10-July-2024, ESTEC – Final Project Presentations

LaSol – Large Lens Soldering

Bond-Match - Laser-based Bonding of optical Components to CTE-matched Substrates

Dr. Thomas Peschel, Grucheska Rosario-Rodriguez, Dr. Erik Beckert / F-IOF

Agenda

- Part 1 – Soldering for Optics
  - Motivation
  - Solderjet Bumping (SJB), comparison with other technologies
- Part 2 – LaSol
  - Design of mounts for large lenses
  - Manufacturing, Assembly and Integration
  - Testing
- Part 3 – Bond-Match
  - Material combinations, demonstrator and mount designs
  - Manufacturing, Assembly and Integration
  - Testing

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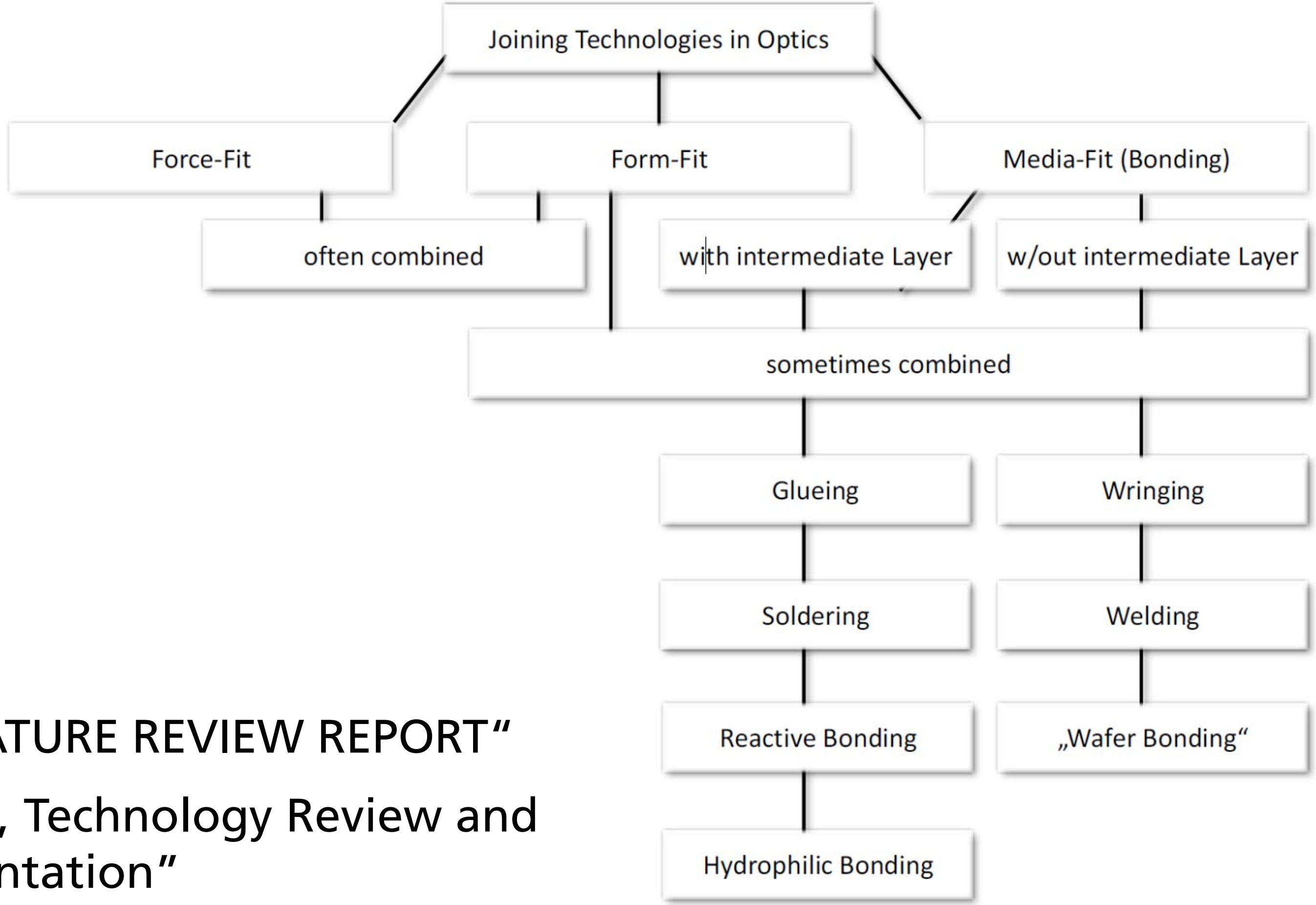
Part 1 - Soldering of Optics

Dr. Erik Beckert

Soldering of Optics

Motivation – Joining of Optics in Mounts



LaSol TN1: „LITERATURE REVIEW REPORT“

Bond-Match TN1: „ Technology Review and Trade-Off Documentation”

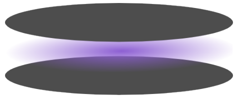
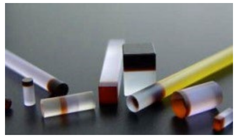
Soldering of Optics

Motivation – Bonding of Optics

- Bonding technologies
  - With interlayer
    - Adhesive bonding
    - Laser Soldering
    - Silicate bonding
  - Without interlayer
    - Optical contacting
    - Direct bonding
    - Diffusion bonding
    - Laser welding





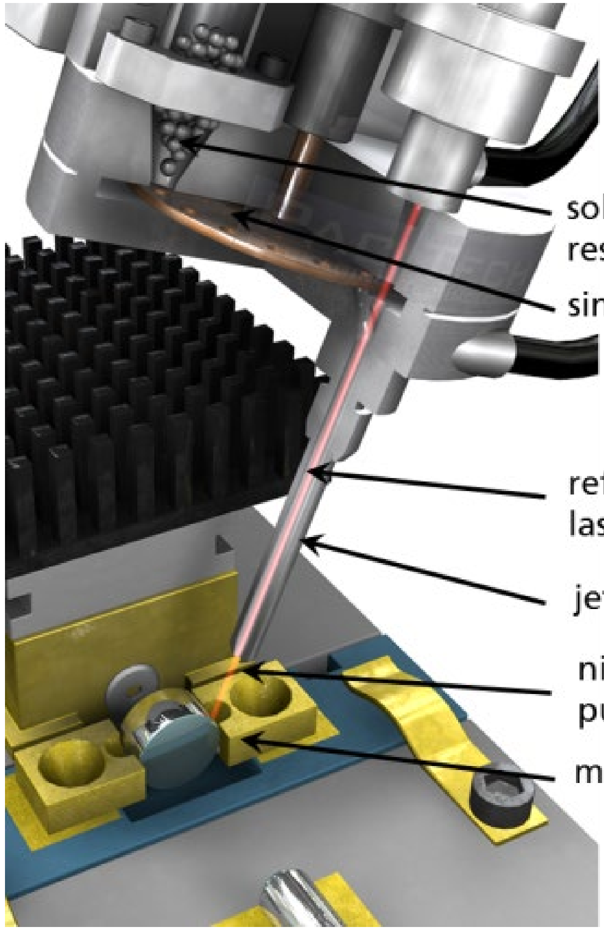

Soldering of Optics

Motivation – Pro‘s and Con‘s of optical, polymer-based Adhesives for Bonding

Temperature Stability	**< 120° C**
Vacuum Compatibility	**-**
Radiation Stability	**- -**
Long-Term Stability	**-**
Transparency	**+ +**
Electrical / thermal Conductivity	**+ / -**
Stress Compensation	**+ +**

