-Rev0000
TN1.3	Endurance test of novel multizone mirror *and space qualification*	End of task 1	24/06/2022	June 2022	ET-0-4070097-Rev0000
TN1.4	Report on potential new pump optics interface design	End of task 1	23/11/2020	Nov. 2020	ET-O-4070032-Rev0000
TN2.1	Improvement of thick disks OPD and comparison of models with experimental data	End of task 2	24/06/2022	June 2022	ET-O-4070012-Rev0003
TN3.1	Thermomechanical analysis of Engineering Qualification model	End of task 3	24/06/2022	June 2022	ET-M-4070062-Rev0001
TN3.2	Detailed Design Justification document for Engineering Qualification Model	End of task 3	24/06/2022	June 2022	ET-P-4070076-Rev0000
TN4.1	Space Qualification	End of task 4	24/06/2022	June 2022	ET-P-4070077-Rev0000
DDVP	Design Development and Verification Plan	End of task 5	08/07/2022	June 2022	ET-P-4070083-Rev0000
ICD	Interface Control Document	End of task 5	24/06/2022	June 2022	ET-P-4070084-Rev0000
RRA	Reliability and Risk Assessment	End of task 5	24/06/2022	June 2022	ET-P-4070085-Rev0000
TDP	Final Review Technical Data Package	Final Review	24/06/2022	June 2022	ET-P-4070086-Rev0000
AB	Abstract	Final Review	24/06/2022	June 2022	ET-P-4070087-Rev0000
BR	Brochure	Final Review	24/06/2022	June 2022	ET-P-4070088-Rev0000
FP	Final Presentation	Final Review	24/06/2022	June 2022	ET-P-4070100-Rev0000
ESR	Executive Summary Report	Final Review	24/06/2022	June 2022	ET-P-4070090-Rev0000
FR	Final Report	Final Review	24/06/2022	June 2022	ET-P-4070091-Rev0000
TAS	Technology Achievement Summary	Final Review	24/06/2022	June 2022	ET-P-4070092-Rev0000
HW	Updated Breadboard	Final Review	NA		On loan on site
CCD	**Contract Closure Documentation**	Contract closure	12/07/2022	June 2022	ET-P-4070093-Rev0000

TDE - FINAL REVIEW

- Date: End of project **(T0+30, June 2022)**
- Location: ESTEC + visioconference
- Input:

✓ Contract **4000129323/19/NL/AR/idb** : 3-16131_Contract_CILAS signed.pdf
✓ Statement of Work : **ESA-TRP-TEC-SOW-014837**
✓ MoM Negotiation meeting : **DDC-19-0244**
✓ Contractor's Detailed Proposal **: M219-151**
✓ **ET-P-2132 173 Rev0000** FR_TRP 400 mJ_signed.pdf
✓ MS1: **ET-P-4070043-Rev0000** MS1 EXPRO
✓ MoM of MS1: **ET-P-4070044-Rev0000_** MoM MS1.pdf
✓ MS2: **ET-P-4070072-Rev0000** Presentation MS2 EXPRO + MS1 GSTP BB.pdf
✓ MoM of MS2: **ET-P-4070073-Rev0000**_MoM MS2.pdf

- Output :

✓ **TDP for TDE 400 mJ project**

- Description: the objectives of this Review are:

✓ Improvement of multizone mirror
✓ Improvement of OPDs with new process
✓ Production of CAD drawings for the amplifier
✓ Thermomechanical design and analysis
✓ Space compatibility review
✓ Preliminary design of amplifier layout

TDE - WP1.1 REVIEW OF THE LASER CHARACTERISTICS AS THE REPETITION RATE IS INCREASED TO 100 HZ

T0→T0+4

Output : TN1.1. Review of the 100 Hz laser beam characteristics, and its possible spatial and temporal modulations

Objective of the task :

Understand the reasons for the failure of the multizone mirror by :

- Measuring temporal and spatial distribution of the laser beam. Verifying polarization.
- Measuring micrographies of damaged mirrors.

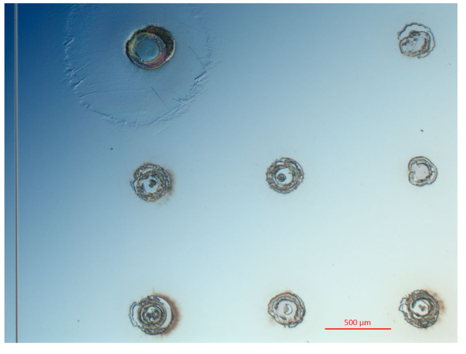
TDE - WP1.1 – MICROGRAPHS OF DAMAGED MULTIZONE MIRROR

DLR performed LIDT tests on non-damaged HR zones of mirror used in amplifier

> 25 J/cm² measured

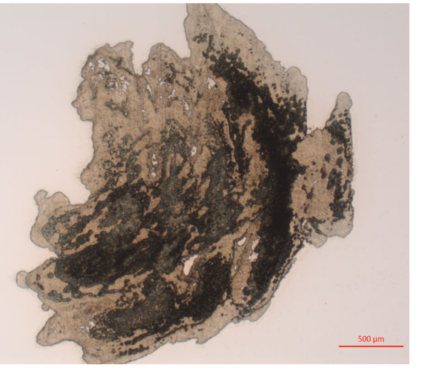
Micrographs taken by LaserOptik

LIDT



« Clean » damage spots, some show a dark cloud around them

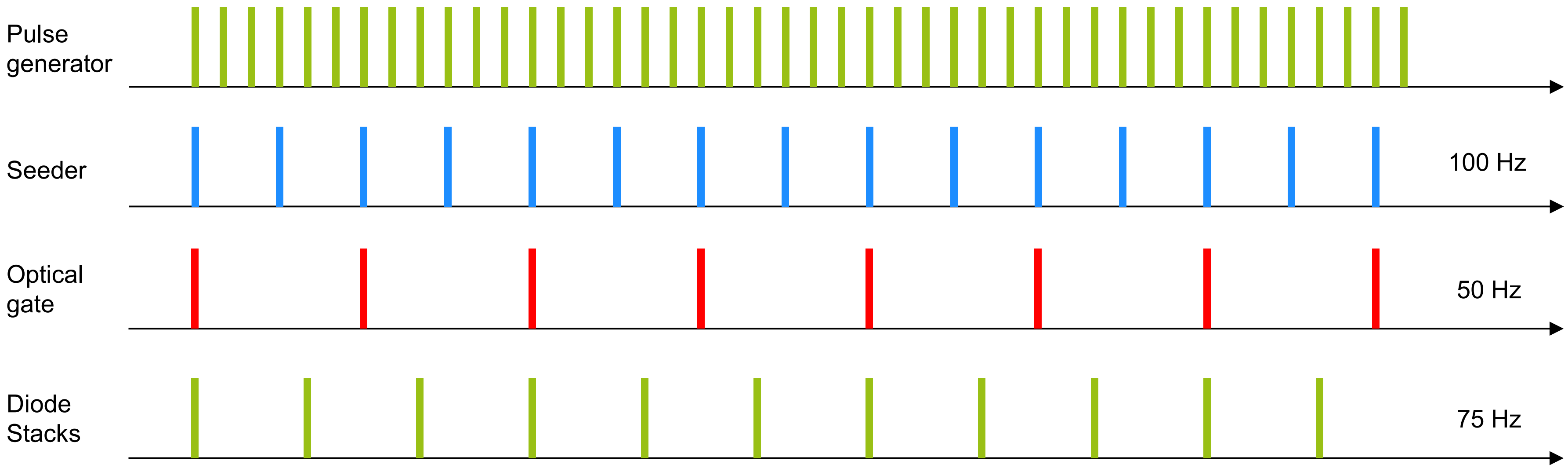
Damage in 400-mJ, 100-Hz amplifier



Quite large, darkened zones

TDE - WP1.1 – CHARACTERIZATION OF 400-mJ AMPLIFIER

Synchronization of elements



Thermal load from 50 Hz to 100 Hz can be applied to the disks, while the seeding pulse train remains at 50 Hz

➡ **The amplifier performed for hours at high energy (375 mJ), 100 Hz thermal load.**

TDE - WP1.1 – CHARACTERIZATION OF 400-mJ AMPLIFIER

Depolarization losses

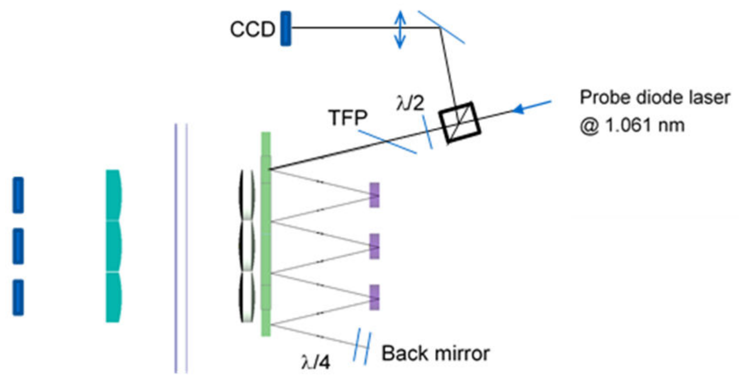
Thermal load doubles at 100 Hz, compared to 50 Hz :

→ **higher disk temperature, more deformations, more stress**

Stress-induced birefringence causes losses on the coupling polarizer

→ **efficiency reduction, possible feedback to stages up the laser path**

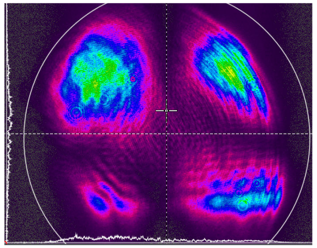
The fluence seen inside the amplifier could be higher than that at 50 Hz

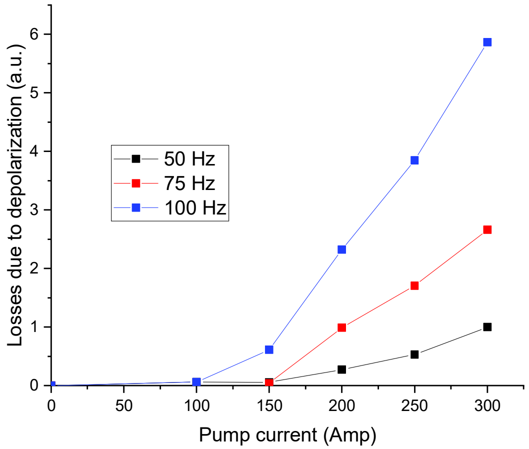


TDE - WP1.1 – CHARACTERIZATION OF 400-mJ AMPLIFIER

Depolarization losses

At 50 Hz, stress induced birefringence is very weak.
At 100 Hz, a typical pattern is recorded





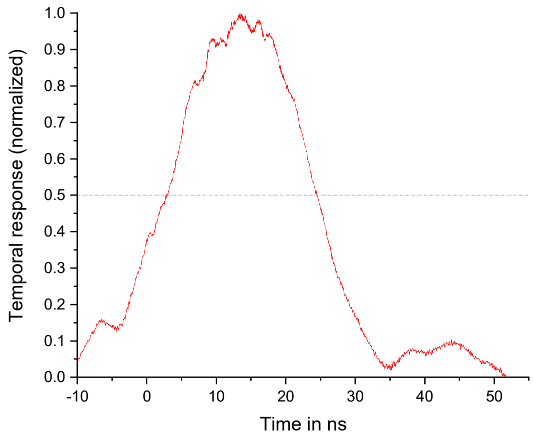
The increase in losses is strongly non-linear

An isolator between the 2 stages becomes mandatory

A reduction of the operating temperature would be very beneficial

TDE - WP1.1 – CHARACTERIZATION OF 400-mJ AMPLIFIER

Temporal characterization



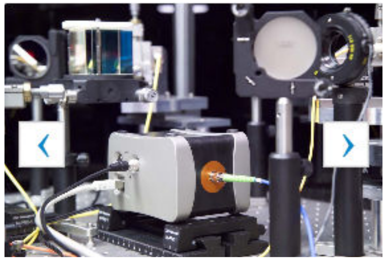
22 ns pulse FWHM, 4 GHz bandwidth detection system

Stable from 50 Hz to 100 Hz thermal load, no visible modulation

TDE - WP1.1 – CHARACTERIZATION OF 400-mJ AMPLIFIER

Spectral characterization

Use of Zoom Spectra Laser Spectrum Analyzer



Key features

- 3 GHz high spectral resolution
- Excellent absolute accuracy: 600 MHz
- Simultaneous bandwidth of a few nm
- High measurement rate capability: 30 kHz
- Compact size
- Robust life-long factory calibration
- User-friendly SpectraResolver software
- Trigger

@ 50 Hz, $\lambda_{50\ Hz}$ = 1064.444 nm

@ 100 Hz, $\lambda_{100\ Hz}$ = 1064.457 nm

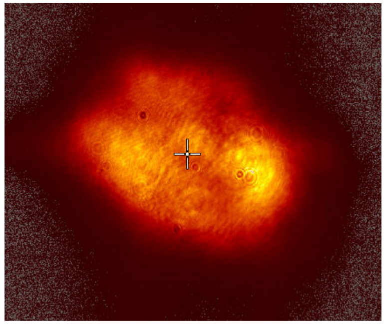
The redshift of the amplified beam, while the seeder wavelength remains stable is proof of the increase in temperature.

→ A reduction of the operating temperature would be very beneficial

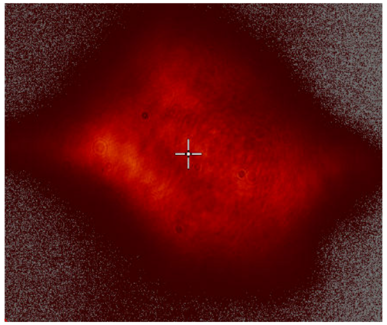
TDE - WP1.1 – CHARACTERIZATION OF 400-mJ AMPLIFIER

Spatial characterization

The beam is imaged on a CCD with a magnification factor of 1/3



400 mJ, 50 Hz thermal load



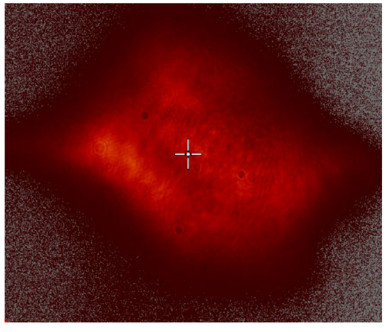
400 mJ, 75 Hz thermal load

The measured beam is rather stable, uniform. No hotspot is observable.

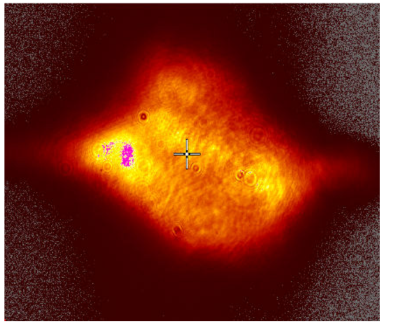
The output energy is stable : no decrease in efficiency.

TDE - WP1.1 – CHARACTERIZATION OF 400-mJ AMPLIFIER

Spatial characterization



400 mJ, 75 Hz thermal load



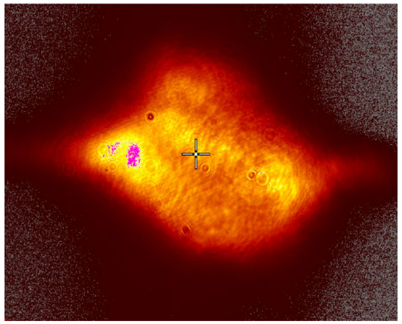
350 mJ (same current), 100 Hz thermal load

Some deformation is getting noticeable, but the distribution remains quite flat.

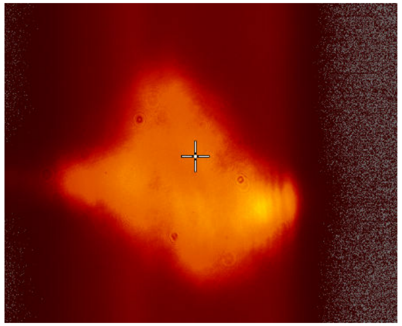
The diode current is kept constant in both stages, but the energy drops: the efficiency is reduced.

TDE - WP1.1 – CHARACTERIZATION OF 400-mJ AMPLIFIER

Spatial characterization



350 mJ, 100 Hz thermal load



375 mJ (max energy), 100 Hz thermal load

The beam size is a little reduced, but the distribution remains quite flat.

The 2nd stage diode current is increased up to energy saturation at 375 mJ: the efficiency is reduced, but the amplifier operated at this energy and 100 Hz thermal load for 20 hours without mirror damage.

➞ A reduction of the operating temperature would be very beneficial

TDE - WP1.1 – CHARACTERIZATION OF THE 400-mJ AMPLIFIER

The amplifier was operated at ~ 400 mJ, with the thermal load of 100-Hz diode pump for 20 hours.

The beam characteristics did not change much, and do not justify a large increase of fluence on the optics.

The mirror was not damaged while the amplified beam operated at 50 Hz, even when a thermal load equivalent to 100 Hz on the disks.

The damage appears to result from an increase in average power in the amplified beam, not an increase in peak fluence.

➡ **This supports the hypothesis that the photoresist used for the photolithography leaves a residue even after cleaning. It is consistent with the micrographs taken of the damage.**

TDE - WP1.1 – SYNTHESIS

- ✓ The monolithic multizone mirror has been analyzed.
- ✓ The amplifier has been characterized for different thermal loads, with the objective to understand the cause of the mirror failure.
- ✓ Necessary improvements to the laser design have been brought to light (reduction of operating temperature).
- ✓ The most likely cause of the mirror failure has been understood.
- ✓ TN1.1 has been delivered.

TDE - WP1.2 PROCUREMENT OF A NEW MULTIZONE MIRROR BATCH

T0→T0+8
Output : Purchase order for a new multizone mirror batch

Objective of the task :
Purchase order of a new multizone mirror batch:

- Review the specifications with suppliers (substrate, scratch & digs, process (IBS, magnetron…), improved cleaning process…)

TDE - WP1.2 – PROCUREMENT OF A NEW MULTIZONE MIRROR BATCH

The multizone mirror specifications have been updated to maximize the chances for best LIDT :

- **material, scratch&digs, thickness and flatness, have been changed in agreement with the coating and the substrate suppliers**
- **the dimensions have been adjusted to conform to the new disk thickness**

The supplier (LaserOptik) has been made aware that the previous coating performed well at 50 Hz, but showed damage at 100 Hz. We informed them that we believe the photolithographic process leaves a residue on the HR coating.

They made a calorimetric measurement of the new HR coating with and without photolithographic process to bring to light any residual effect due to the process : no noticeable difference was measured.

They modified the process to improve the cleaning steps of the photolack.

TDE - WP1.2 – PROCUREMENT OF A NEW MULTIZONE MIRROR BATCH

The multizone mirrors were more difficult to produce than LaserOptik expected.

We received 3 mirrors out of 5 ordered, after 3 trials.

LaserOptik signified to us that they would need an additional development phase with a research laboratory before commiting to realizing a new multizone mirror.

If those improvements cannot be demonstrated, a monolithic mirror might not be advantageous to buy, and we would consider the procurement of an assembled multizone mirror.

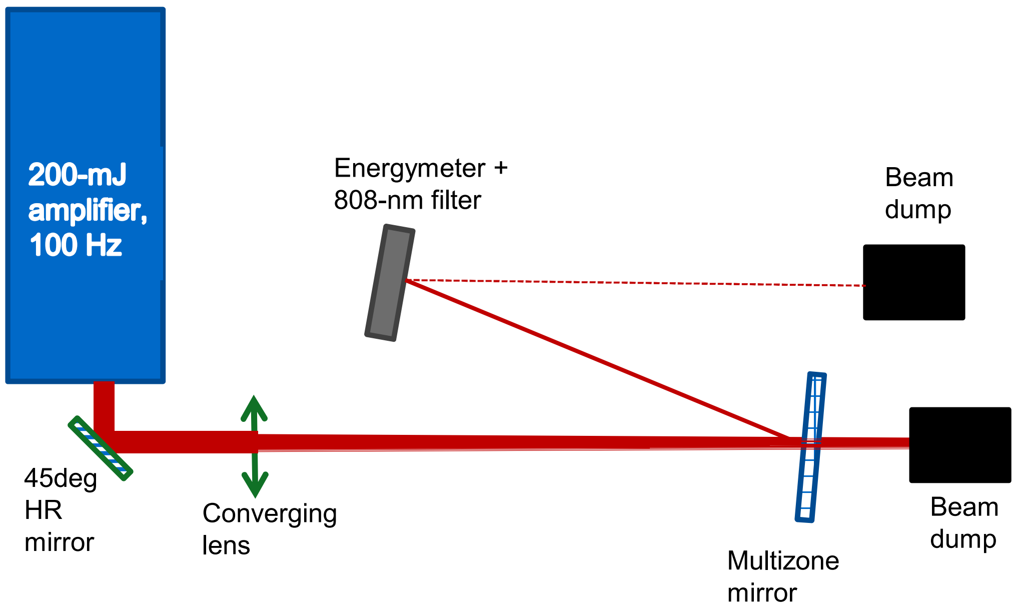
TDE - WP1.3 - TESTING AND COMPARISON OF PERFORMANCE FOR 2 TYPES OF MULTIZONE MIRRORS

T0→T0+23
Output : TN1.2_Laser damage testing of the new multizone mirror

Objective of the task :
Experimental comparison of 2 types of mirrors
- Test laser damage resistance of new mirror compared to first generation multizone mirror

TDE - WP1.3 – TESTING AND COMPARISON OF 2 MULTIZONE MIRRORS

Bench set-up



TDE - WP1.3 – TESTING AND COMPARISON OF 2 MULTIZONE MIRRORS

Property		1st generation mirror	2nd generation mirror
Supplier		LaserOptik	LaserOptik
Serial number		20117ti1	24022Ke3
Substrate	material	Fused silica	Fused silica
	size	77 x 25 x 3 mm^3	96 x 25 x 7 mm^3
	Scratch&dig	20-10	5-1
	LIDT	10 J/cm^2	30 J/cm^2
Coating		IBS	IBS
Extra specification			Extra care for cleaning step
Incident energy		200 mJ	200 mJ
Pulse length		22 ns	22 ns
Repetition rate		100 Hz	100 Hz
Spot size at mirror (diameter), number of test locations Fluence (J/cm^2)		5.2 mm, 1 location 0.9 J/cm^2	5.2 mm, 1 location 0.9 J/cm^2
		2.9 mm, 1 location 3 J/cm^2	2.9 mm, 1 location 3 J/cm^2
		2.0 mm, 3 locations 6.4 J/cm^2	2.0 mm, 3 locations 6.4 J/cm^2

TDE - WP1.3 – TESTING AND COMPARISON OF 2 MULTIZONE MIRRORS

No damage is observed with either mirror, despite fluence > 6 J/cm².

Fluence inside the amplifier < 2 J/cm².

Size of the irradiated spot is smaller in this experimental test than in the amplifier.

Possible explanation: heat dissipates easier with small beam size: thermal effects insufficient to cause damage in our bench set-up.

Energy that would be needed to achieve comparable laser fluence and beam size: 1 J/cm².

WP1.3 is inconclusive: improvement of the new multizone mirror is not demonstrated.

TN1.2 has been delivered.

TDE - WP1.4 - TESTING OF THE NEW MIRROR INTEGRATED IN THE LASER

T0→T0+26
Output : TN1.3_Endurance test and space qualification of novel multizone mirrors

Objective of the task :
Integrate new mirror in the amplifier set-up, and run the system 100 hours continuously at 100Hz, with its characteristics monitored.

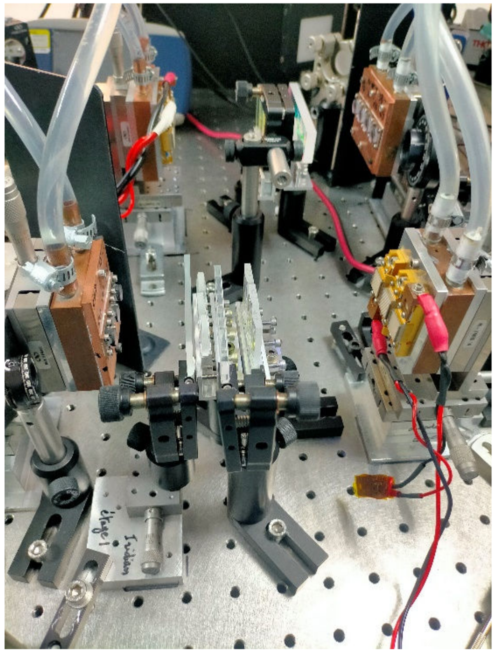
- Characterize the amplifier at 100 Hz

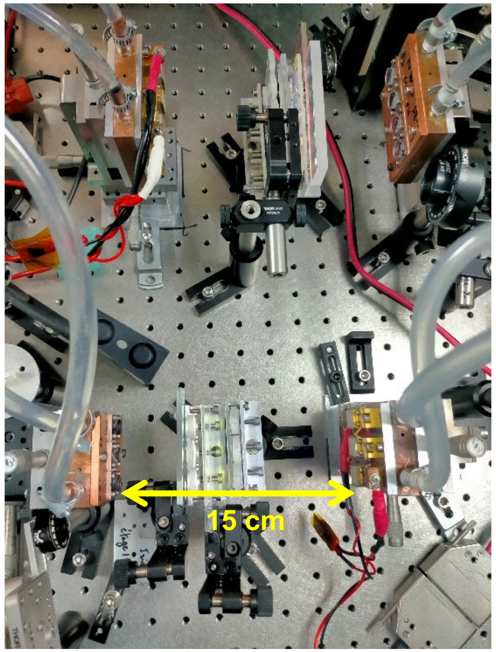
TDE - WP1.4 - TESTING OF THE NEW MIRROR INTEGRATED IN THE LASER

The different elements of the new amplifier design are integrated in the breadboard:

- new disk thickness, doping concentration, and diameter
- new adhesive (space qualified), new interface
- new pump module and pump size
- new absorptive coating (space qualified)
- new multizone mirror in stage 2

TDE - WP1.4 - TESTING OF THE NEW MIRROR INTEGRATED IN THE LASER





TDE - WP1.4 - TESTING OF THE NEW MIRROR INTEGRATED IN THE LASER

Unfortunately, amplification at 400 mJ, 100 Hz lead to failure of another optical element.

TN1.3 has been delivered.

TDE - WP1.5 - INVESTIGATION OF A DIFFERENT MIRROR DESIGN IN ORDER TO AVOID THE MASKING PROCESS

T0→T0+8

Output : TN1.4 Report on potentiel new pump optics interface design

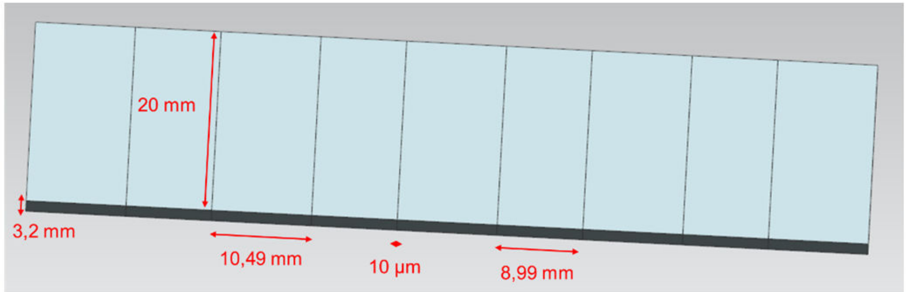
Objective of the task :

- Identify and specify a different multizone mirror design

- Avoid the masking process by assembly (optical bounding, cementing…) of monozone mirrors

TDE - WP1.5 - ASSEMBLED MULTIZONE MIRROR

Dimensions adequate for new design are considered



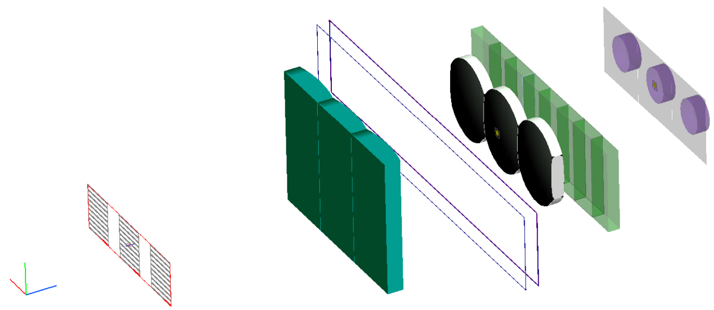
Questions to be answered:

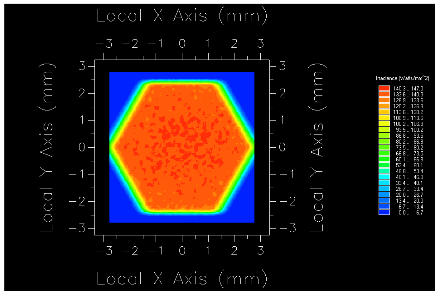
- ✓ **Any optical effect ?**
- ✓ **Any thermal effect ?**
- ✓ **What mechanical tolerances ?**
- ✓ **Resistance to vibrations for space compatibility ?**
- ✓ **Industrial feasability and cost ?**

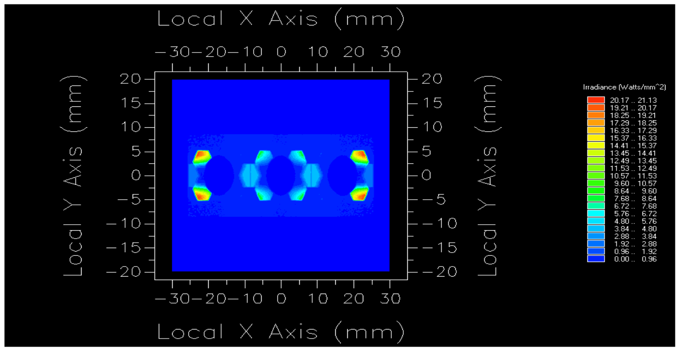
TDE - WP1.5 - OPTICAL SIMULATIONS

Fictionnal glue made up of bad case scenario physical properties:

Index : 1.55
Absorption : 0.1 cm^{-1}
Shore D : 70
Thermal conductivity : 0.1 W / (m.K)
CTE : 200 µm / (m.K)
Density : 1231 kg / m^3
Young modulus: 1034 Mpa
Poisson ratio : 0.34
Tensile strength : 20 Mpa





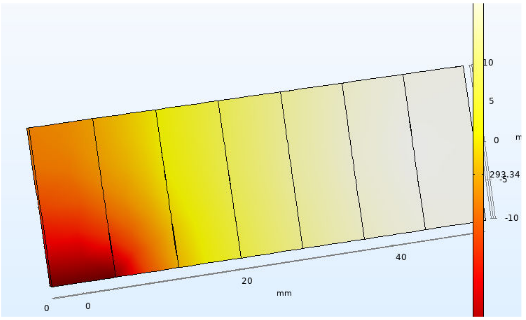


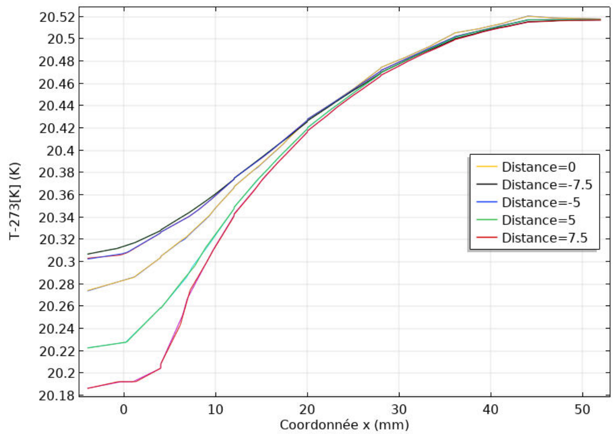
No visible effect on radiation deposition pattern

TDE - WP1.5 - THERMAL SIMULATIONS

Optical simulation yielded 0.61 mW absorbed in each adhesive volume, almost homogeneous distribution

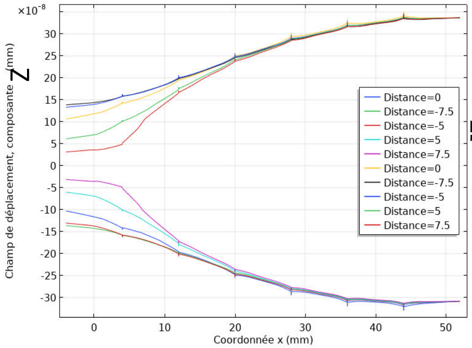
With a very limited contact zone, the mirror temperature was calculated with COMSOL





TDE - WP1.5 - MECHANICAL SIMULATIONS

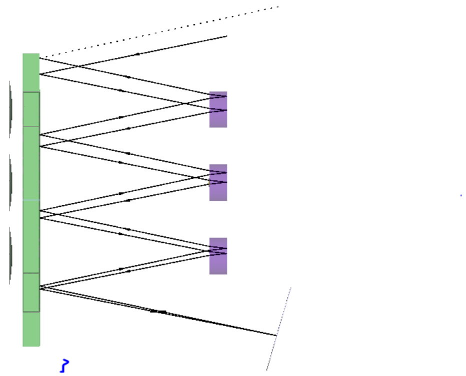
COMSOL also gives the deformation field associated to these conditions



These are very small displacements.