Soldering of Optics

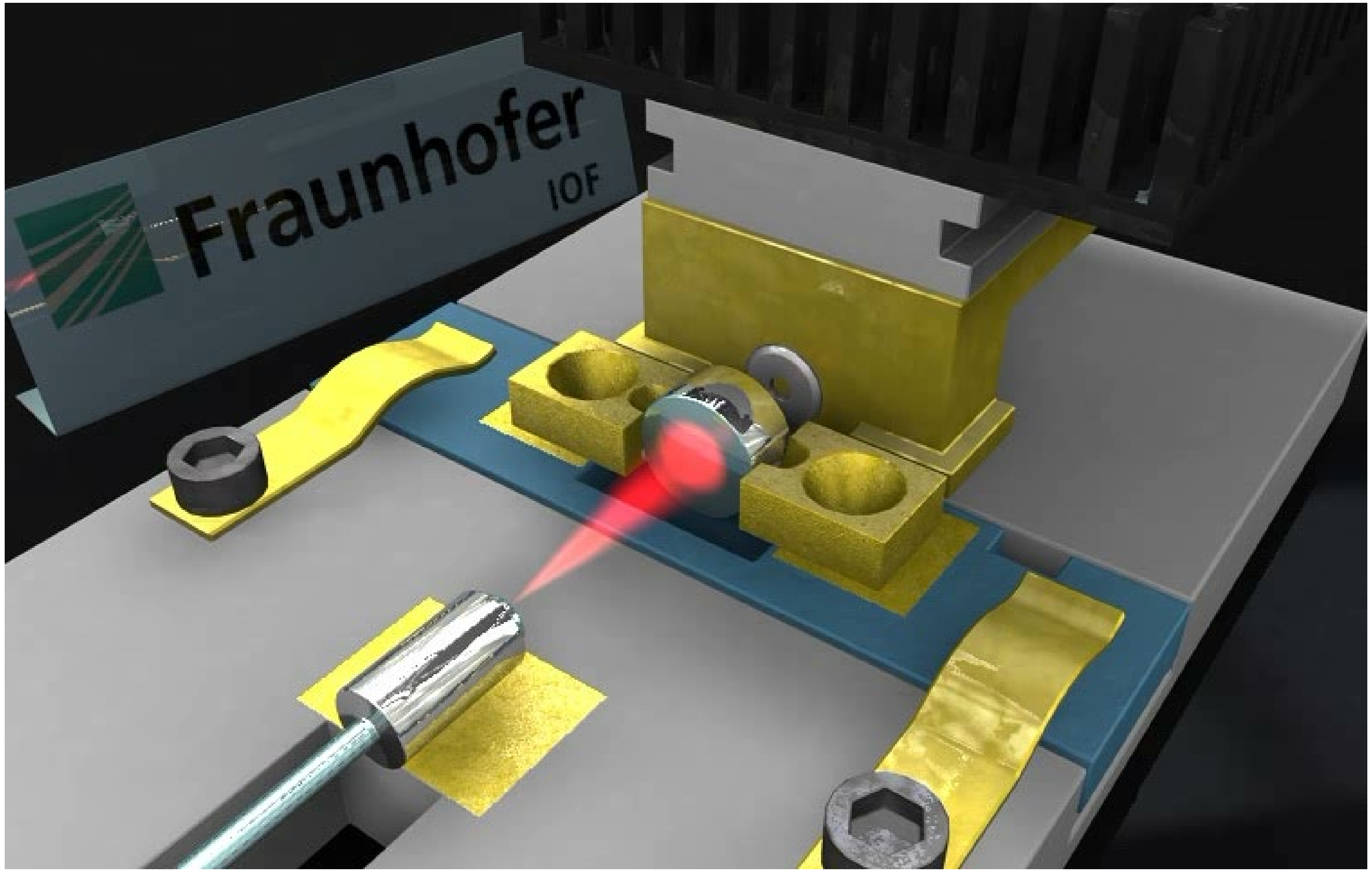
Solderjet Bumping - Technology



- **Solderjet Bumping (SJB)**
  - Reflow of Solder Preforms by IR-Laser
  - Pulse Energy up to 5 J, 1..25 ms
  - Various Soft Solder Alloys to be processed: e.g. AuSn, SnAgCu, SnAg, SnCu, SnBi, AuSi, AuGe…
  - Spherical Preform Ø 60..760 µm
  - Solder Application under local inert Atmosphere (N2)
  - Flux-free, no Pre-heating
  - Jetting of liquid Solder - contactless
  - Free Space Application – 6 DOF
- **SJB – courtesy of Packaging Technologies GmbH**

Soldering of Optics

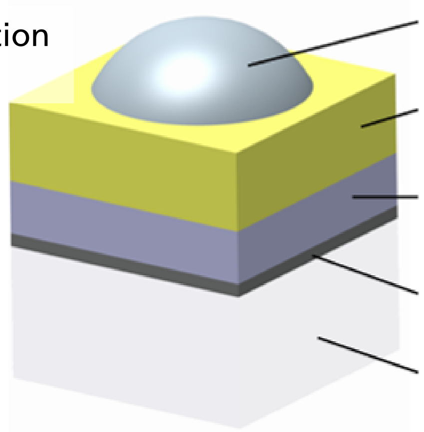
Solderjet Bumping - Technology



Soldering of Optics

Solderjet Bumping - Requirements

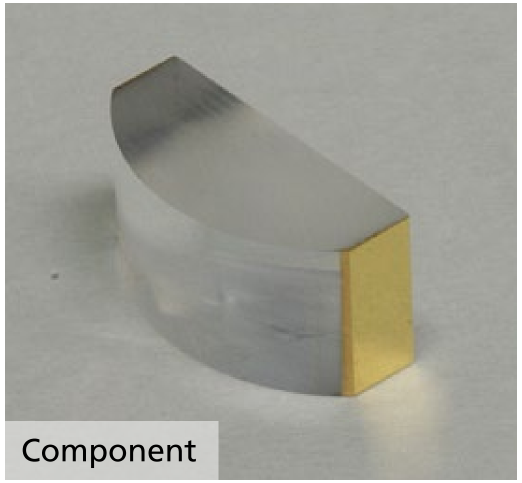
Metallization System



- **Mandatory: Adherent Metallization**
  - Surfaces – Polished, Stability against thermal Shock
  - Ti/Pt/Au (0.5 µm) – Batch Sputtering (PVD)
- **Metallization technology -> component's size!**

Mechanical Masking

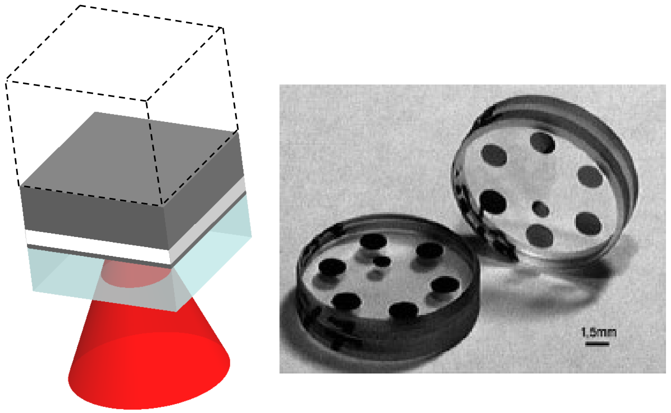
e.g. DC Magnetron Sputtering



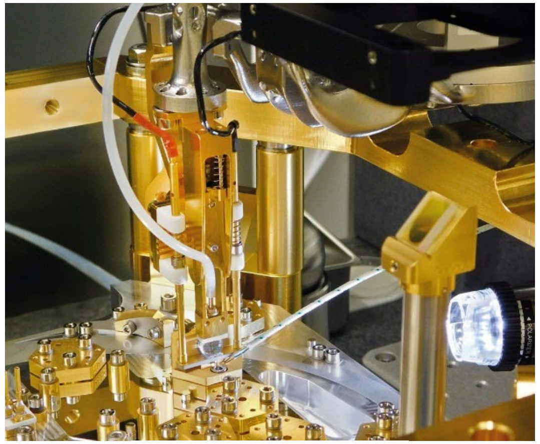
Component

Soldering of Optics

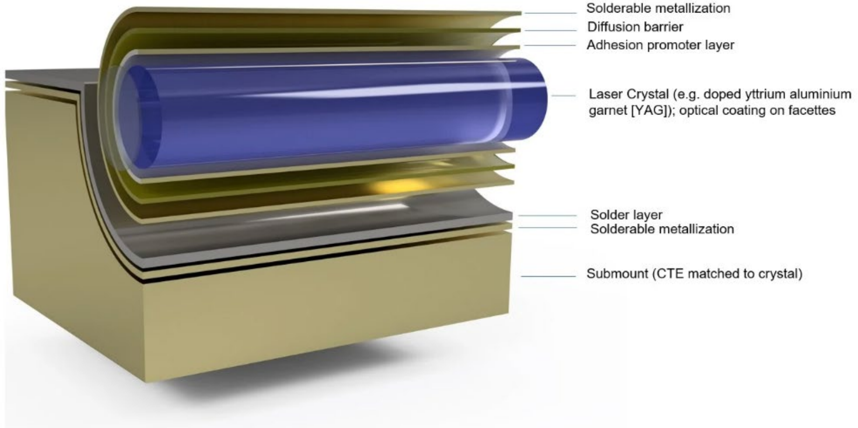
Other Technologies



Fraunhofer IOF



Fraunhofer ILT



PHOTONICPARTS

- Laser reflow
- Thin Film 80Au20Sn
- Planar bonding surfaces
  - 3DOF active alignment

- Ohmic resistance heater reflow
- Various solder alloys, thick
- Planar bonding surfaces
  - 6DOF active alignment, re-alignment possible

- Global (oven?) reflow
- Various solder alloys, thick layer (?)
- Various bonding surfaces
  - Passive alignment

10-July-2024, ESTEC – Final Project Presentations

Part 2 – LaSol (A0/1-9092/17/NL/PS)

Dr. Erik Beckert

LaSol

Statement of Work

- The objective of the current activity is to devise and experimentally test an optimum approach for the **design, manufacture and test of high stability opto-mechanical mounts for large optical lenses** which have an application, in high resolution (spectral and spatial) Earth Observation satellites and within the UV, Visible and NIR wavelength regime.
- […] use a parametric approach to design, quantify and test the performance of an optical mount for large lenses. This shall include addressing the **challenging requirements** such as the **positioning accuracy, the long-term stability, low outgassing contamination, the low induced stress on the glass material and reliable operation in space environment** (thermal and vacuum aspects).
- Design and manufacture a set of mounted lens samples based on, for example, a selection from the following **commonly used glass materials**; **LaK9**, N-BK7G18, **CaF2**, **Fused Silica**, ZnS and ZnSe. […]