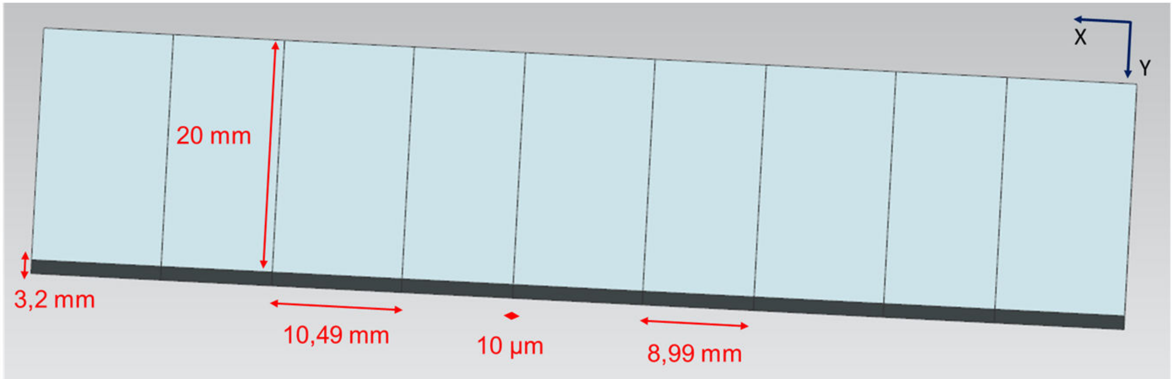
…ever, the multizone mirror amplifies the

A tilt of 0.05 deg of the mirror yield the following misalignment



The deformation due to the absorption of the adhesive would yield a tilt of about 0.1 µrad, and a misalignment of about 1 µm on the last disk

TDE - WP1.5 - VIBRATION SIMULATIONS



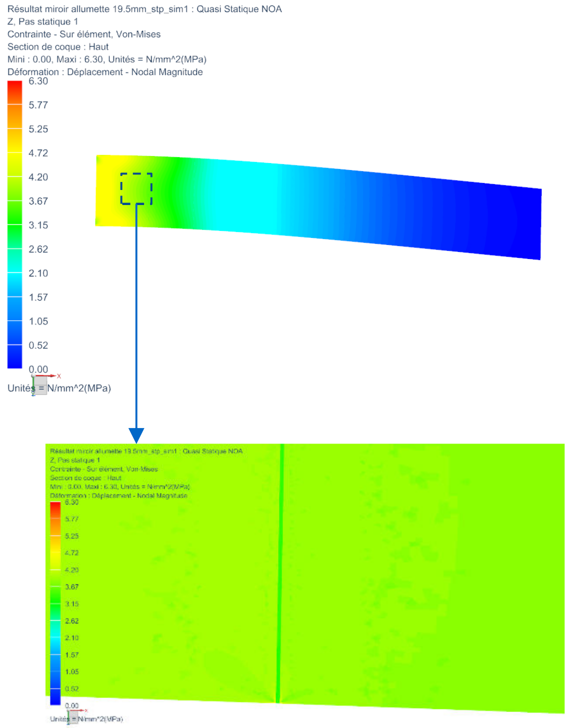
Substrate : BK7
Adhesive : NOA61

- Objective: to estimate what the mirror can withstand
  This is not intended to replace qualification by the supplier
- Vibration and shock depend on the whole assembly
- Quasi-static approach (gravity load) does not depend on the mount:
  gravity field (26 g) applied separately along each direction (adverse case)

TDE - WP1.5 - VIBRATION SIMULATIONS

Results

- Most adverse case : Out of Plane (along Z axis)
- Peak values at edge due to idealized boundary conditions



- Max value in glass : 5 MPa (Tensile Str : 37 MPa)
- Max value in glue : 3.5 MPa (Tensile Str : 20 MPa)

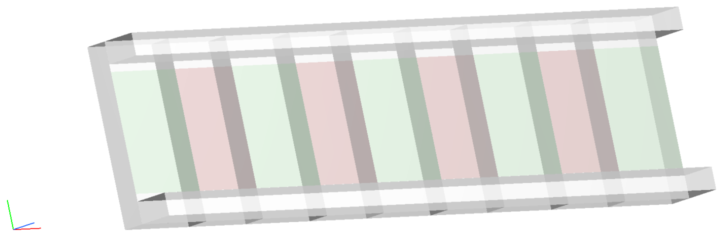
Initial estimate shows that the mirror should withstand 26g load

TDE - WP1.5 - INDUSTRIAL REALIZATION

WinLight + CILAS have demonstrated the feasibility of a space compatible, assembled optical element in the MicroCarb mission (TRL 8).

They use NOA61, which is not LIC certified unless a certain process is used.

Standard elements of hard coated optics with high LIDT could be assembled as shown here :



A second potential supplier has also been identified: Materion

An early ROM shows a cost of ~3 times that of a monolithic mirror.

TDE - WP1.5 - SYNTHESIS

The possibility to replace the monolithic multizone mirror by an assembled optics has been considered.

According to the simulations, there is no showstopper to the use of an assemblage of standard, high LIDT, optical elements.

These assembled components can be made space-compatible.

It would eliminate the use of a photoresist during a lithophotographic process, so no residue would likely cause mirror failure at high repetition rate.

Several suppliers have been identified.

TN1.4 has been delivered.

TDE - WP2.1 - IMPROVEMENT OF THE OPD AND MODELS VALIDATION

T0→T0+23
Output : TN2.1 Improvement of thick disks OPD and comparison of model with experimental data

Objective of the task :

- Reduce OPD and improve Gain of second stage amplifier.
- Test of a single element.

TDE - WP2.1 - MOTIVATIONS

Previous work showed that:

- **the functionalized disks presented a persistant non-zero OPD that appeared after the bonding process (bi-metallic strip concept)**
- **the large functionalized disks under pumping presented an OPD that was astigmatic**
- **the disks temperature at 100 Hz was causing several issues:**
  - **stress-induced by refringence, and losses by depolarization**
  - **red-shifting of the amplified beam wavelength**
  - **loss of efficiency (emission cross-section and line shift)**
  - **phasefront perturbations**

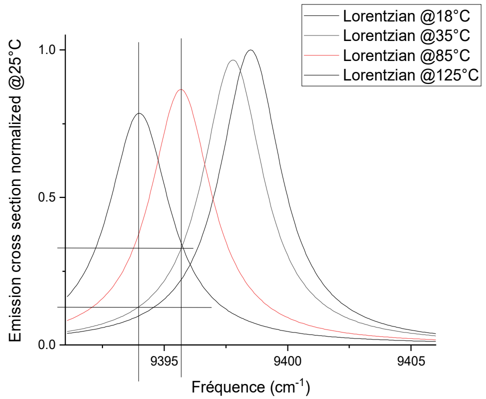
A decision was made to redesign the amplifier on top of improving the engineering of the bonding process.

TDE - WP2.1 - REDUCTION OF THE DISKS OPERATING TEMPERATURE

Nd^{3+}:YAG coefficient of thermal conductivity is ~10 W / (m.K) and decreases with temperature.

Under pumping, the rear face temperature is close to that of the coldplate (~30°C), while the front face temperature reaches ~130°C at 100 Hz with the old design (4-mm thick disks)

Nd^{3+}: YAG emission cross-section depends on temperature
Matching the line at the top and at the bottom of the disks becomes impossible at 100 Hz.



TDE - WP2.1 - REDUCTION OF THE DISKS OPERATING TEMPERATURE

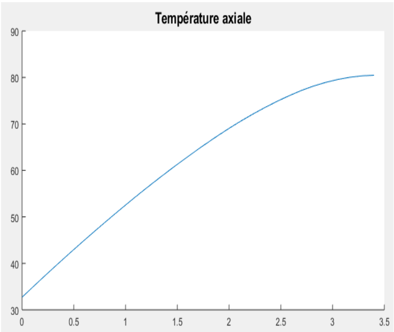
Simulations for various thickness combinations (no SHB, no effect due to temperature on small signal gain)

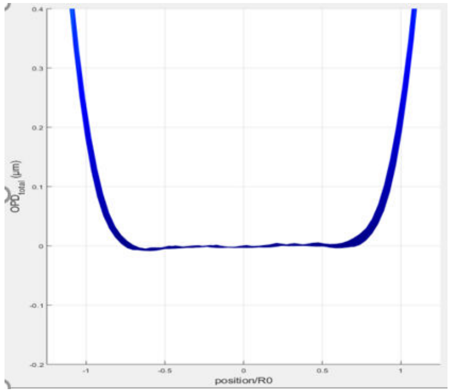
Thickness – configuration cases	Stage 1 : 4 mm Stage 2 : 4 mm	Stage 1 : 4 mm Stage 2 : 3.4 mm	Stage 1 : 3.4 mm Stage 2 : 3.4 mm	
Case number	1	2	3	4
Number of disks	2 3	4 3	3 4	3 3
Pump diameter	5.5 mm 6.4 mm	5.5 mm 8 mm	5.5 mm 6.4 mm	5.5 mm 7.9 mm
Disk diameter	8.5 mm 9.5 mm	8.5 mm 12 mm	8.5 mm 9.5 mm	8.5 mm 11 mm
Average pump power per disk @100 Hz (peak pump power)	29 W 40 W	29 W 43 W	28 W 35 W (1.6 kW)	28 W 48 W (2.2kW)
O2O efficiency	22.1 %	21.2 %	21.0 %	20.4 %
Front face temperature (°C)	123 133	123 85	80 102	80 94
Output energy	98 mJ 490 mJ	226 mJ 490 mJ	140 mJ 490 mJ	140 mJ 490 mJ

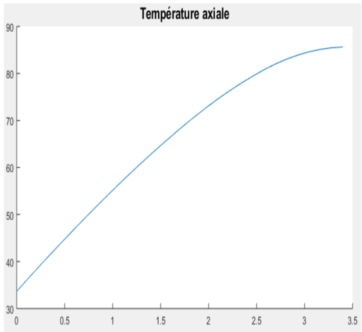
1.2 % is maximum doping concentration, so 3.4 mm is minimum thickness achievable

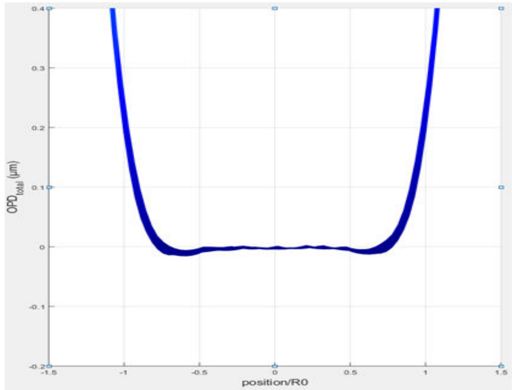
TDE - WP2.1 - REDUCTION OF THE DISKS OPERATING TEMPERATURE

With the new design (3.4-mm thick disks in both stages), the calculations yield:









Stage 1 **Stage 2**

➡ **The maximum temperature reached is similar to that of current design at 50 Hz.**

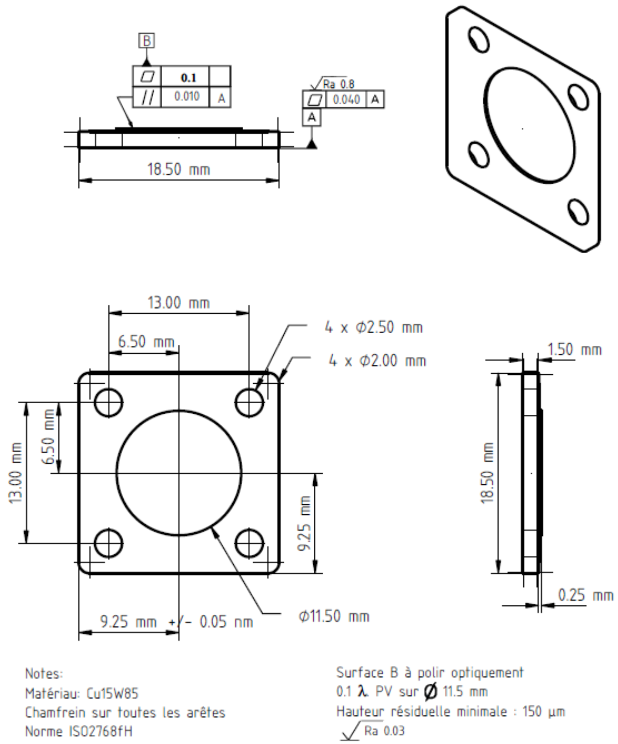
➡ **Flat OPD across the beam.**

TDE - WP2.1 - IMPROVED ENGINEERING OF BONDING PROCESS

The CuW base have been redesigned squared to avoid causes for astigmatism.

They have been provisionned and have arrived at CILAS, ready for bonding

This will not eliminate all astigmatism, because the pump pattern is intrinsically non-symmetrical



TDE - WP2.1 - IMPROVED ENGINEERING OF BONDING PROCESS

New low-temperature cured epoxy identified to reduce the OPD

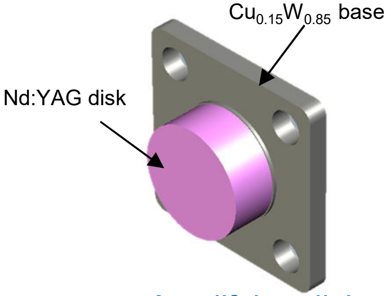
Previous adhesive used : **EPOTEK 353ND** (Cures at T > 70°C)

- not suitable because of a slight bimetallic effect
- Classified CMR in 2019

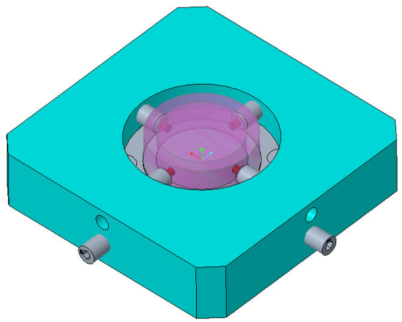
New adhesive selected : **EPOTEK 301-2**

- Similar mechanical and physical properties to EPOTEK 353ND
- NASA approved, low outgassing Epoxy
- Resistant to impacts and vibrations
- Suitable for bonding optics inside scientific instruments
- Curing at low temperature (down to RT)
- Safe to use

Toolings for bonding process (disks, bases, tools and adhesive) have been designed and provisioned.



Amplifying disk assembled

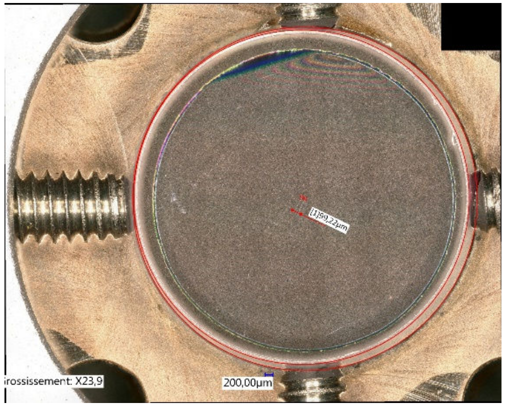


Tooling for disk bonding

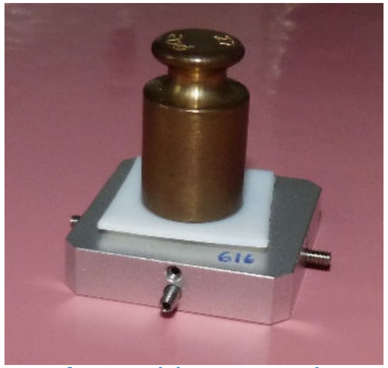
TDE - WP2.1 - IMPROVED ENGINEERING OF BONDING PROCESS

Differential scanning calorimetry measurements :

- **Cure optimization to achieve 90% cross-linking rate + Tg > 50°C**
- **Results → 2 cure schedules are tested :**
  - **48h at 23°C + reheat 3h 60°C**
  - **15h at 50°C**



Centering of the disk

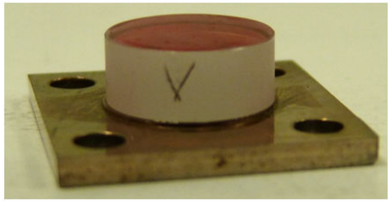

Assembly pressed

Bonding tested on 3 disks Ø8.5mm:

- 2 during 48h 23°C + reheat 3h at 60°C
- 1 during 15h at 50°C

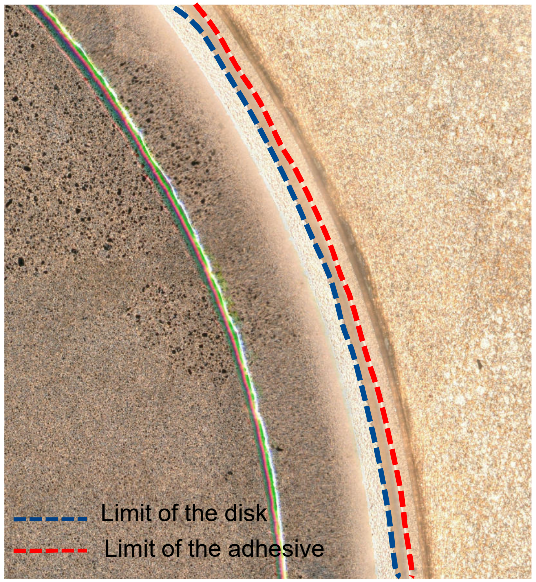
8 disks Ø11 mm were bonded :

- 4 during 48h 23°C + reheat 3h at 60°C
- 4 during 15h at 50°C

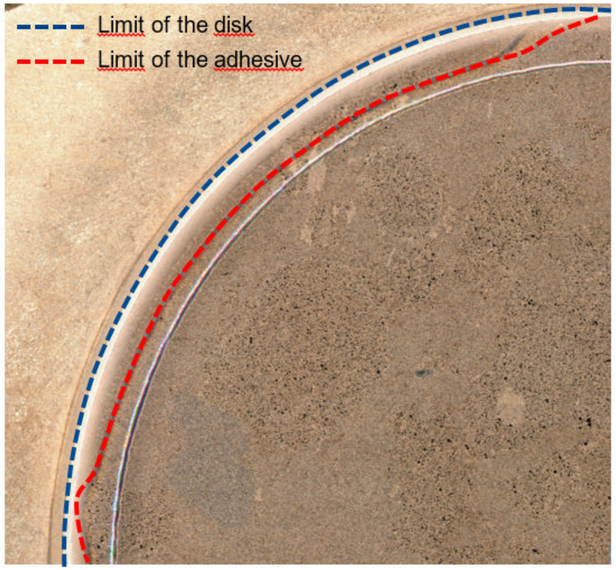

Final result

TDE - WP2.1 - IMPROVED ENGINEERING OF BONDING PROCESS

- Most disks present a slight overflow of the adhesive → 100% of disk surface is bonded :



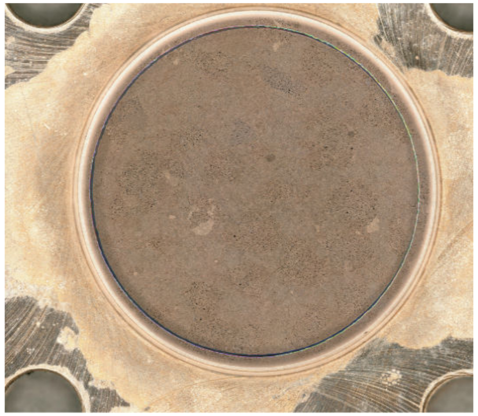
- Only 4 disks present small areas without adhesive without compromising the bonding :



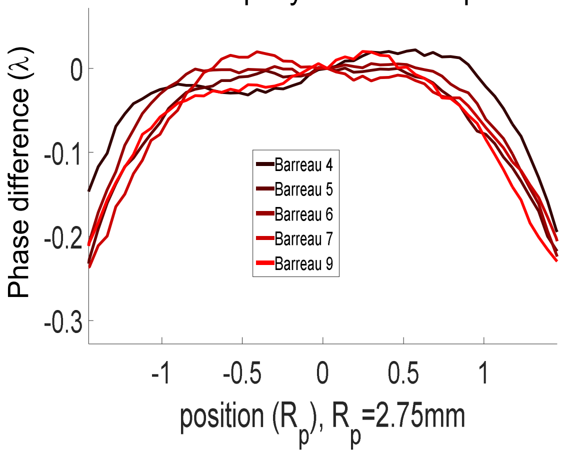
TDE - WP2.1 - IMPROVED ENGINEERING OF BONDING PROCESS

Bonded element on square CuW interface, low temperature curing schedule

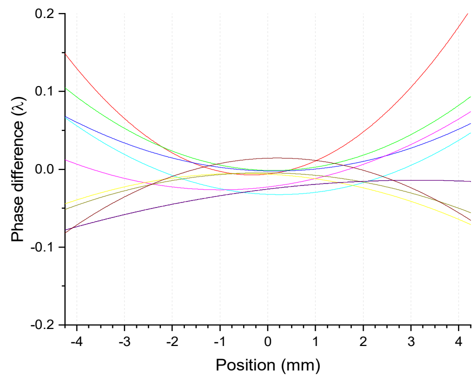
Micrograph of a 11-mm disk



353ND epoxy – horizontal profile



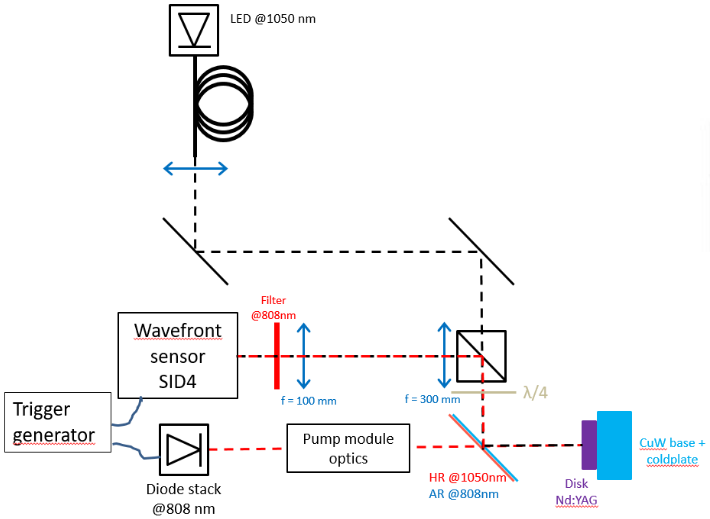
301-2 epoxy – horizontal profile



Bimetallic effect reduced by > ½ with new, not CMR, space qualified, adhesive.

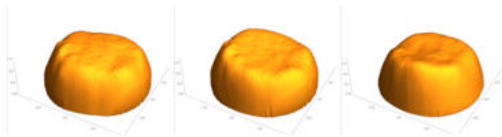
TDE - WP2.1 - WAVEFRONT MEASUREMENT WITH 1ST GENERATION DISKS

Same set-up as for TRP

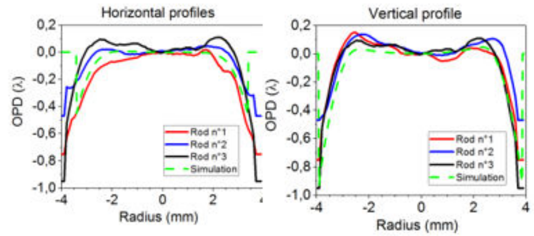


Stage 1 showed good compensation

Stage 1

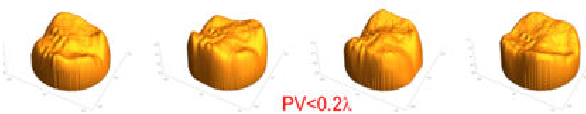


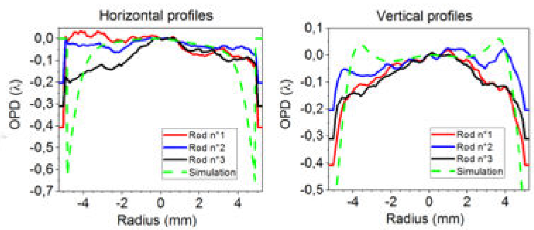
PV<0.1λ



Stage 2 suffered from astigmatism and P2V too high

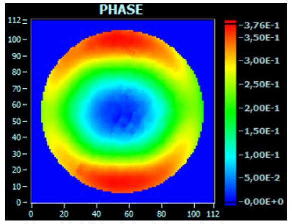
Stage 2



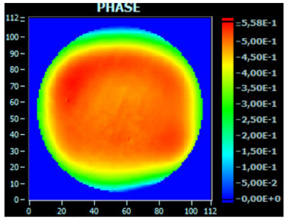


TDE - WP2.2 - STAGE 2 DISKS WAVEFRONT CORRECTION

Stage 2 disks under pumping, before and after functionalization

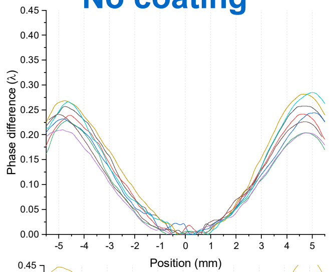


No coating

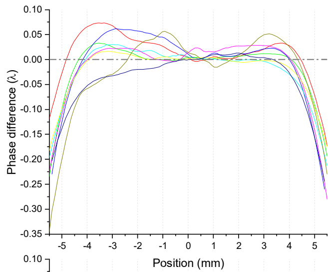


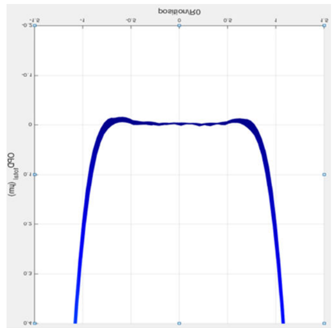
Coating optimized

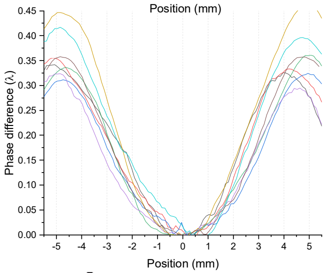
COMSOL Simulations



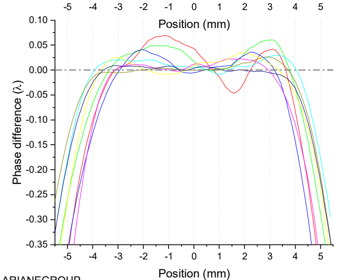
Horizontal profiles





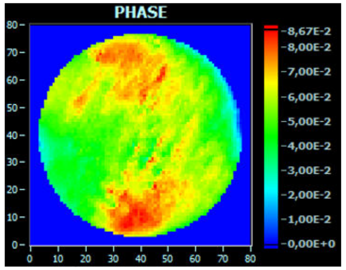


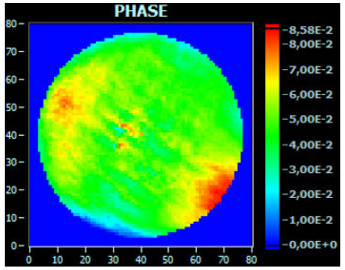
Vertical profiles

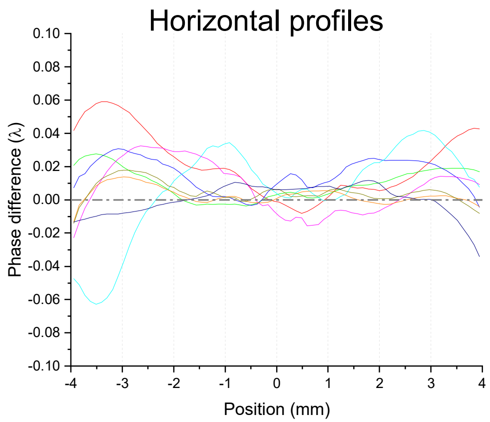


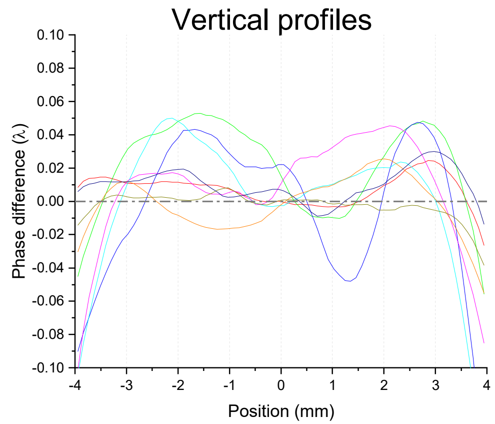
TDE - WP2.2 – STAGE 2 WAVEFRONT DISTORTIONS REDUCTION

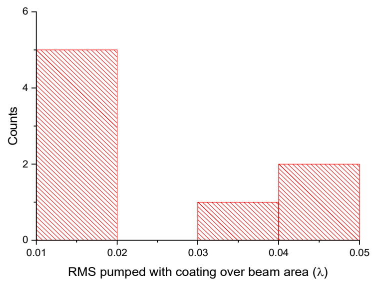
Stage 2 disks under pumping, with functionalization, over the beam area





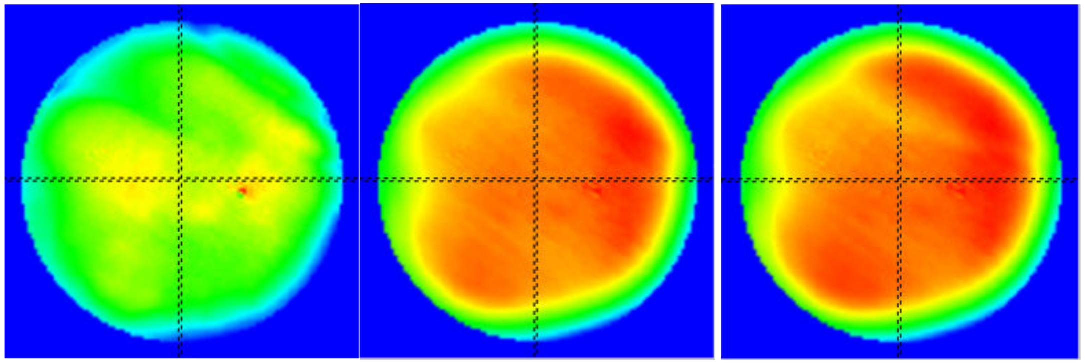






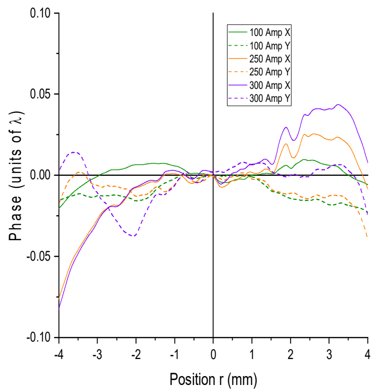
RMS < 0.02 λ !

TDE – WP2.1 - DEPENDENCE ON PUMP AVERAGE POWER



5 W 18 W 26 W

Wavefront correction is efficient at any pump power with only passive elements



TDE - WP2.1 - SYNTHESIS

The amplifier has been redesigned to lower the operating temperature inside the disks, improve efficiency, and reduce astigmatism of the large disks OPDs.

A new epoxy and low temperature curing schedule makes it possible to reduce the bimetallic effect introduced by the bonding process.

Characterization of the disks wavefront at rest, and under pumping before and after functionalization validate the technological choices made to reduce stage 2 disks OPD.

The result is a phase distortion of less than 0.02λ RMS over the beam area, with a quasi uniform distribution.

TN2.1 was delivered in its final installment.