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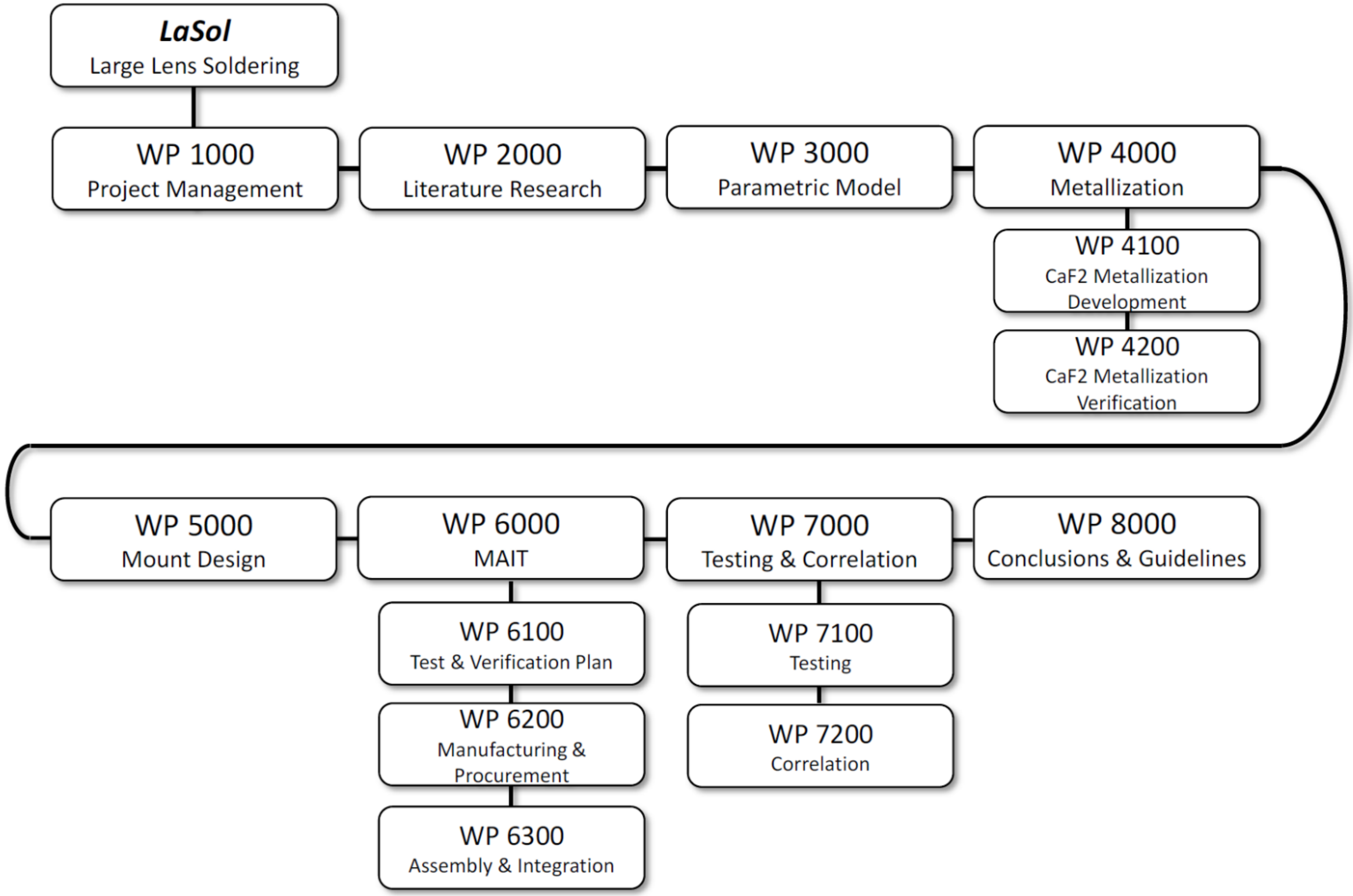
Work Logic



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Design (WP3, WP5) – Involved Material

	Lenses			Mounts			
Material	**Fused Silica**	**Lak9 G15**	**CaF_2**	**Invar 1.3912**	**TiAl6V4 3.7165**	**X6CrNiMoTi1 7-12-2 1.4571**	**Solder SAC305 Sn3Ag0.5Cu**
Young's modulus [GPa]	73.2	108.0	75.8	141.0	114.0	200.0	43.0
Poison number	0.167	0.288	0.260	0.290	0.340	0.290	0.400
Density [g/cm³]	2.20	3.53	3.18	8.05	4.43	7.95	7.43
CTE [ppm/K]	0.56	6.30	18.85	1.30	8.50	16.40	22.4
Thermal conduc-tivity [W/m/K]	1.37	9.71	0.88	10.15	6.60	12.00	56.3
Yield strength [MPa] (metals), Ultimate strength [MPa] (brittle mat.)	80	70*	157	276	830	635	35

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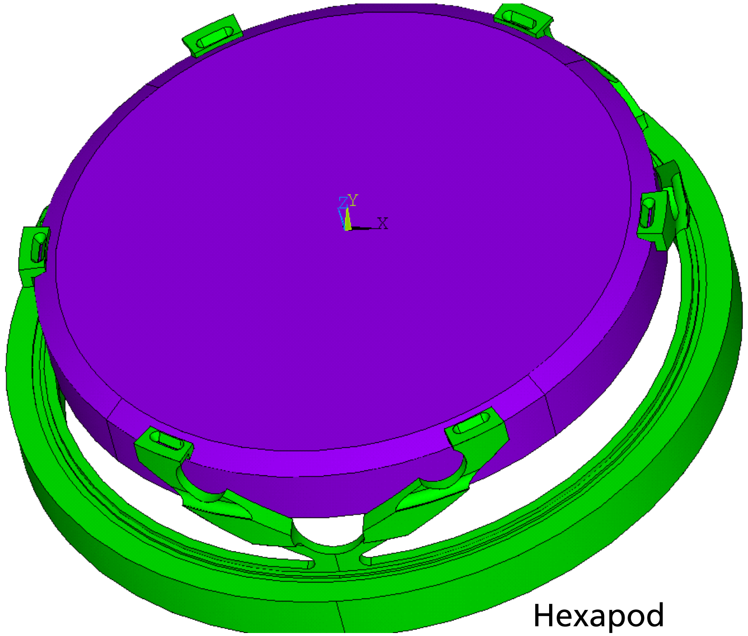
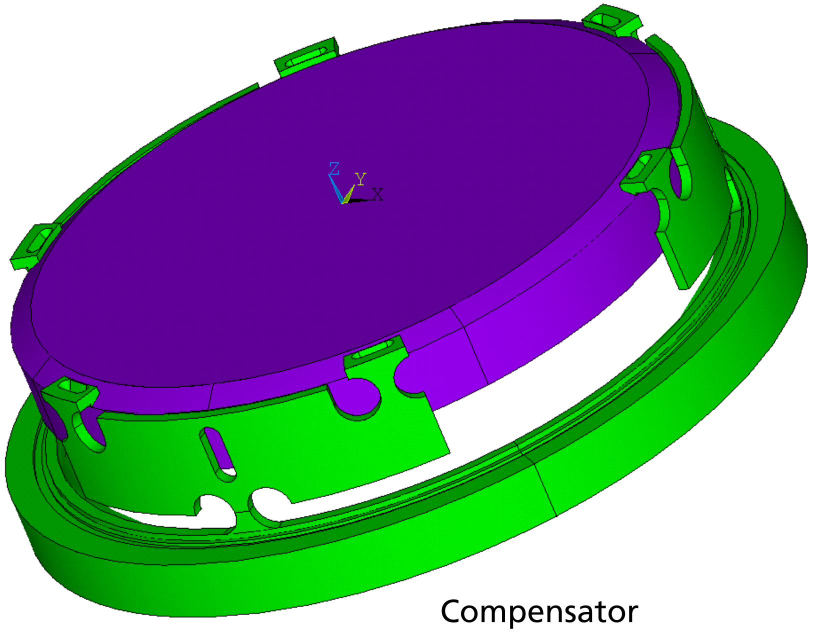
Design (WP3, WP5) – Mount Designs – Parametric Hexapod and Compensator Designs



Hexapod



Compensator

- Hexapod: 6 bonding interfaces, classical hexapod strut structure
- Compensator: 6 bonding interfaces, groups of 2 with compensating geometry
- Both are fully constrained

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Design (WP3, WP5) – Mount Designs – Parametric Hexapod and Compensator Designs

Lens dummy			Load [g]	38.1	Strength		
Radius	0.06	m	Force/Pad (worst case)		Solder strength	30	MPa
Thickness	0.014	m	Factor in-plane	0.33333333	Factor of safety	2	
Volume	0.000158336	m³	Factor axial	0.16666667	Assumed strength	15	MPa
				Worst case Force/Pad			
Material	Density [kg/m³]	Mass [kg]	Total force [N]	F_tan [N]	F_ax [N]	F_tot [N]	Min. area [mm²]
SQ	2202	0.3487	130.31	43.44	21.72	48.57	3.24
CaF2	3180	0.5035	188.19	62.73	31.37	70.14	4.68
LAK9G15	3530	0.5589	208.91	69.64	34.82	77.85	5.19

- Analytical calculation of required interface (pad) area per bonding geometry
- Based on equivalent acceleration load for vibration and shock
- Input for detailed design and numerical simulation