TDE - WP3.1 - PRODUCTION OF CAD DRAWINGS FOR THE AMPLIFIER

T0→T0+23

Output : TN3.1. Thermomechanical analysis of Engineering Qualification model
3D file of the CAD for the elegant breadboard and description

Objective of the task :

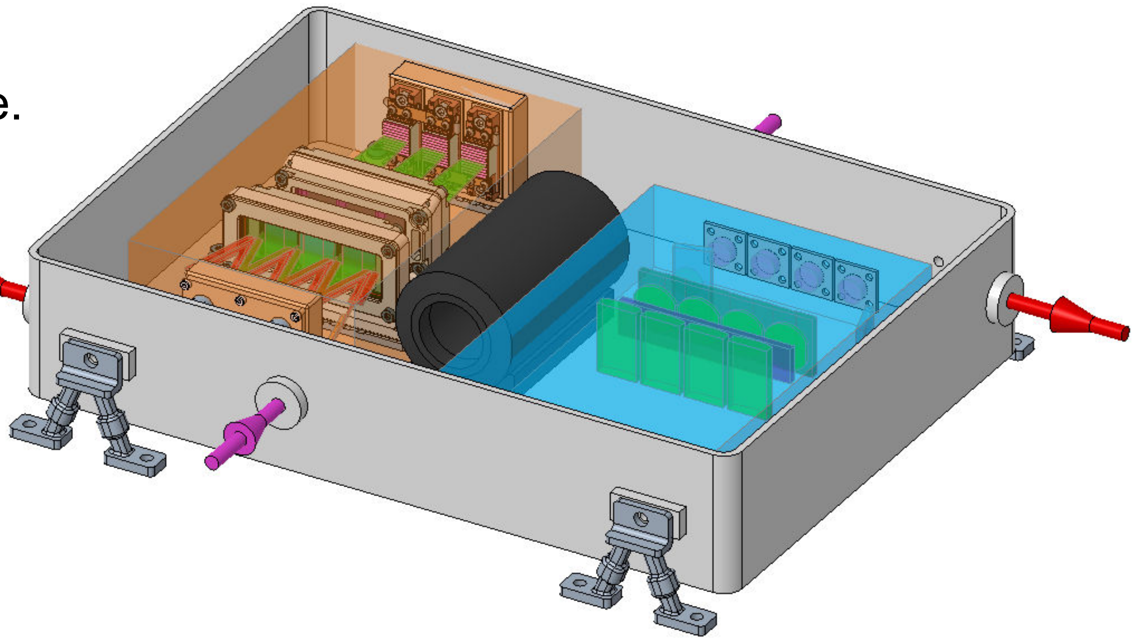
Production of CAD drawings for the amplifier

Thermomechanical design and analysis of amplifier layout

TDE - WP3.1 - CAD DRAWINGS

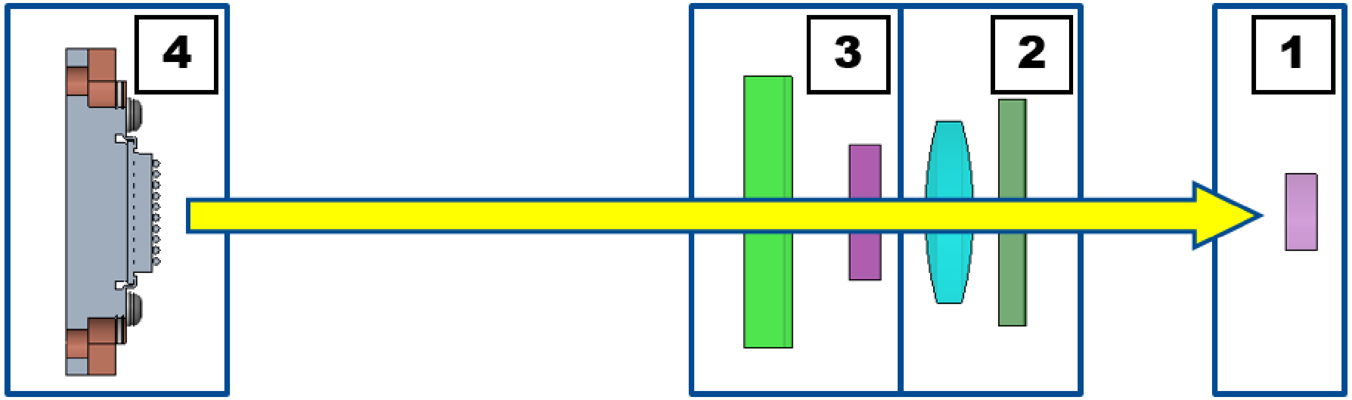
Preliminary design: similar to laboratory breadboard in TRP

2 stages layed side by side.
The pump modules
and the optical isolator
make up most of the
components of the system



TDE - WP3.1 - CAD DRAWINGS

Partition of a pump module

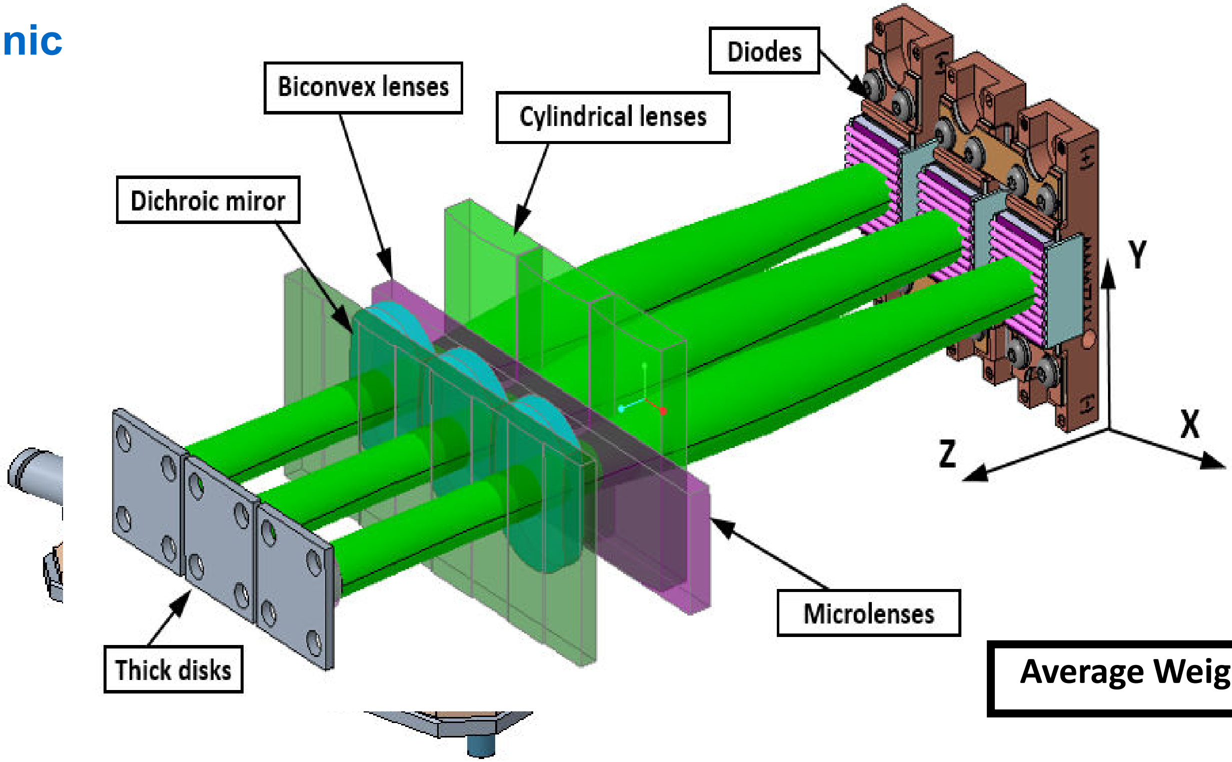


1. Beam input zone including the disks + coldplate
2. First optical group comprising the multizone mirror and the biconvex lenses
3. Second optical group comprising the microlens array and the cylindrical lenses
4. Source block regrouping the diode stacks + coldplate

TDE - WP3.1 - CAD DRAWINGS

3D view of optical elements

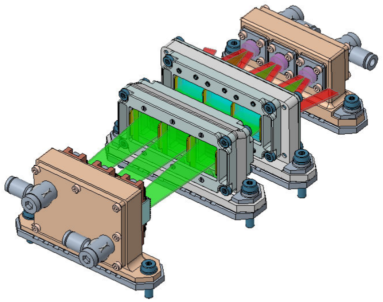
+ optomechanic

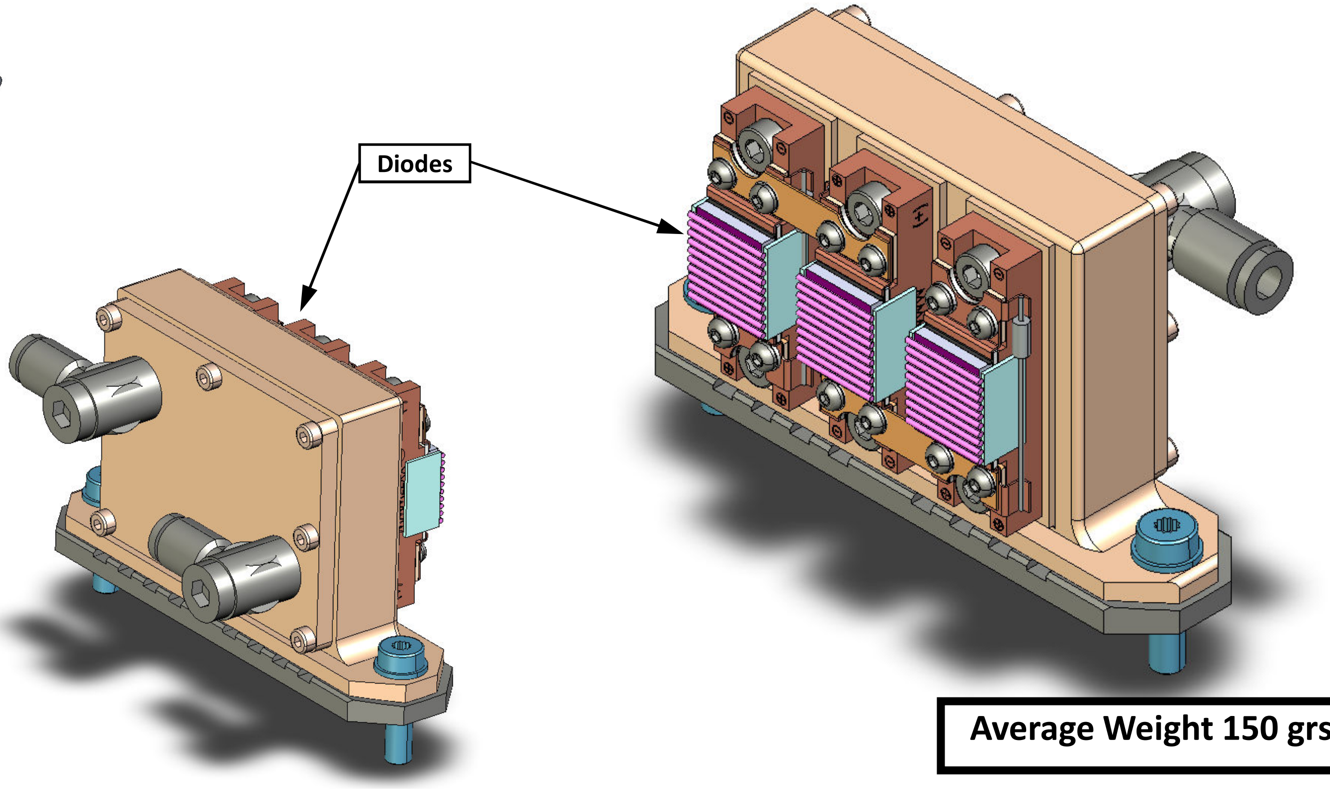


Average Weight 500 grs

TDE - WP3.1 - CAD DRAWINGS

Source block

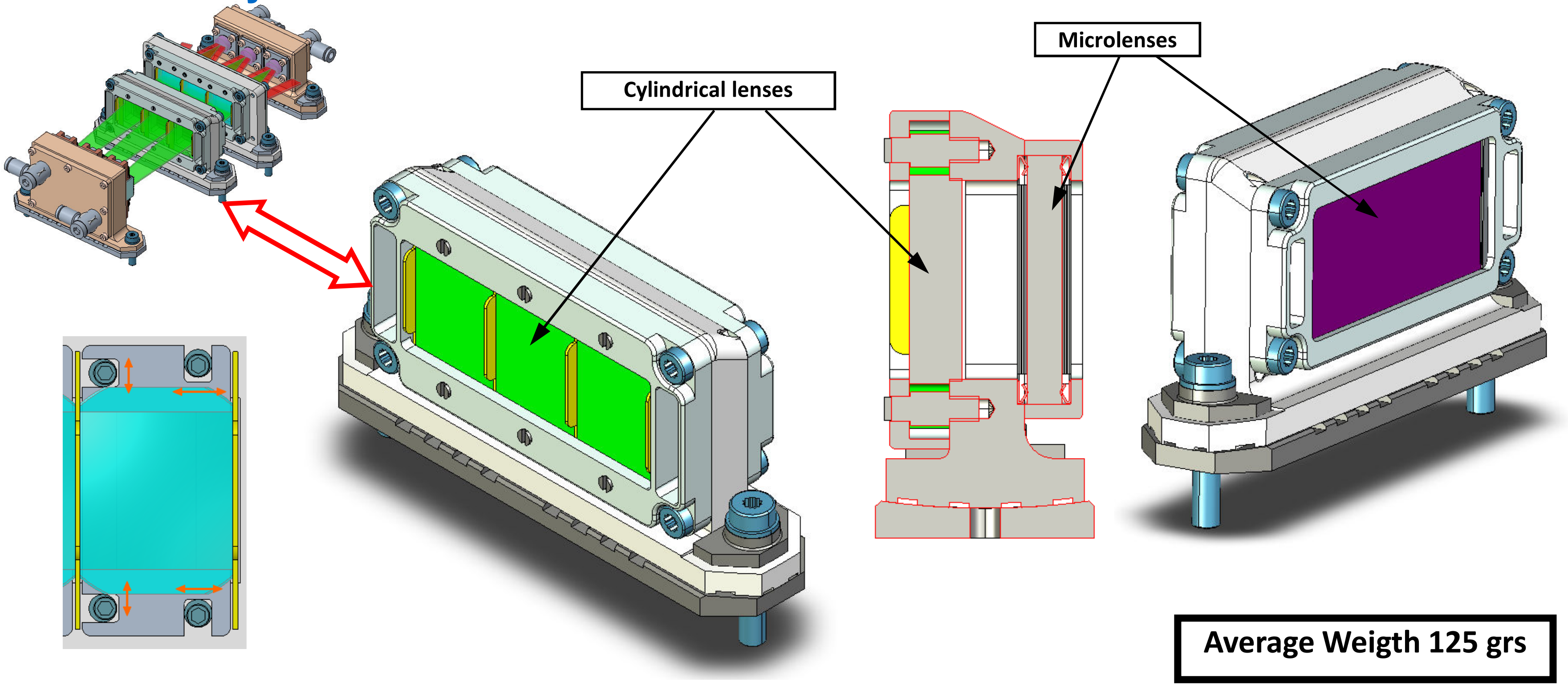




Average Weight 150 grs

TDE - WP3.1 - CAD DRAWINGS

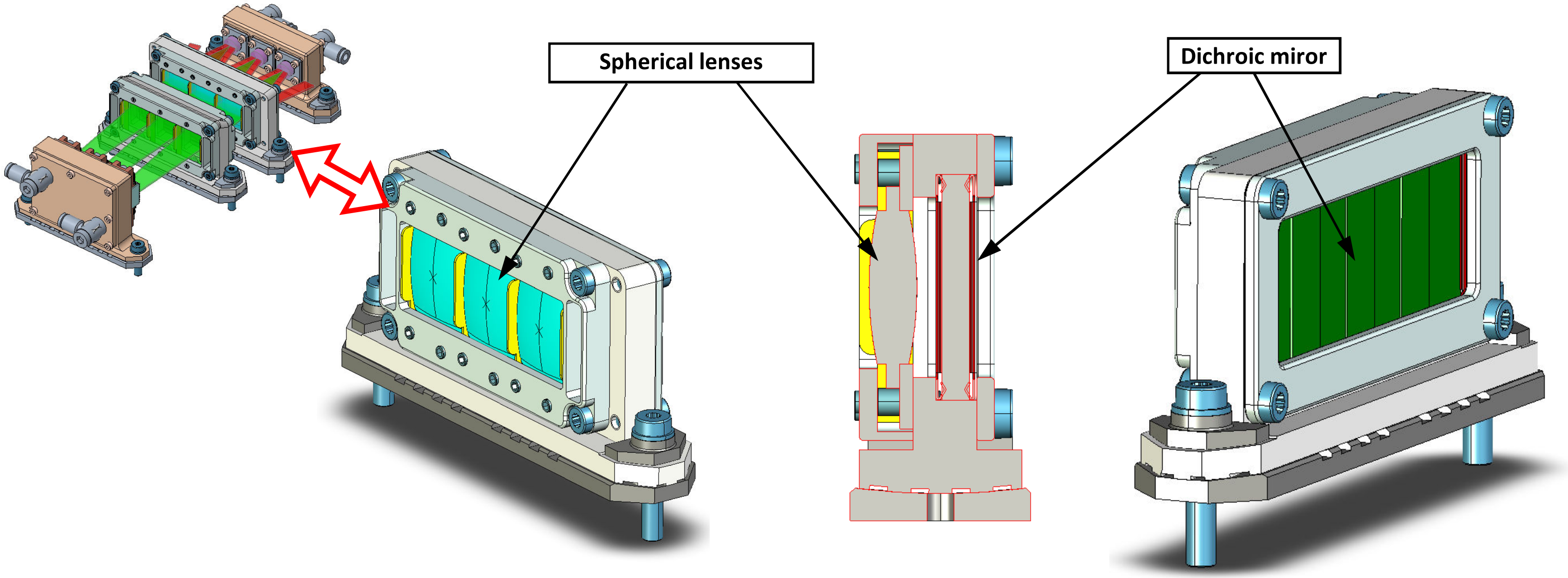
Microlens array



Average Weigth 125 grs

TDE - WP3.1 - CAD DRAWINGS

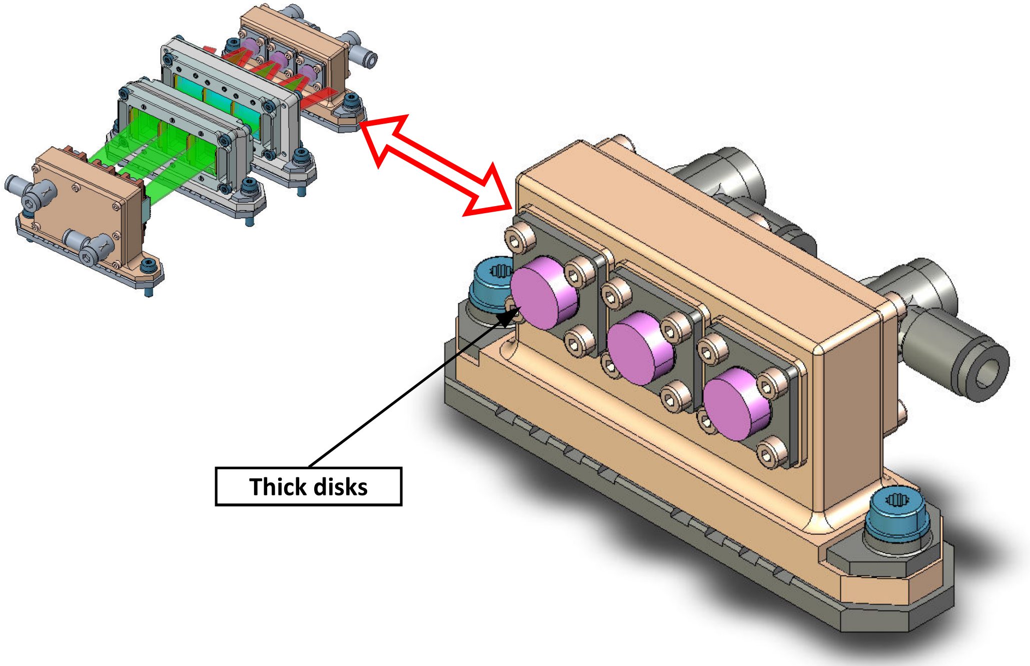
Multizone mirror

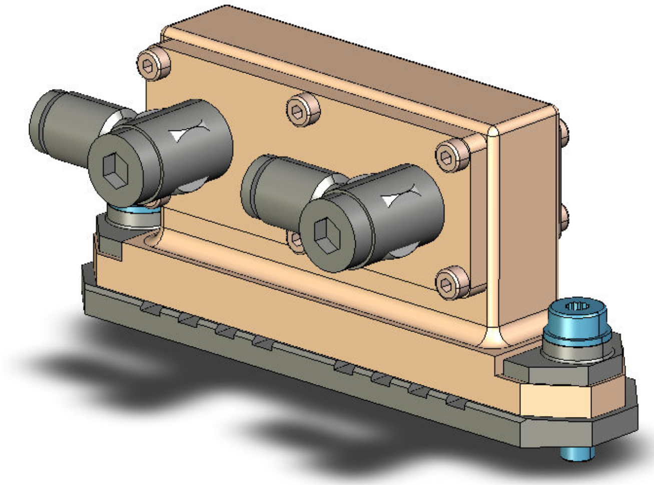


Average Weigth 120 grs

TDE - WP3.1 - CAD DRAWINGS

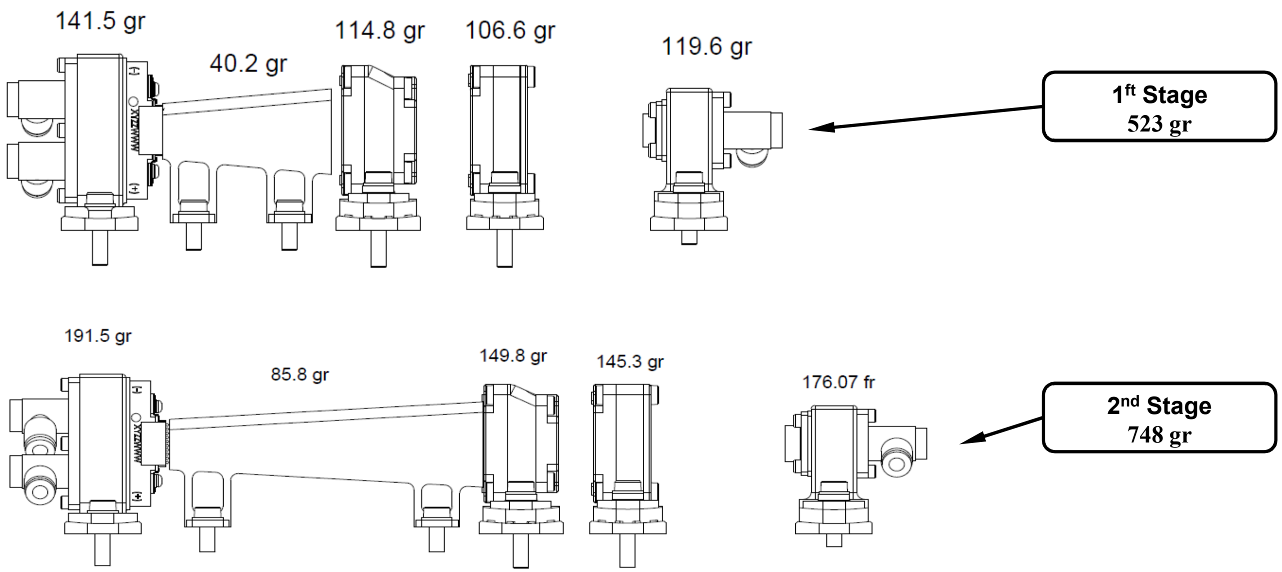
Disks





Average Weigth 125 grs

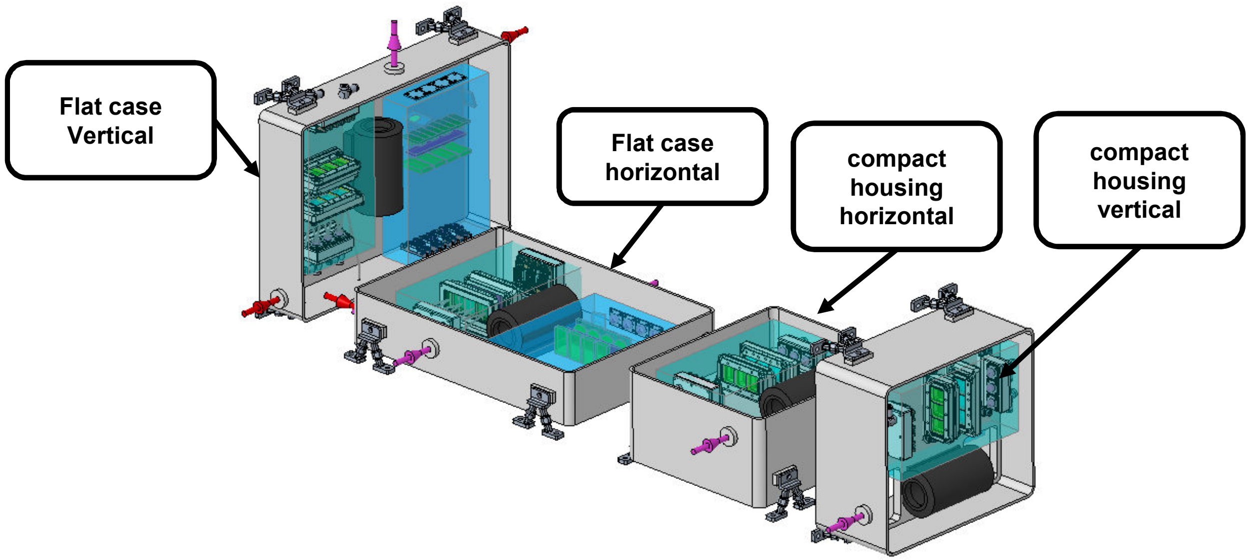
TDE - WP3.1 - CAD DRAWINGS - MASS



Total Mass for 2 pump modules 1271 gr

TDE - WP3.1 - CAD DRAWINGS

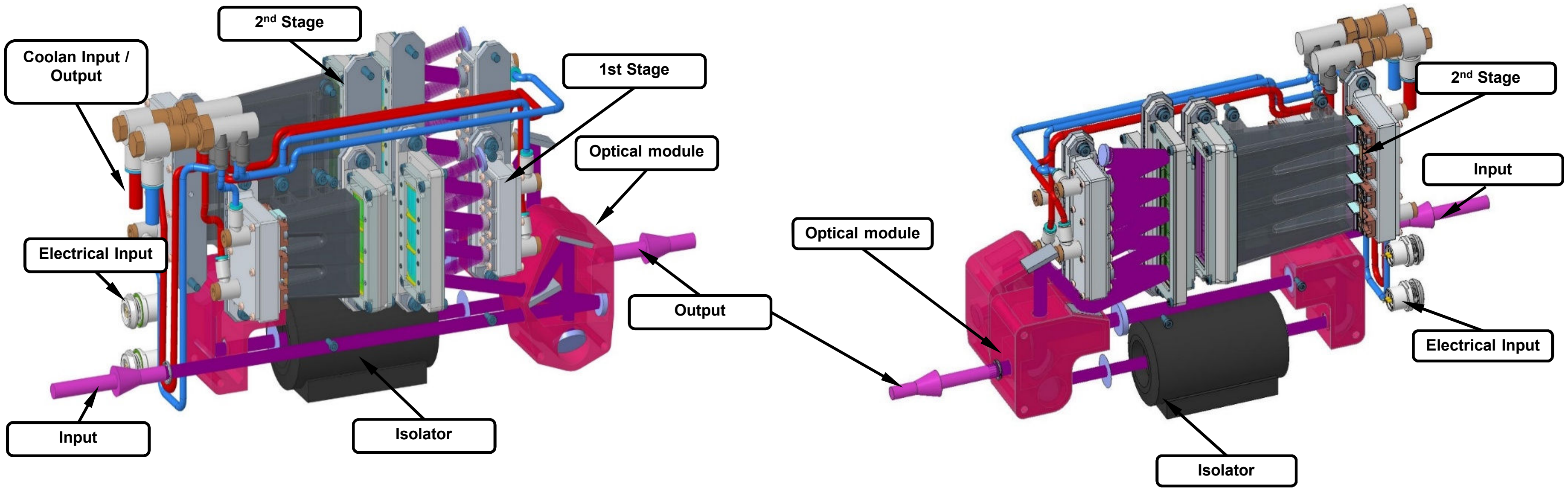
Several lay-out considered



The compact versions have a reduced footprint while maintaining good accessibility for assembly and optical adjustments.
It optimizes placement of the various components and therefore reduces the total mass.

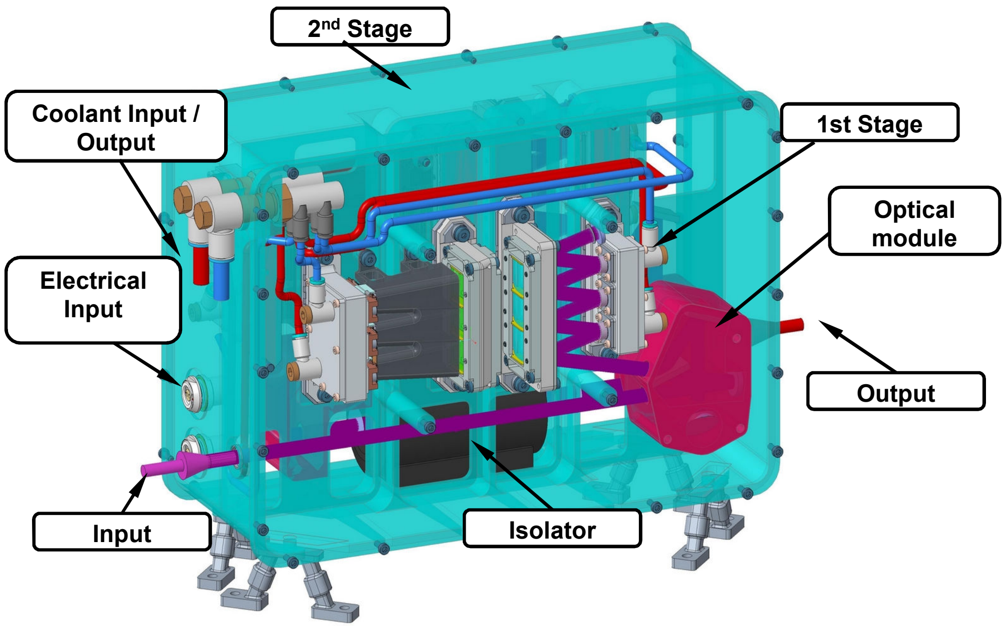
TDE - WP3.1 - CAD DRAWINGS

Vertical compact lay-out



TDE - WP3.1 - CAD DRAWINGS

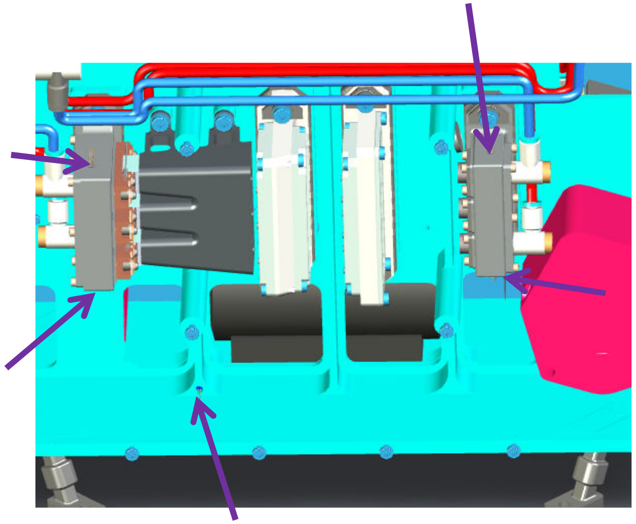
Main structure included

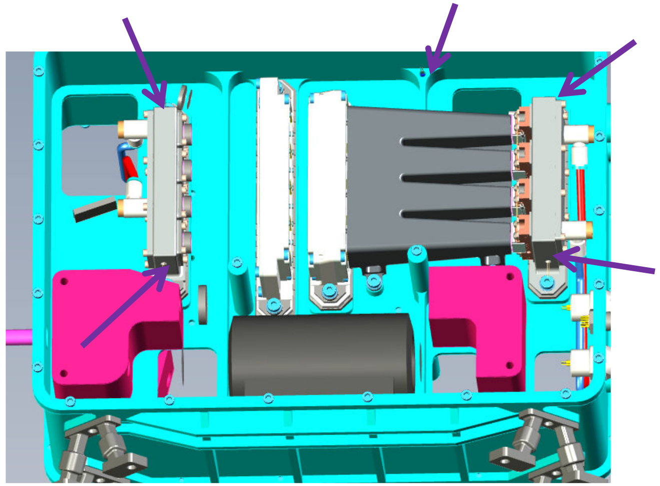


TOTAL MASS of the amplifier : 4.8 kg, 7.7 Liters
(wires and fluid tubes not included)