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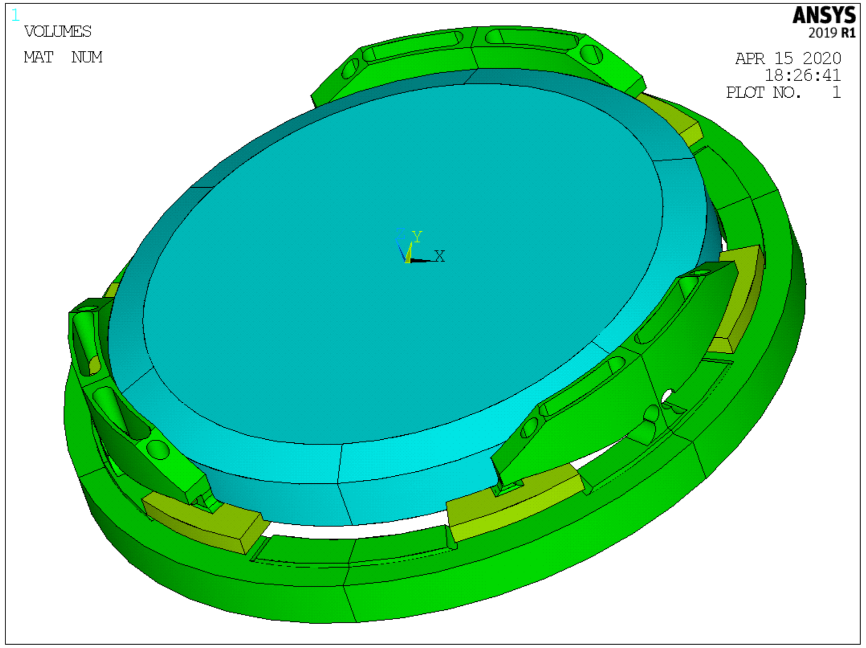
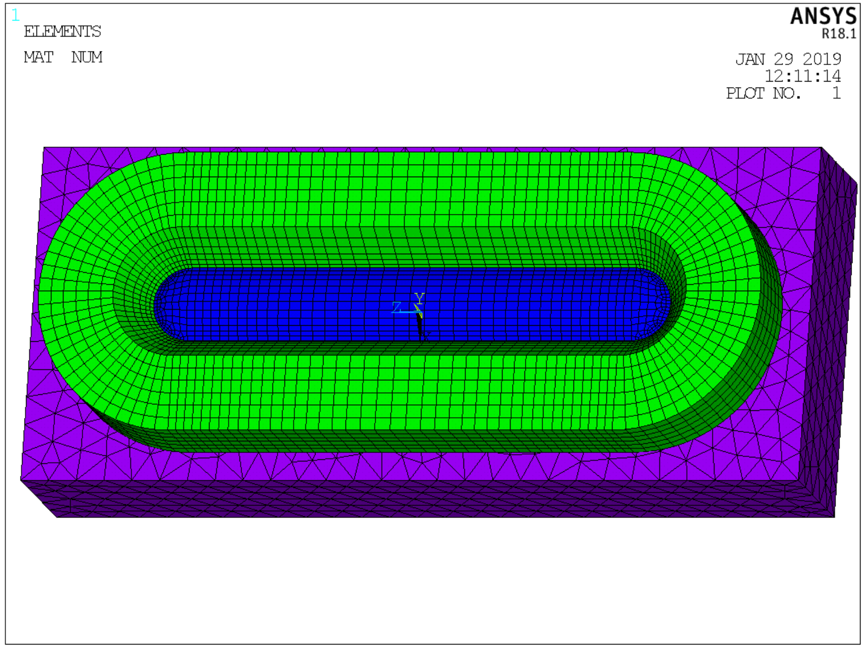
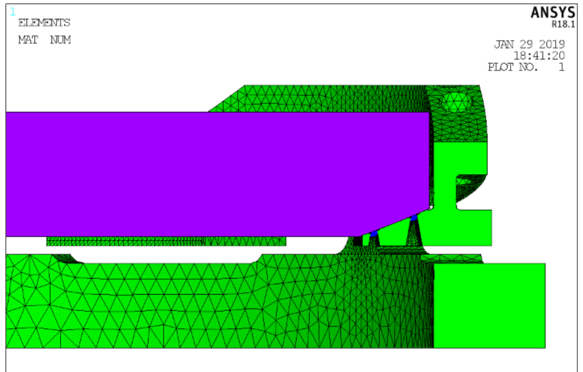
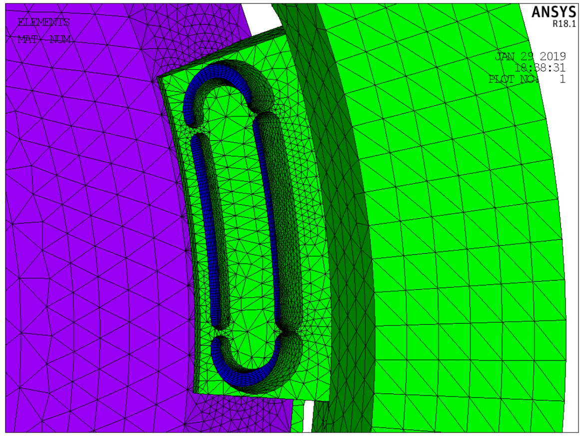
Design (WP3, WP5) – Mount Designs – Detailed Design and Simulation of Compensator Designs







Local bond geometry on sphere



Local bond geometry on sphere

Lens material	Silica	N-LAK9	CaF_2
Mount material	Invar	TiAl4V6	X6CrNiMoTi17-12-2
Mass	857	829	993

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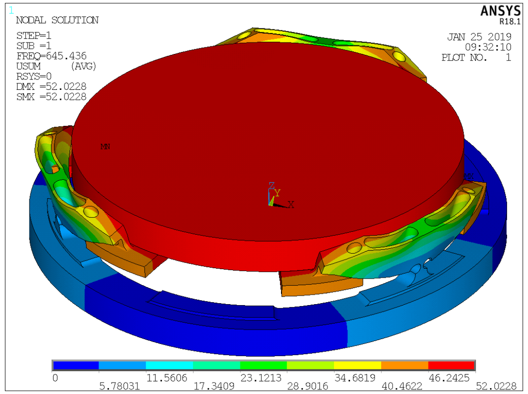
Design (WP3, WP5) – Mount Designs – Detailed Design and Simulation of Compensator Designs

- Eigenfrequencies

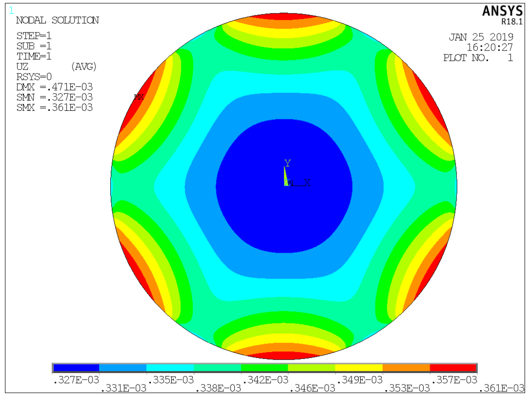
Lens material	Silica	N-LAK9	CaF_2
Mount material	Invar	TiAl4V6	X6CrNiMoTi17-12-2
1	645.44	490.53	623.9
2	757.61	600.31	732.1
3	758.32	600.69	732.7

- e.g. 10 K ambient temperature change

Lens material	Silica	N-LAK9	CaF_2
Mount material	Invar	TiAl4V6	X6CrNiMoTi17-12-2
r.m.s. surface deformation [nm]	8.19	8.16	9.17
p.-v. surface deformation [nm]	33.54	33.90	38.32
MoS for the solder	**-0.81**	**-0.79**	**-0.43**
MoS for the glass	**-0.64**	**-0.69**	0.02
MoS for the solid-state hinges	30.54	41.86	10.61



First Eigenmode



Axial deformation @ Δ10 K ambient

- Other load cases simulated: 60 K ambient and global optics/ mount temperature change, accellerations
- Summary: Eigenmodes >>250 HZ, plasticity in solder @ Δ60 K negative MoS due to FEM artifacts

LaSol TN3: „LENS MOUNT DESIGN REPORT“

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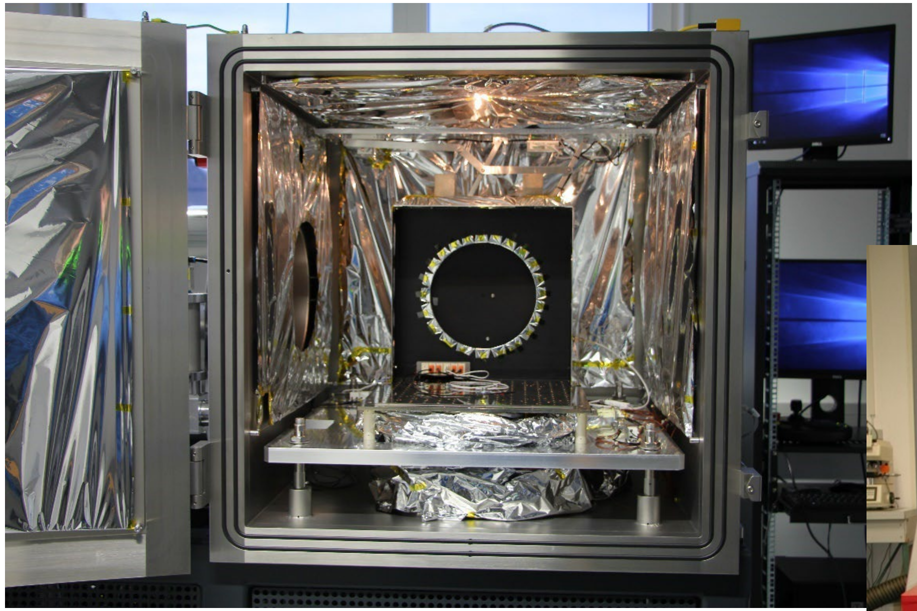
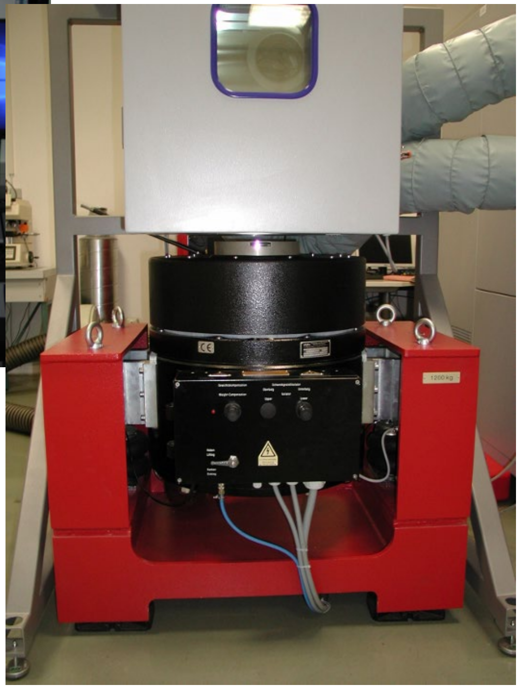
Test Plan (WP6) – Measurement Types, Testing Infrastructure

- A) Visual inspection (optics, mount)
- B) Flatness by means of interferometry (optics)
- C) Displacement optics vs. mount by means of 3D coordinate measurement system
- D) Tip/Tilt optics vs. mount by means of auto-collimation telescope and 3D coordinate measurement system)
- E) Stress birefringence (optics) by means of polarimetry
- F) Wave front deformation (optics) by means of Shack-Hartmann wave front sensor



Thermal vacuum chamber @ F-IOF



Shaker @ F-ENAS

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Test Plan (WP6) – Measurement Procedure (planned)

No.	Test Type	Test Description	Remark
1	Demonstrator Measurement	Measurement Type A, B, E, ~~F~~	Initial measurement of optics
2	Demonstrator Measurement	Measurement Type A – E (~~F~~)	After optics in mount positioning
3	Demonstrator Measurement	Measurement Type A – E (~~F~~)	After optics in mount attachment
4	Demonstrator Measurement	Measurement Type A – E (~~F~~)	Before environmental load testing
5	Demonstrator Testing	Thermal Cycling[i]	~~Includes demonstrator measurement 3.6~~
~~6~~	~~Demonstrator Measurement~~	~~Measurement Type F~~	~~During demonstrator testing 3.5~~
7	Demonstrator Measurement	Measurement Type A – E (~~F~~)	After thermal cycling testing
8	Demonstrator Testing	Random Vibration[ii]	
9	Demonstrator Measurement	Measurement Type A – E (~~F~~)	After random vibration testing
10	Demonstrator Testing	Sine Vibration[iii]	
11	Demonstrator Measurement	Measurement Type A – E (~~F~~)	After sine vibration testing

- F) Wave front deformation (optics) by means of Shack-Hartmann wave front sensor
  - Discarded due to complexity of integration into SJB and testing equipment

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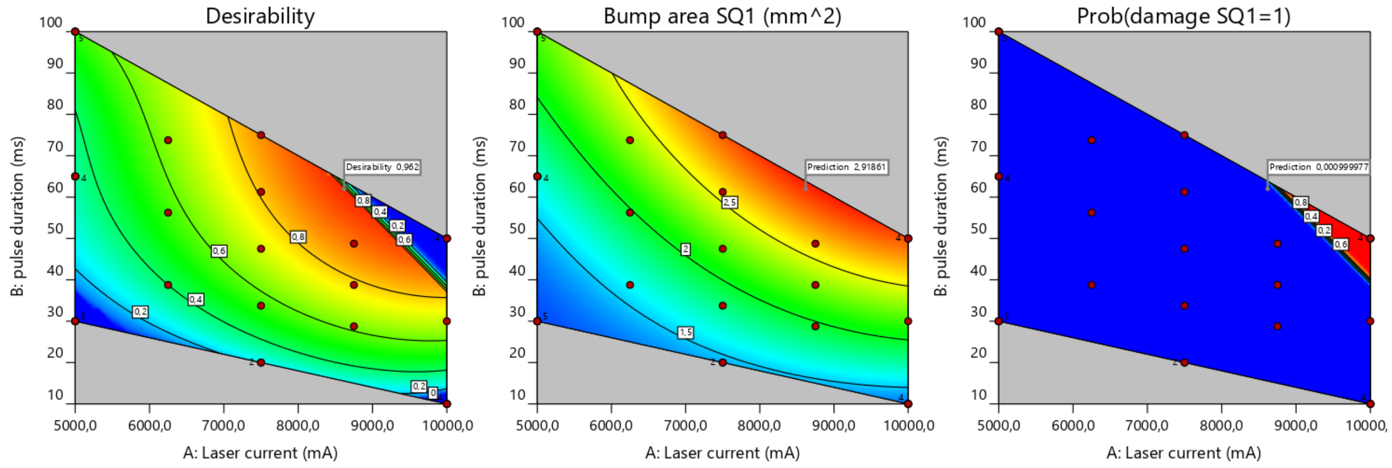
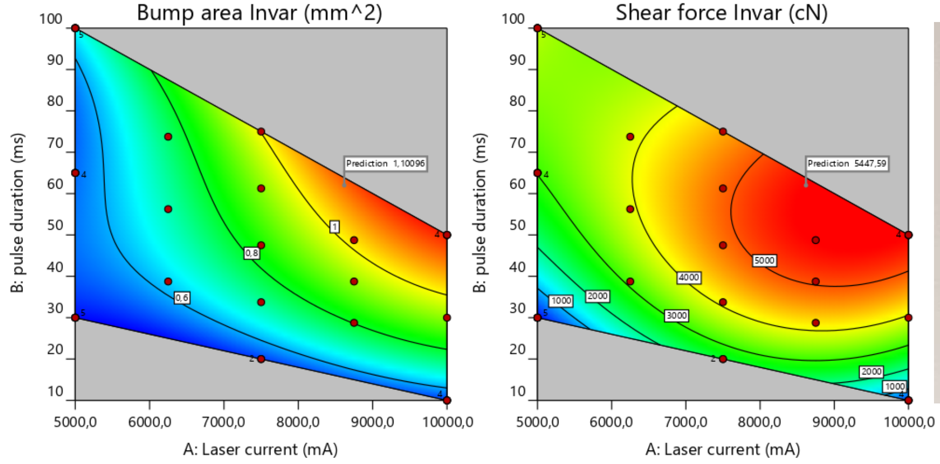
Technology Development (WP6) – SJB Parameterization





DoE

- **DoE for SJB Parameters**
  - Pulse energy (laser current) and duration
- **Observation criteria**
  - Bump area, shear force, visual damage
- **DoE on both materials (component, mount)**
- **Final parameters used = common denominator**

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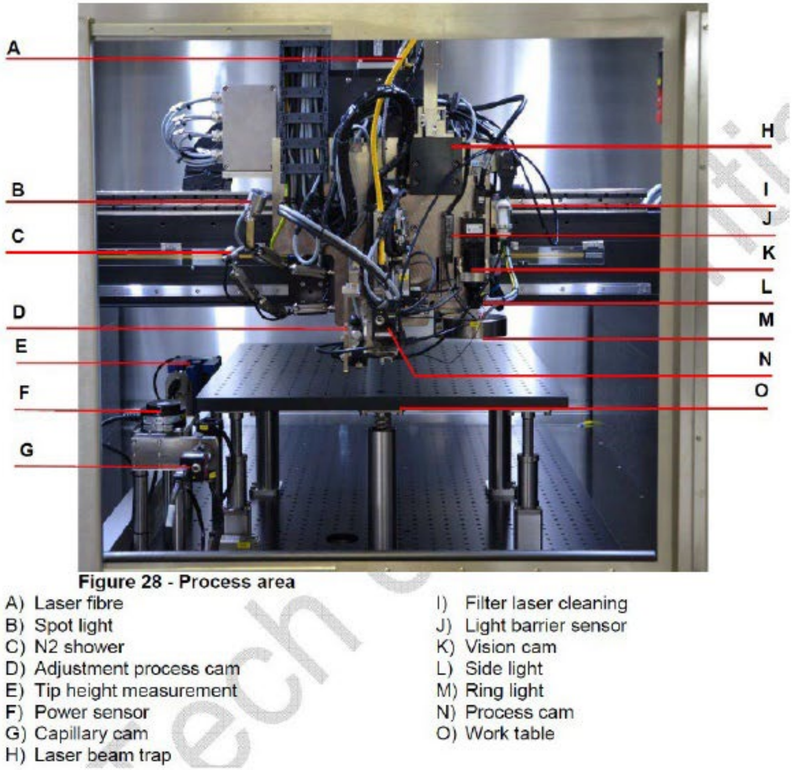
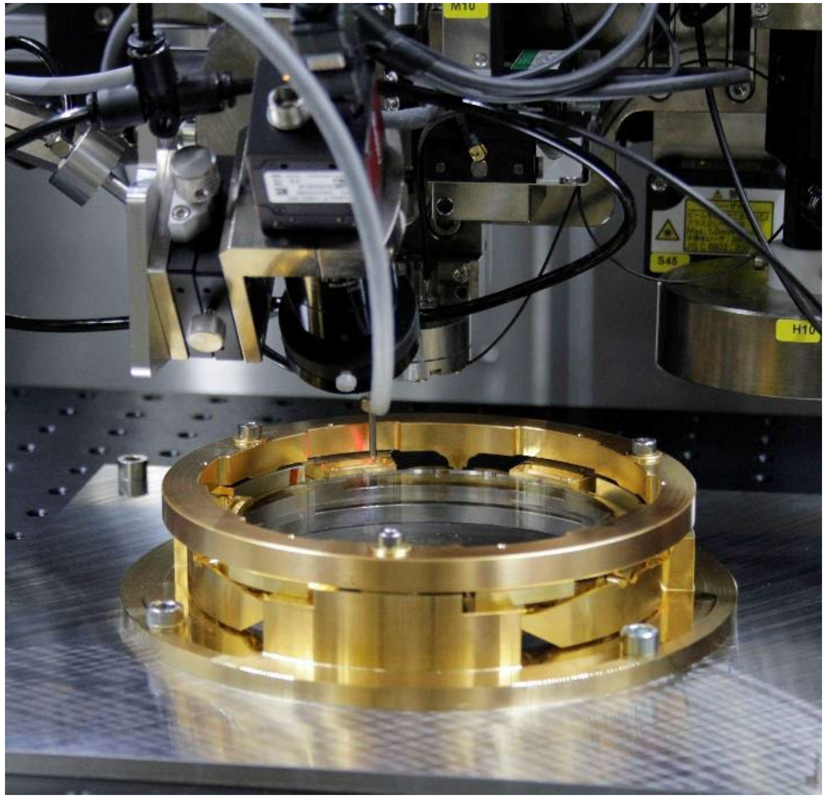
MAI (WP6)

SJB Machine





Lens Soldering Setup

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MAI (WP6) - Demonstrators

Lens Material	Mount Material	Demonstrator Name	Name Extension	Remarks
SQ1	**INVAR**	1092-001-IN-01	n.a.	Spherical bonding contact surface
		1092-001-IN-02		
		1092-001-IN-03		
		1092-001-IN-04		
		1092-001-IN-05		
N-LAK9	**TiAl6V4**	1092-002-Ti-11		Planar bonding contact surface
		1092-002-Ti-12		
		1092-002-Ti-13		
		1092-002-Ti-14		
CaF2	**X6CrNiMoTi 17-12-2**	1092-002-SS-21	_CaF2_04	Planar bonding contact surface CaF2 [111] orientation
		1092-002-SS-22	_CaF2_05	
		1092-002-SS-23	_CaF2_03	
		1092-002-SS-24	_CaF2_R01	Planar bonding contact surface CaF2 random orientation
		1092-002-SS-25	_CaF2_R02	

- SQ1 – MICROS Optics GmbH & Co. KG,
- N-LAK9 - Hellma GmbH, and
- CaF2 - POG Präzisionsoptik Gera GmbH