TDE - WP3.1 - CAD DRAWINGS

PT1000 probes have been added to the model for temperature monitoring

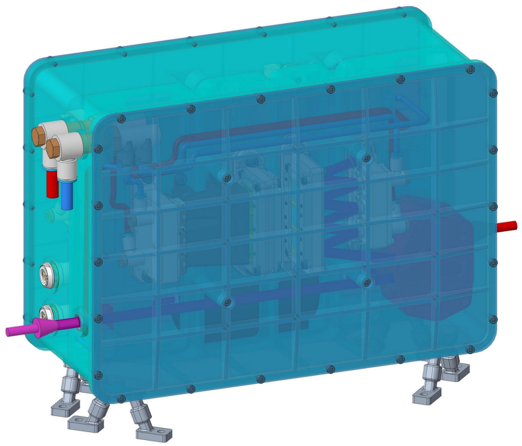


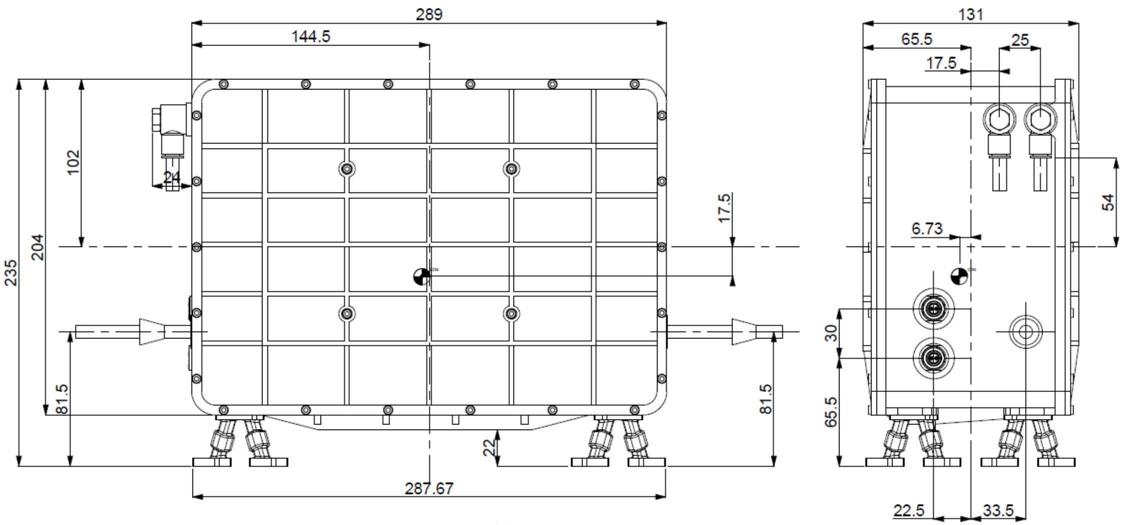


Without change of mass

TDE - WP3.1 - CAD DRAWINGS

Dimensions and interfaces





Materials: 6061 T6 aluminum for case
Titanium for screws (compatible with aeronautical standards)
The 2 covers are screwed to the case body. The case is not sealed to enable pressure balancing.

TDE - WP3.1 - CAD DRAWINGS

- Achieved a system mass < 5 kg in a small volume
- Different architectures have been proposed
- The vertical layout has a smaller footprint
- Other architecture could also be used if necessary depending on the constraints
- Optical input and output could be rearranged by using additionnal mirrors
- Optical isolator is ~20% of the total mass ! Optimisation is possible if a space qualified optical isolator is developed.
- Creative, robust, and compact solutions have been proposed for the EBB

TDE - WP3.1 - THERMOMECHANICAL ANALYSIS

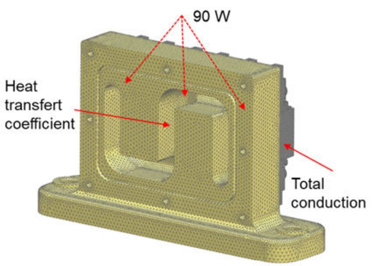
Objective:

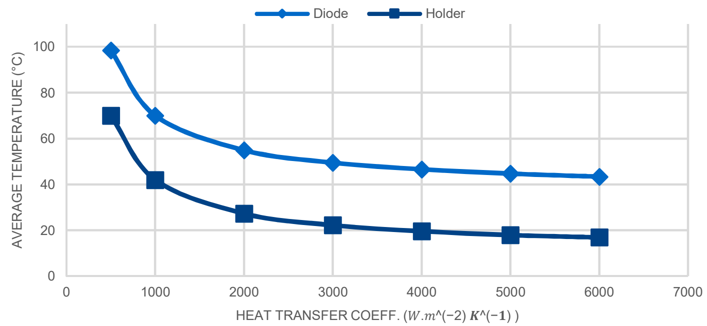
- **To initiate the mechanical models required to increase the TRL of the amplifier**
- **To perform a vibration and shock analysis on the elegant breadboard design**
- **To identify ways of improvement that could be implemented in the future**
- **To dimension the cooling system required**

Computation have been performed using NX

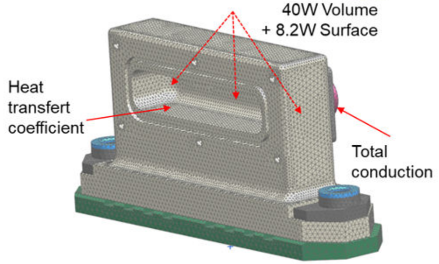
TDE - WP3.1 - COOLING SYSTEM DIMENSIONING – STAGE 1

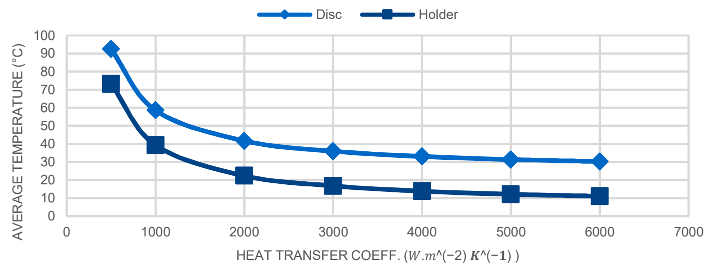
Diode stacks support





Thick disks





Environment temperature: 5°C

- A correlation model has been used to get the order of magnitude for the required flow rate
- Estimated flow rate ~$10^{-1} cm^3 . s^{-1}$ (example of operating temperature of 20°C)

TDE - WP3.1 - MODAL ANALYSIS - AGENCY REQUIREMENTS

For dynamic environment, all parts should have a first eigenfrequency above 600 Hz (REQ-AMP-013). On the other hand, the random vibration spectrum (REQ-AMP-006) covers a frequency band up to 2000 Hz.

If a computed eigenmode is much higher than 2000 Hz, it will not be amplified.

REQ-AMP-013
Stiffness
The amplifier shall be designed to ensure full decoupling between eigen–frequencies of lower level assemblies and minimize the deformations due to gravity release (1g-> 0 g). First eigen-frequency shall be >600 Hz.

REQ-AMP-006
Mechanical Environment
The requirements are resulting from typical launch profiles. The future subunit shall be able to withstand the following vibration environment.
Quasi Static Loads (qualification lvls) ± 26 g (all axis)
Quasi Static Loads (acceptance lvls) ± 21 g (all axis)
Sinusoidal vibration (qualification lvls Sweep rate: 2 oct./min; Duration: 1 sweep up)

Frequency [Hz]	Input Levels [g]
5	1.0
25	26
100	26
100	7
150	11

Sinusoidal vibration (acceptance lvls Sweep rate: 2 oct./min; Duration: 1 sweep up)

Frequency [Hz]	Input Levels [g]
5	1.0
25	21
100	21
100	6
150	9

Random vibration (qualification lvls Overall g RMS: 15; Duration: 120 seconds)

Frequency [Hz]	Input Levels [g2/sqrt(Hz)]
20	0.02
180	0.3
195	1.5
200	1.5
220	3.5
225	3.5
250	0.2
270	0.2
290	2.0
300	2.0
350	0.038
385	0.038
2000	0.00006

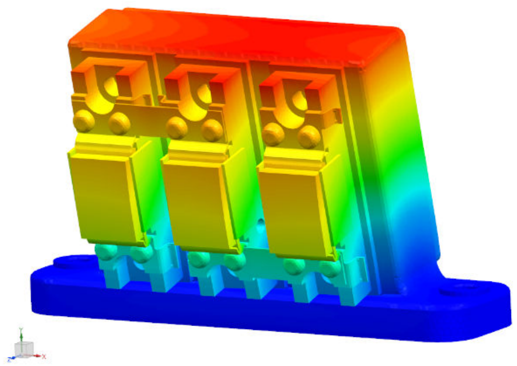
Random vibration (qualification lvls Overall g RMS: 21; Duration: 120 seconds)

Frequency [Hz]	Input Levels [g]
20	0.02
210	0.3
240	9.5
255	9.5
315	0.075
400	0.075
2000	0.0152

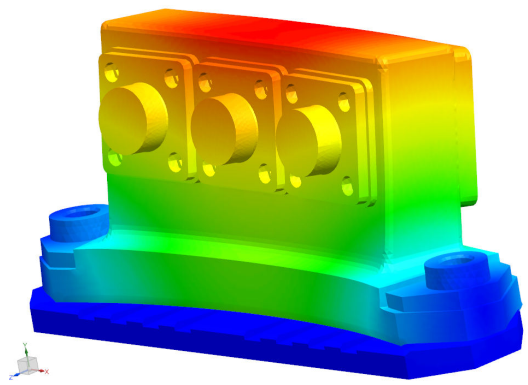
Shocks
The unit shall be designed to withstand without degradation a shock pulse equivalent to a half sine input of 300g amplitude during 0.5 ms.

TDE - WP3.1 - MODAL ANALYSIS – STAGE 1

Diode stacks & Disks



Vibration
1st mode :
4100 Hz

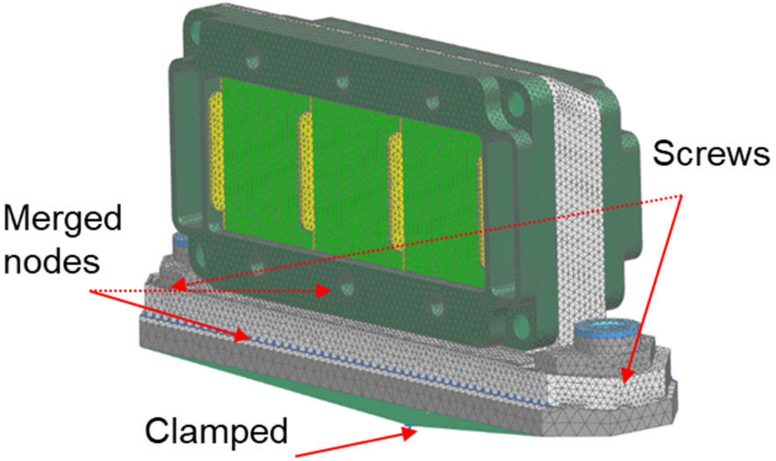


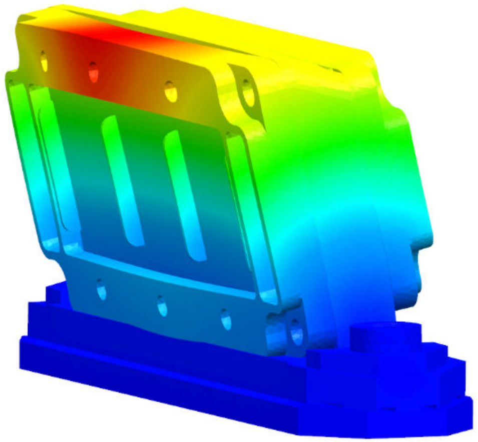
Vibration
1st mode :
4000 Hz

Shall withstand vibrations < 2000 Hz

TDE - WP3.1 - MODAL ANALYSIS – STAGE 1

Cylindrical lenses & Microlens array

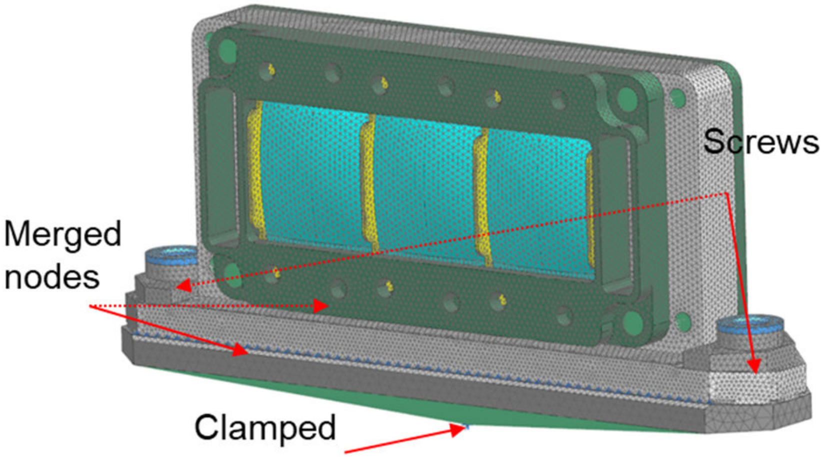


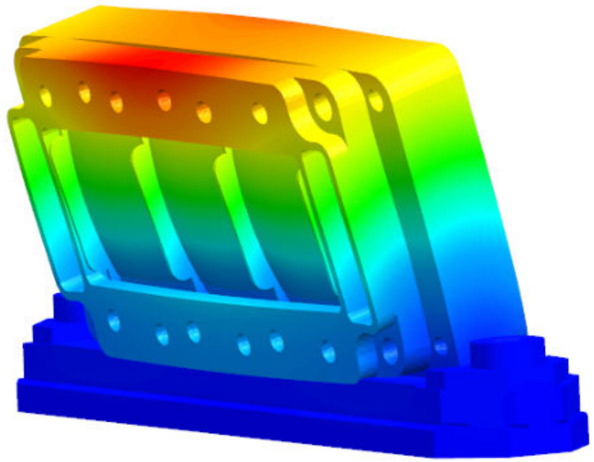


- First mode : 2800 Hz > 2000 Hz
- Shall withstand vibrations < 2000 Hz

TDE - WP3.1 - MODAL ANALYSIS – STAGE 1

Biconvex lenses & Multizone mirror





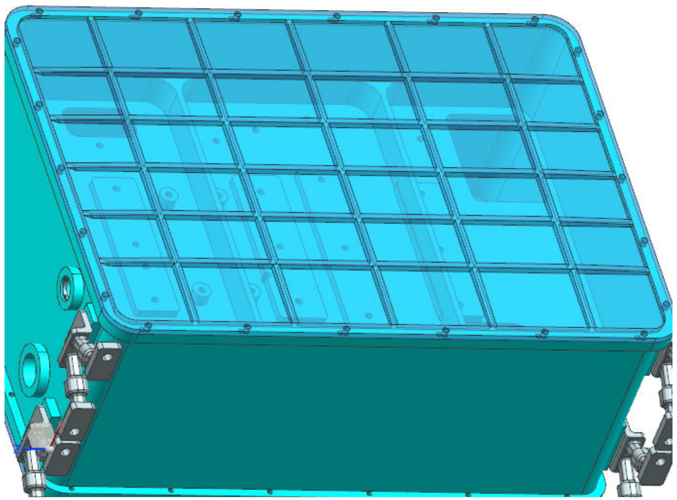
- First mode : 2250 Hz > 2000 Hz
- Base can be thickened where rotation occurs to shift the frequency up

TDE - WP3.1 - MODAL ANALYSIS CONCLUSION – STAGE 1

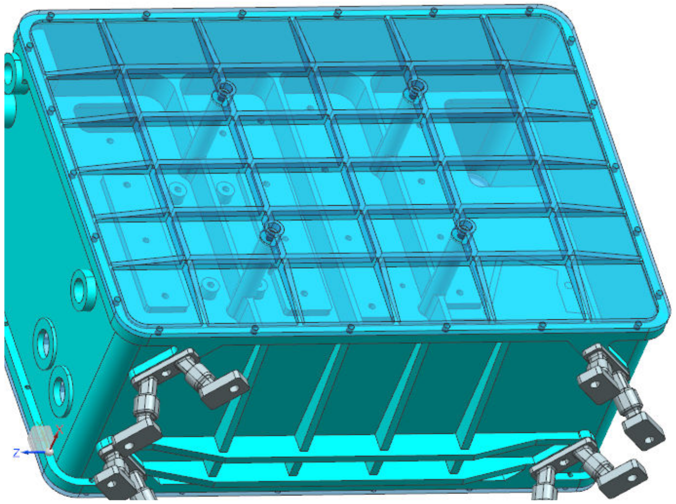
For the elegant breadboard design

- **First amplification stage:**
  - **Individual components eigenfrequencies are higher than excitation spectrum (< 2000 Hz)**
  - **Warning: module with biconvex lenses and multizone mirror should be reinforced**
  - **This can be done in a next study**
- **Second amplification stage:**
  - **4 amplification units with optics larger than in stage 1, so heavier modules**
  - **Eigenvalues are lower, and come close to the REQ-AMP-006 excitation spectrum so an optimisation will be required**