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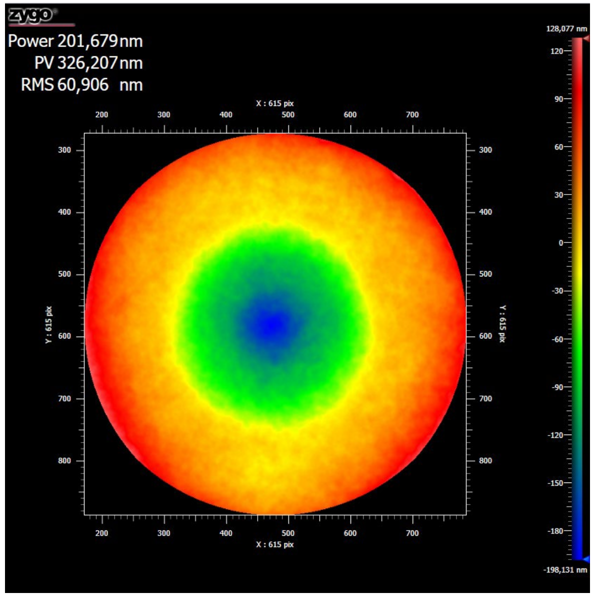
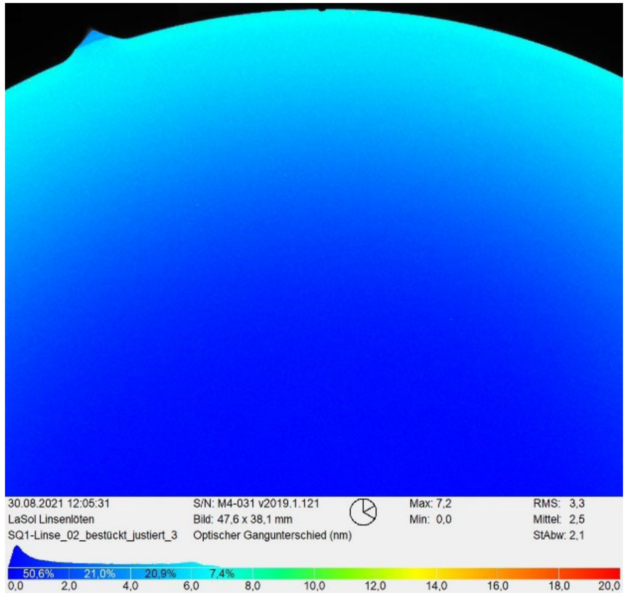
MAI (WP6) – Demonstrator Measurements

Lens Material	Mount Material	Demonstrator Name	Initial Characterization	Soldering performance evaluation
SQ1	INVAR	1092-001-IN-01	P-V, B	broken
		1092-001-IN-02	P-V, B	P-V, B, CMM
		1092-001-IN-03	B	P-V, B, CMM
		1092-001-IN-04	B	P-V, B
		1092-001-IN-05	B	P-V, B, CMM
N-LaK9	TiAl6V4	1092-002-Ti-11	B	P-V, B, CMM
		1092-002-Ti-12	B	P-V, B, CMM
		1092-002-Ti-13	B	P-V, B, CMM
		1092-002-Ti-14	B	P-V, B, CMM
CaF2	X6CrNiMoTi17-12-2	1092-002-SS-21	B	P-V, B, CMM
		1092-002-SS-22	B	P-V, B, CMM
		1092-002-SS-23	B	P-V, B, CMM
		1092-002-SS-24	B	B, CMM
		1092-002-SS-25	B	P-V, B, CMM





Exemplary P-V and birefringence before soldering

- Directly after soldering induced birefringence was 2 nm to 8 nm
- ΔP-V < 100 nm (but only measured one time, stativ P-V after soldering ca. 300..400 nm)

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Testing (WP7) – Demonstrator Measurements

Lens Material	Mount Material	Demonstrator Name	Initial Characterization	Soldering performance evaluation	Operation Temperature Cycling	Non-operational temperature cycling	Intermediate characterization	Vibration testing	Final characterization
SQ1	INVAR	1092-001-IN-01	P-V, B	broken	n.a.	n.a.	n.a.	n.a.	n.a.
		1092-001-IN-02	P-V, B	P-V, B, CMM	P-V, B	P-V, B	P-V, B	P-V, B, CMM	P-V, B
		1092-001-IN-03	B	P-V, B, CMM	P-V, B	P-V, B	P-V, B	P-V, B, CMM	P-V, B
		1092-001-IN-04	B	P-V, B	n.a.	n.a.	n.a.	n.a.	n.a.
		1092-001-IN-05	B	P-V, B, CMM	n.a.	n.a.	n.a.	n.a.	n.a.
N-LaK9	TiAl6V4	1092-002-Ti-11	B	P-V, B, CMM	P-V, B	P-V, B	P-V, B	broken	n.a.
		1092-002-Ti-12	B	P-V, B, CMM	P-V, B	P-V, B	P-V, B	P-V, B, CMM	P-V, B
		1092-002-Ti-13	B	P-V, B, CMM	P-V, B	P-V, B	P-V, B	P-V, B, CMM	P-V, B
		1092-002-Ti-14	B	P-V, B, CMM	P-V, B	P-V, B	P-V, B	P-V, B, CMM	P-V, B
CaF2	X6CrNiMoTi17 -12-2	1092-002-SS-21	B	P-V, B, CMM	P-V, B	P-V, B	P-V, B	P-V, B, CMM	P-V, B
		1092-002-SS-22	B	P-V, B, CMM	P-V, B	P-V, B	P-V, B	P-V, B, CMM	P-V, B
		1092-002-SS-23	B	P-V, B, CMM	P-V, B	P-V, B	P-V, B	P-V, B, CMM	P-V, B
		1092-002-SS-24	B	B, CMM	P-V, B	P-V, B	P-V, B	P-V, B, CMM	P-V, B
		1092-002-SS-25	B	P-V, B, CMM	P-V, B	P-V, B	P-V, B	P-V, B, CMM	P-V, B

B – Birefringence

P-V – Interferometry incl. Rms

CMM – 3D CMM

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Testing (WP7) – What happened?

Lens Material	Mount Material	Demonstrator Name	Comments
SQ1	INVAR	1092-001-IN-01	**Soldering failed, broken SQ1 material after soldering (see discussion)**
		1092-001-IN-02	Demonstrator ok
		1092-001-IN-03	Demonstrator ok
		1092-001-IN-04	Only soldered, not tested nor characterized, demonstrator saved for ESA
		1092-001-IN-05	Only soldered, not tested nor characterized, demonstrator saved for ESA
N-LAK9	TiAl6V4	1092-002-Ti-11	Demonstrator for testing purposes, **broken during vibration**
		1092-002-Ti-12	Demonstrator ok
		1092-002-Ti-13	Demonstrator ok
		1092-002-Ti-14	Demonstrator ok
CaF2	X6CrNi MoTi17-12-2	1092-002-SS-21	Demonstrator ok ([111] CaF2 orientation)
		1092-002-SS-22	Demonstrator ok ([111] CaF2 orientation)
		1092-002-SS-23	Demonstrator ok ([111] CaF2 orientation)
		1092-002-SS-24	**Demonstrator for testing (random CaF2 crystal orientation), broken CaF2 material after soldering**
		1092-002-SS-25	**Demonstrator for testing (random CaF2 crystal orientation), broken CaF2 material after soldering**

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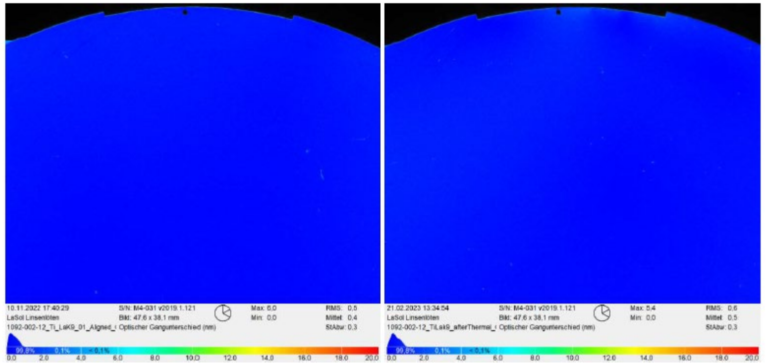
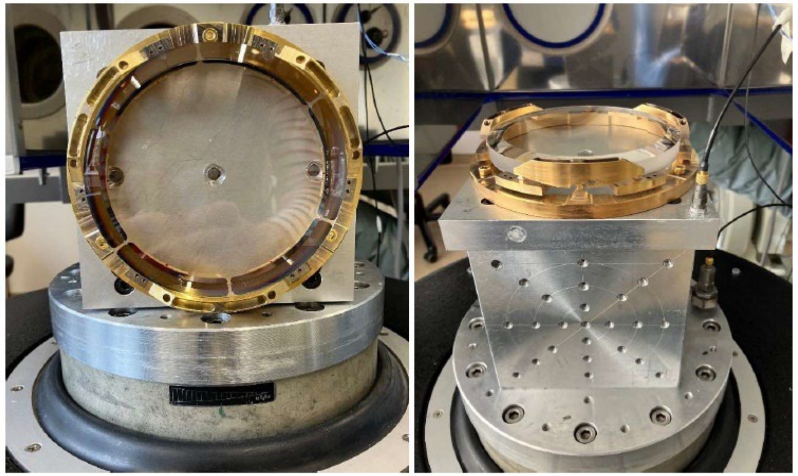
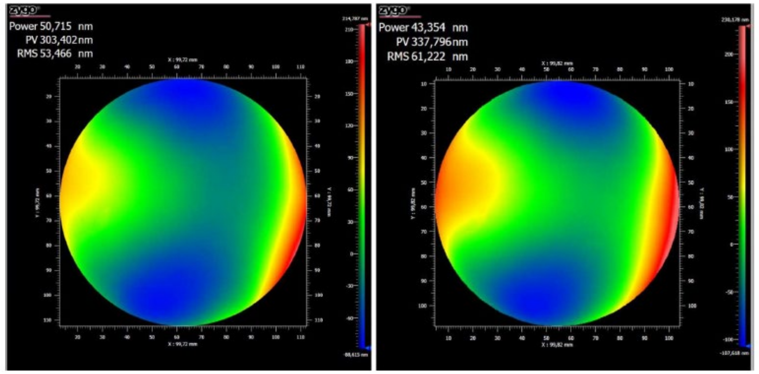
Testing (WP7) – Impressions



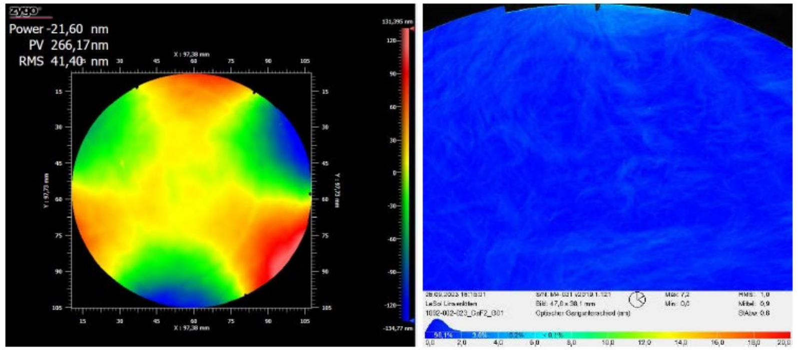
Birefringence 1092-002-Ti-12 before and after thermal cycling



1092-002-SS-23 on the shaker



P-V 1092-002-Ti-11 before and after thermal cycling



P-V and birefringence 1092-002-SS-23 after vibration

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Testing (WP7) – Results for P-V and RMS (after Soldering vs. after Vibration)

Lens Material	Mount Material	Demonstrator Name		DP-V$_{Mech-Sold}$ [nm] Side A	Side B
SQ1	INVAR	1092-001-IN-01		broken	
		1092-001-IN-02		47	103
		1092-001-IN-03		46	3
		1092-001-IN-04		n.a.	n.a.
		1092-001-IN-05		n.a.	n.a.
SQ1: Mean(±3s)				**46±1**	**53±149**
N-LAK9	TiAl6V4	1092-002-Ti-11		broken	
		1092-002-Ti-12		389	157
		1092-002-Ti-13		158	17
		1092-002-Ti-14		183	43
N-LAK9: Mean(±3s)				**244±311**	**73±183**
CaF2	X6CrNi MoTi17-12-2	1092-002-SS-21		386	384
		1092-002-SS-22		415	408
		1092-002-SS-23		365	404
		1092-002-SS-24		broken	
		1092-002-SS-25		broken	
CaF2: Mean±3s				**349±215**	**390±31**

ΔP-V

Lens Material	Mount Material	Demonstrator Name		DInterferom RMS$_{Mech-Sold}$ [nm] Side A	Side B
SQ1	INVAR	1092-001-IN-01		broken	
		1092-001-IN-02		-8	0
		1092-001-IN-03		-4	-4
		1092-001-IN-04		n.a.	n.a.
		1092-001-IN-05		n.a.	n.a.
SQ1: Mean(±3s)				**-6±7**	**-2±9**
N-LAK9	TiAl6V4	1092-002-Ti-11		broken	
		1092-002-Ti-12		115	106
		1092-002-Ti-13		46	7
		1092-002-Ti-14		9	10
N-LAK9: Mean(±3s)				**-57±162**	**-34±188**
CaF2	X6CrNi MoTi17-12-2	1092-002-SS-21		-59	-61
		1092-002-SS-22		-62	-64
		1092-002-SS-23		-60	-61
		1092-002-SS-24		broken	
		1092-002-SS-25		broken	
CaF2: Mean±3s				**-60±5**	**-62±5**

ΔRMS

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Testing (WP7) – Results for Birefringence and 3D CMM (after Soldering vs. after Vibration)

Lens Material	Mount Material	Demonstrator Name		DBirefringe$_{Mech\text{-}Sold}$ [nm]
SQ1	INVAR	1092-001-IN-01		broken
		1092-001-IN-02		11.8
		1092-001-IN-03		4.7
		1092-001-IN-04		n.a.
		1092-001-IN-05		n.a.
SQ1: Mean(±3s)				**8.2±15.6**
N-LAK9	TiAl6V4	1092-002-Ti-11		broken
		1092-002-Ti-12		5.0
		1092-002-Ti-13		6.5
		1092-002-Ti-14		8.7
N-LAK9: Mean(±3s)				**6.7±7.9**
CaF2	X6CrNi MoTi17-12-2	1092-002-SS-21		1.6
		1092-002-SS-22		2.7
		1092-002-SS-23		9.5
		1092-002-SS-24		broken
		1092-002-SS-25		broken
CaF2: Mean±3s				**4.6±13.3**

ΔBirefringence

Lens Material	Mount Material	Demonstrator Name	CMM$_{Sold}$ [mm]			CMM$_{Mech}$ [mm]			DCMM$_{Mech\text{-}Sold}$ [µm]		
			X	Y	//	X	Y	//	X	Y	//
SQ1	INVAR	1092-001-IN-01	broken								
		1092-001-IN-02	-0.029	-0.088	0.082	-0.022	-0.098	0.082	7	10	0
		1092-001-IN-03	-0.004	-0.086	0.138	0.002	-0.096	0.138	6	10	0
		1092-001-IN-04	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		1092-001-IN-05	-0.224	0.0561	0.062	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
N-LAK9	TiAl6V4	1092-002-Ti-11	0.012	0.074	0.035	broken					
		1092-002-Ti-12	0.113	-0.023	0.032	0.113	-0.023	0.032	0	0	0
		1092-002-Ti-13	0.026	-0.052	0.012	0.026	-0.052	0.012	0	0	0
		1092-002-Ti-14	0.031	-0.065	0.015	0.031	-0.065	0.015	0	0	0
CaF2	X6CrNi MoTi17-12-2	1092-002-SS-21	-0.025	-0.05	0.015	-0.025	-0.05	0.015	0	0	0
		1092-002-SS-22	-0.007	0.026	0.032	-0.007	0.026	0.032	0	0	0
		1092-002-SS-23	0.041	-0.033	0.068	0.041	-0.033	0.068	0	0	0
		1092-002-SS-24	broken								
		1092-002-SS-25	broken								

ΔCMM

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Final Compliance Statement I

- **Requirement 1 - Minimum optical element diameter: 100 mm**
  - Initial compliance: Y, Final compliance: Y, Comments:
    - Limitation in size regarding the mass of the component vs. the available attachment area.
    - Demonstrator assemblies had a mechanical diameter of 120 mm, and an optical aperture of 100 mm for the optical elements attached within respective mounts.
- **Requirement 2 - Wavelength Range: 300 nm to 2 µm, Requirement 3 - Radiation Environment: LEO and GEO orbits**
  - Initial compliance: Y, Final compliance: Y, Comments:
    - Solder alloy Sn3Ag0.5Cu used as bonding medium, and chosen laser-soldering process are suitable for given wavelength range.

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Final Compliance Statement II

- **Requirement 4 - Reflective elements: shall not be included**
  - Initial compliance: Y, Final compliance: Y, Comments:
    - The laser-based soldering technology is also suitable for reflective optical elements, if their material’s thermal conductivity is less than ca. 100 W/m/K.
- **• Requirement 5 - MOC Contamination level: < 10-7 g/cm2**
  - Initial compliance: Y, Final compliance: P, Comments:
    - The laser-based soldering technology is inherent clean, it does not use flux. The demonstrator assembly took place in a cleanroom environment class 10.000. No dedicated particle nor contamination measurements carried out during the project.

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Final Compliance Statement III

- **Requirement 6 - Stress Induced Birefringence: <1 nm/cm (<2.5 nm/cm) over clear aperture**
  - Initial compliance: P, Final compliance: P, Comments:
    - Birefringence was measured by means of polarimetry within the optical aperture of the optical components before and after soldering, and after testing. High standard deviation 3σ up to >10 nm. Directly after soldering induced birefringence was 2 nm to 8 nm, after testing it annealed to ca. 1 nm.
- **Requirement 7 - Maximum level of transmission loss: < 1%**
  - Initial compliance: Y, Final compliance: Y, Comments:
    - Was considered by design and analysis, see also comment about Requirement 8.
- **Requirement 8 - Coating effects: shall not be included**
  - Initial compliance: Y, Final compliance: Y, Comments:
    - Localized, non-transparent, and wettable metallization is a mandatory pre-requisite for the laser-based soldering process, to be applied outside of intended optical aperture of the optical components.

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Final Compliance Statement IV

- **Requirement 9 - “Exotic” materials (Beryllium, KBr, laser crystals…): shall be excluded**
  - Initial compliance: Y, Final compliance: Y, Comments:
    - Tested CaF_2 material can be considered as an exotic material, being very sensitive vs. thermal shock and thus being highly critical for the intended laser-based soldering process.
- **Requirement 10 - Aging effects (creep, change of material properties e.g. temporal CTE change): Shall be taken into account**
  - Initial compliance: Y, Final compliance: Y, Comments:
    - Aging effects were taken into account by analysis and expertise from past projects.
- **Requirement 11 - Operational thermal range: -40 °C to + 70 °C, Requirement 12 - Thermal cycling: Minimum of 8 cycles over the thermal range**
  - Initial compliance: Y, Final compliance: Y, Comments:
    - Bonding geometries were designed to withstand this load at a certain safety margin, thermal cycling load was tested on the assembled demonstrators.

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Final Compliance Statement V

- **Requirement 13 - Random vibration environment, Requirement 14 - Sine vibration environment**
  - Initial compliance: Y, Final compliance: Y, Comments:
    - Bonding geometries were designed to withstand this load at a certain safety margin, first eigenmode of the chosen assembly designs were 645.4 Hz (SQ1 vs. INVAR), 490.5 Hz (N-LAK9 vs. TiAl6V4), and 623.9 Hz (CaF2 vs. X6CrNi MoTi17-12-2).
    - Random and sine vibration load was tested on the assembled demonstrators, the following demonstrators survived: 2/3 for SQ1 vs. INVAR, 3/4 for N-LAK9 vs. TiAl6V4, 3/5 for CaF2 vs. X6CrNi MoTi17-12-2

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Final Compliance Statement VI

- **Requirement 15 - Displacement of the mounted optical element after thermal and mechanical loads (line of sight): < 1 µm in any directions**
  - Initial compliance: P, Final compliance: Y, Comments:
    - Displacement measured by 3D coordinate measurement machine. SQ1 vs. INVAR demonstrators: 6 µm to 10 µm (non-optimized bonding area geometries), N-LAK9 vs. TiAl6V4 and CaF2 vs. X6CrNi MoTi17-12-2 demonstrators: displacement below CMM uncertainty of ca. 1 µm.
- **Requirement 16 - Tilt of the mounted optical element after thermal and mechanical loads (line of sight): < 1 Arc-sec in any direction**
  - Initial compliance: P, Final compliance: P, Comments:
    - Tilt calculated based on the CMM measurement for Requirement 15 (base length ca. 100 mm): displacement below CMM uncertainty of ca. 1 µm.