TDE - WP3.1 - MODAL ANALYSIS: AMPLIFIER CASING



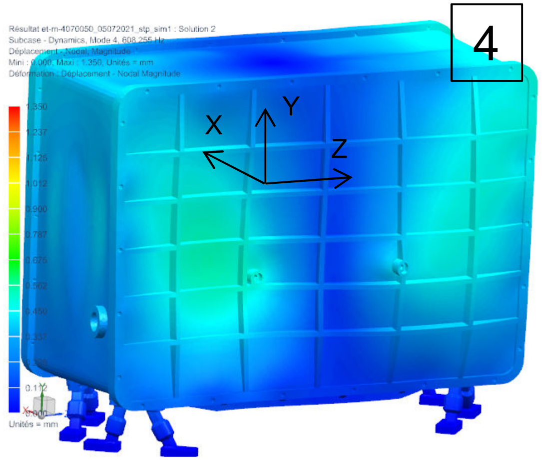
after 3 steps

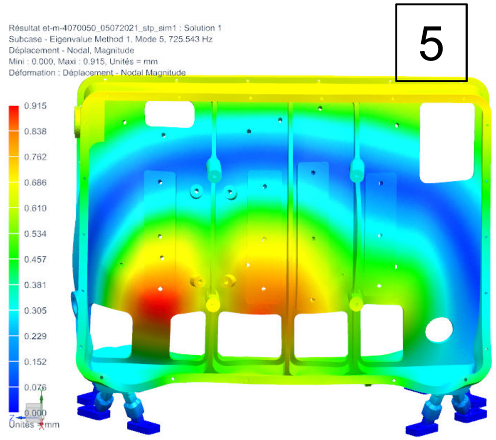


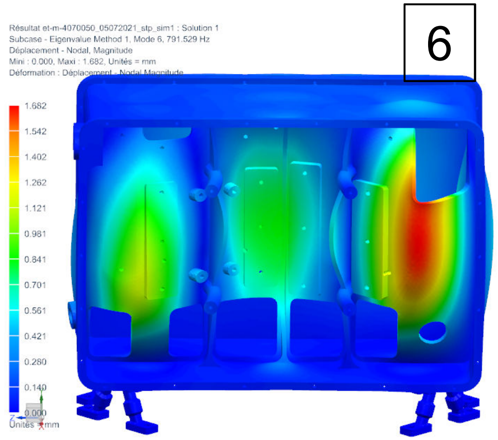
Through iterative steps, some improvement have been identified:

- covers attached to the main structure using columns
- additional ribs to the bottom

TDE - WP3.1 - MODAL ANALYSIS: AMPLIFIER CORE







# Mode	Frequency (Hz)	Comment
1	193	RZ (bending of flexures and casing bottom)
2	371	RX (bending of flexures and casing bottom)
3	503	TY (bending of flexures and casing bottom)
4	608	2nd flexural, covers + RY
5	726	1st flexural, interior plate + RZ
6	792	2nd flexural, interior plate + RZ

- First three modes can be shifted up or suppressed by improving the flexure design
- Other modes > 600Hz

TDE - WP3.1 - MODAL ANALYSIS: MATERIAL CHOICE

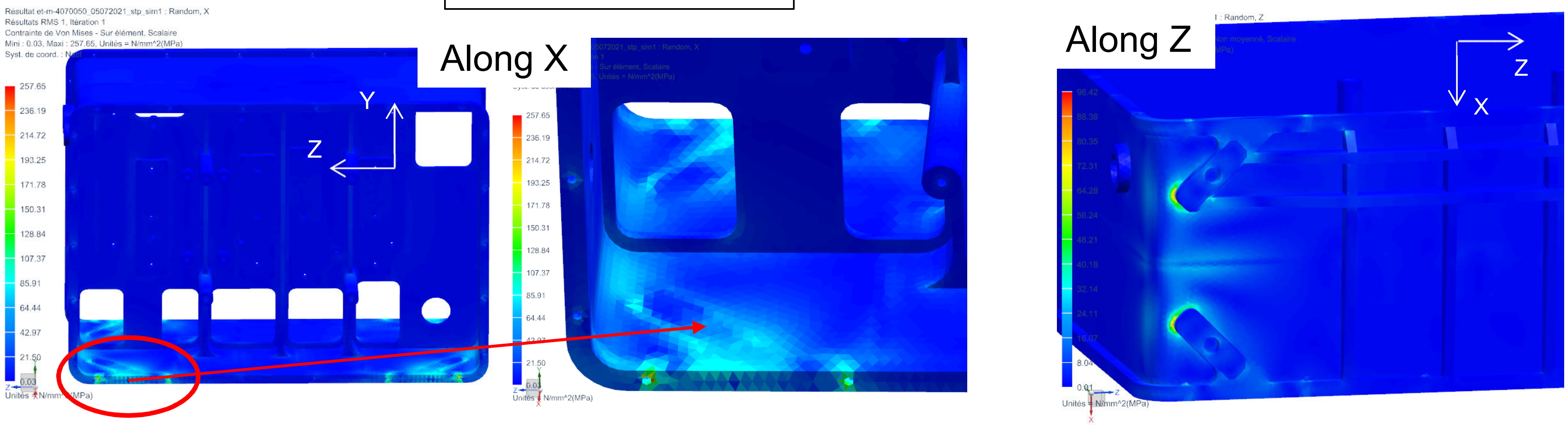
# Mode	Nominal (Hz) (820g Isolator)	600g Isolator (Hz)	Casing in Beralcast (Hz)	Casing and flexures in Beralcast (Hz)
1	193	193	298	349
2	371	373	550	672
3	503	523	820	890
4	608	609	967	1072
5	726	745	1077	1307
6	792	792	1365	1366

Material	Young Modulus (MPa)	Density $(kg.m^{-3})$	Poisson coefficient	Yield Strength (MPa)	Ultimate Tensile strength (MPa)
6061T6	69 500	2700	0.34	276	310
BeralCast	202 000	2160	0.20	213.7	289.6

TDE - WP3.1 - DYNAMIC RESPONSE

Random vibrations

Input : Grms = 21 g



Random Excitation $(3\ \sigma)$	Max VM stress (MPa)	Max VM stress without singularities (MPa)
X	774	300
Y	90	/
Z	288	210

Aluminium Yield Strength: 276 MPa

In the next study, the bottom plate around the flexures should be reinforced

TDE - WP3.1 - DYNAMIC RESPONSE

Sine Sweep vibrations

Input : REQ-AMP-006

Frequency (Hz)	Input Levels (g)
5	1
25	26
100	26
100	7
150	11

→

Sine excitation	Max Von Mises Stress (MPa)
X	0.01
Y	0.01
Z	0.01

- **Excitation spectrum far below the 1st eigenfrequency**
- **Low stress induced**

TDE - WP3.1 - DYNAMIC RESPONSE

Shocks

Input : 300g
0.5 ms (2000 Hz)

Aluminium Yield Strength :
276 MPa

Transient acceleration (W Flexures) 300 g, 0.5 ms	X	Y	Z
Max VM stress (MPa)	90	236	104
Max VM stress without singularities (MPa)	60	150	70

Transient acceleration (W/O Flexures) 300 g, 0.5 ms	X	Y	Z
Max VM stress (MPa)	111	290	179
Max VM stress without singularities (MPa)	70	200	100

- **Max stress is a bit high**
- **Flexures help to reduce shock-induced stress**
- **Bottom plate & Flexures optimisation to be done in a follow-up activity**

TDE - WP3.1 - DYNAMIC RESPONSE CONCLUSION

- **Some modifications to the amplifier housing have been made to shift the eigenfrequencies up.**
- **Still, the elegant breadboard design would not withstand launch conditions as is.**
- **Improvements remain to be done in order to increase the TRL of the system from 4 to 5. For example, flexures (bipods) should be optimized, elements should be finalized, and casing material could be discussed.**
- **Optimization should be done after exchanges with end-user, to validate choices.**
- **The current design should bear sine vibrations.**

TDE – WP4.1 – SPACE COMPATIBILITY

T0→T0+23
Output : TN4.1. Space Qualification

Objective of the task :
Technical Note describing **any additional LIC, LIDT as well as integration/manufacturing procedures space qualification tests to be performed at follow up activity.** At the same time, this document shall include the assessment with respect to space qualification as well as **the plan for future activities need to reach qualification** of processes and technologies.

TDE – WP4.1 – SPACE COMPATIBILITY

Isolator

- Commercial product, operational temperature range is 12°C – 32°C, mass 820 g
- SpaceTech GmbH has developed a space compatible isolator for Merlin, aperture size 4 mm
- Development of 9 mm aperture size isolator technically possible, space qualification required

ASE absorptive coating

- Absorptive coating has been replaced by space compatible, CNES qualified, low outgassing coating
- Good optical properties demonstrated (ASE absorption and wavefront distortion correction)
- LIC test at 1064 nm passed, LIC test at 355 nm required. Radiation resistance also

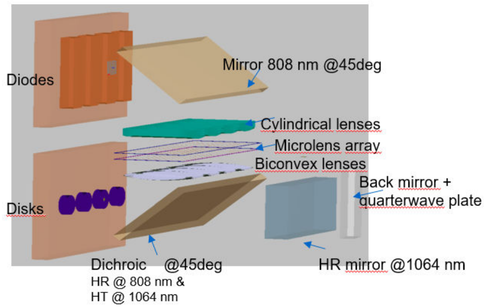
Disk adhesive

- CMR Epoxy adhesive has been replaced by space compatible, NASA qualified low outgassing adhesive
- Low temperature cure reduces bimetallic effect at rest
- LIC test at 355 nm done on similar epoxy, but need to be updated for this new adhesive
- Vibration, temperature, and radiation resistance tests of the bonded disk using this adhesive are required

TDE – WP4.1 – SPACE COMPATIBILITY

Optical coatings

- **IBS coatings are hard, dense coatings. Standard HR and AR coatings that are space compatible (TRL9) exist and can be specified for most optical elements.**
- **Multizone mirror uses a photolithographic process, and photoresin. A special qualification will be required, even if coatings used are individually space compatible.**
- **If monolithic multizone is not qualified, possibility to qualify the assembled multizone mirror discussed in WP1.5**
- **A second option involves multiple optics: high losses expected, despite several advantages**



TDE – WP4.1 – SPACE COMPATIBILITY

Diode stacks

- **Diode stack packages exist that are space qualified (TRL9)**
- **The stacks in CILAS amplifier are FAC, with a cylindrical lens bonded in front of each bar. FAC stack packages probably need to be space qualified.**

Diode duplication option

- **Possibility to easily duplicate the pump source exists with this amplifier: “smart packaging”**
  - Same efficiency
  - Same beam characteristics
  - 3% mass gain, 10 % volume gain, no additional component but the diodes
- **This would prolong the amplifier lifetime, option should be discussed with end-user**
- **If this option is selected, a compact package should be developed for space compatibility, and qualified**
- **Duplication via polarization coupling is not appropriate at this time (high power diodes degree of polarization is too low)**

TDE – WP4.1 – SPACE COMPATIBILITY

Casing and holders

- **3D CAD drawings realized and analyzed**
- **Heat extraction dimensioned**
- **Low frequency modes eliminated with stiffeners and flexure positioning**
- **System not entirely compliant with REQ-AMP-14: dynamic vibrations and shocks lead to stress over the material yield strength**
- **Some calculation hypotheses need to be validated, the system needs to be defined in agreement with end-user (form factor, material, components…), before proceeding to optimization.**
- **Some suggestions are made on how to reach full compliance (material choice, flexure choice, additional stiffeners)**
- **3D CAD drawing of cooling system using loop heatpipes will be required for EQM**
- **A thermo-mechanical analysis at non-operational temperatures will be required**
- **Full qualification of the complete system will lead to TRL6**

TDE – WP5.1 – ELABORATE PRELIMINARY DESIGN

T0+21→T0+23

Outputs :

- o all updated TN from previous tasks
- o DDVP: Design Development and Verification Plan (a document containing plan for preparatory work of Phace C/D)
- o ICD: Interface Control Document
- o RRA: Reliability and Risk Assessment
- o HW: Updated BB from the Previous Activity

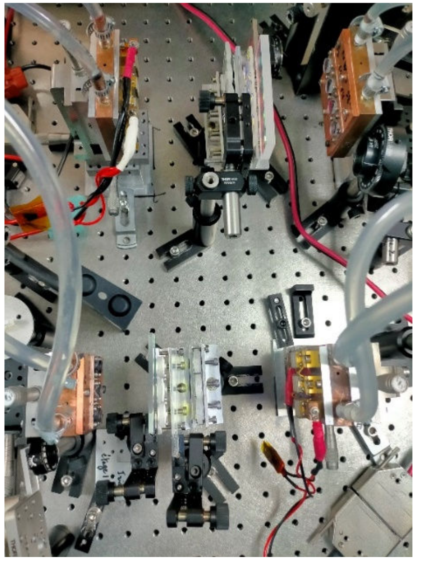
Objective of the task :
Confirm technical solutions selected, trade-off study of disks size, define external interfaces, and recommendations for follow-up activities

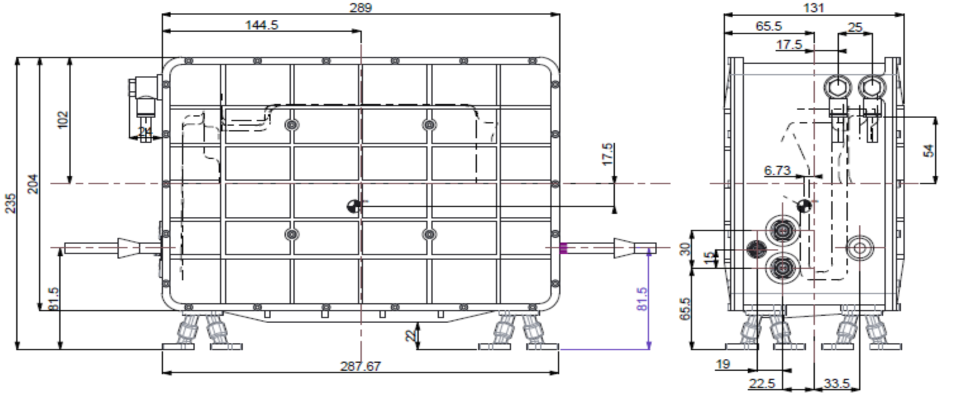
TDE – WP5.1 – ELABORATE PRELIMINARY DESIGN

Trade-off for disks configuration

Layout

Disks thickness	Stage 1 : 3.4 mm Stage 2 : 3.4 mm
Number of disks	3 4
Pump diameter	5.5 mm 7.9 mm
Disk diameter	8.5 mm 11 mm
Average pump power per disk @100 Hz (peak pump power)	28 W 48 W (2.2kW)





TDE – WP5.1 – ELABORATE PRELIMINARY DESIGN

Additional steps required

Component	Current TRL	Required steps to increase TRL	Risk of failure
Diode stacks	4	Decide on pump source redundancy requirement or not Identify a stack packaging Harden the packaging Qualify the packaging	medium
Isolator	4	Develop a wider aperture isolator Qualify the isolator	low
ASE absorptive coating	5	Qualify the coating in a space environment (LIC at 355 nm)	low
Disk adhesive	5	Qualify the coating in a space environment (LIC at 355 nm) Qualify bonded disks for temperature, shock and vibration	low
Optical coatings: general multizone mirror	 9 4	 NA Qualify the multizone mirror in a space environment	 null medium
Microlens array	5	Qualify the array in a space environment	low
Optical mounts	3	Fabricate the CAD models and qualify them in a space environment	low
Housing	3	Finalize the complete system definition Optimize for resistance to vibration Manufacture, assemble, and qualify in space environment	low

CONCLUSIONS

Improvement of the OPDs for the large disks has been achieved: new disks, new baseplates, new adhesive, new absorptive coating, and new process, lead to very flat OPDs, at rest and under pumping, with materials that are space compatible.

CAD files for an elegant breadboard have been drawn and delivered to the Agency, including integrated temperature sensors. Solutions proposed are creative, compact, and robust.

Thermomechanical analysis has been realized on the elegant breadboard. Refinement of the CAD design has been done to improve its resistance to vibrations.
Optimization remains to be done:

- in collaboration with end-user to validate our choices.
- after amplifier components have been space qualified

Thermomechanical analysis at non-operational temperatures is mandatory if project proceeds to next phase.

Operation at 100 Hz with the new mirror should be realized and amplifier characterized to demonstrate improvement of new multizone mirror.

AGENCY APPROVAL

TDE 400 mJ:

FR approval