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Final Compliance Statement VII

- **Requirement 17 - Maximum change of the transmitted WFE: 1/20 of the wavelength (RMS)**
  - Initial compliance: P, Final compliance: N, Comments:
    - Wavefront measurement were discarded
- **Requirement 18 - Number of mounts to be designed, manufactured, tested and delivered: 1 for crystalline glass (CaF2), 1 for amorphous soft glass (e.g. LAK9), 1 for amorphous hard glass (e.g. Fused Silica)**
  - Initial compliance: Y, Final compliance: Y, Comments:
    - 5 demonstrator assemblies per material combination envisaged, only 4 realized for N-LAK9 vs. TiAl6V4, and only 3 survived testing.
    - 5 assembled SQ1 vs. INVAR demonstrators, only 3 tested, and only 2 survived.
    - 5 assembled, tested, and characterized CaF2 vs. X6CrNi MoTi17-12-2 demonstrators, 3 survived testing procedure (CaF2 [111] crystal orientation).

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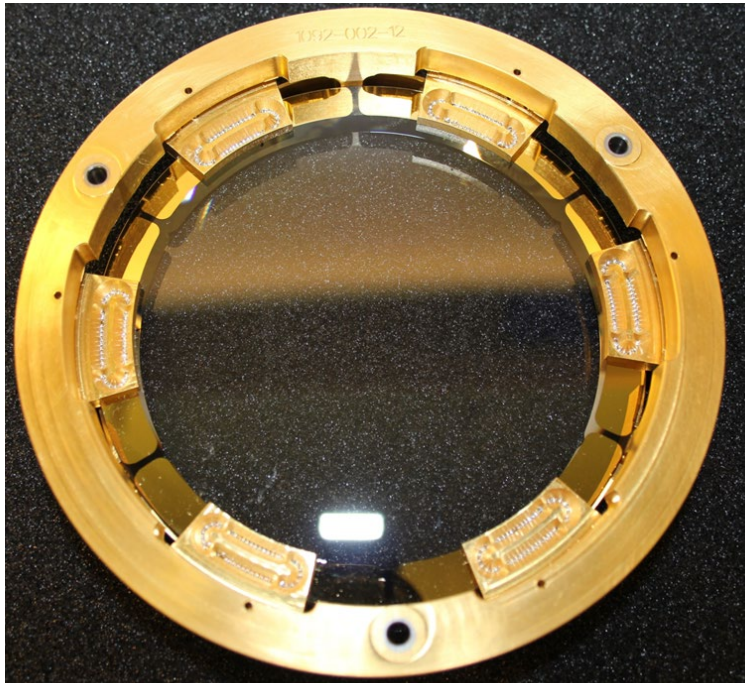
Final Compliance Statement VIII

1092-001-IN-03 (Fused Silica vs. INVAR)



1092-002-Ti-14 (LAK9 vs. Ti)

1092-002-SS-21 (CaF2 vs. 1.4571)

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Main Findings and Lessons learned

1. **Avoid localized mechanical stress (Hertzian contact stress) at mount to component interface**
   - Pre-stressed brittle material (glass) release stress when being subject to thermomechanical stress from soldering -> chipping
     - Even thermo-shock insensitive material (Fused Silica) cracked!

2. **Crystal orientation drives thermo-shock resistivity of sensitive materials**
   - CaF_2 – [111] orientation vs. Random orientation
     - [111] orientation suitable for localized thermo-shock during soldering

Thank you for your attention.

Questions?

Dr. Erik Beckert

10-July-2024, ESTEC – Final Project Presentations

Part 3 – Bond-Match (AO/1-9472/18/NL/AR)

Dr. Erik Beckert

Bond-Match

Statement of Work

- The technical requirements for the technologies to be investigated arise from the objective to **align and bond precision optics made of various, "exotic" optical materials to CTE-matched substrate materials** by means of an anorganic bonding technology. […]
- The four aspects of i) optics **alignment**, ii) **anorganic bonding medium** for the fixation of the alignment state by bonding, iii) **"exotic"** and broad variability of **materials** to be bonded, and iv) generic **environmental conditions** pose the boundaries for the technical requirements […].

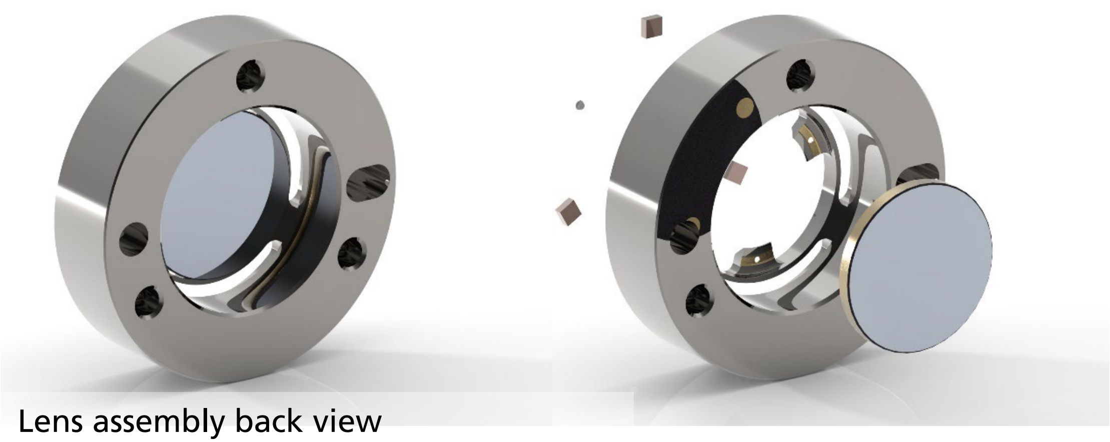
Bond-Match

Materials

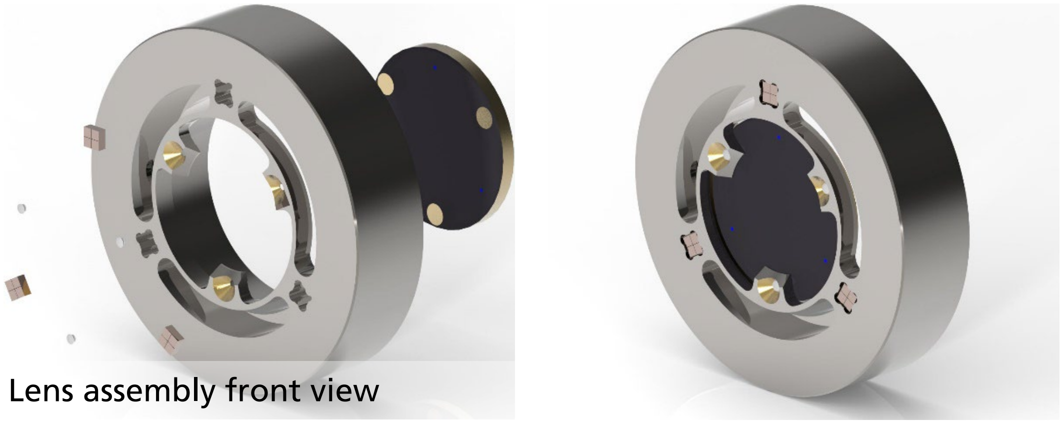
Component	Lens dummy I	Lens dummy II	Laser Crystal I	Laser Crystal II	Lens mount (CaF2)	Lens mount (SQ1)	Mount for laser crystal	Solder
Material	CaF_2	SQ1	BBO	KTP	Steel 1.4571	Invar 36	Kovar	SAC305
Young's modulus [GPa]	75.8	73.2	75.3 (⊥) 26.8 (‖)	136 (⊥) 162 (‖)	200	141	138	43
Poisson number	0.26	0.167	0.186 (xy) 0.268 (xz, yz)	0.15..0.2	0.29	0.29	0.29	0.4
Density [g/cm³]	3.18	2.2	3.85	3.3	7.8	8.05	8.36	7.43
CTE [ppm/K]	18.85	0.56	4 (⊥) 36 (‖)	11 (⊥) 0 (‖)	17.5	1.3	5.86	22.4
Thermal Conductivity [W/m/K]	9.71	1.37	1.2	20..33	15	10.15	17.3	56.3
Heat Capacity [J/kg/K]	854	741	490	707	500	515	460	283
Tensile Strength [MPa]	157	80			650	276	517	35

Bond-Match

Designs – Lens Dummies



Lens assembly back view

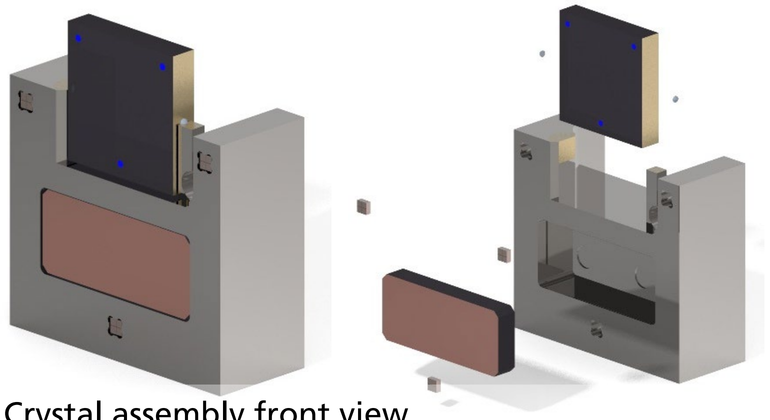


Lens assembly front view

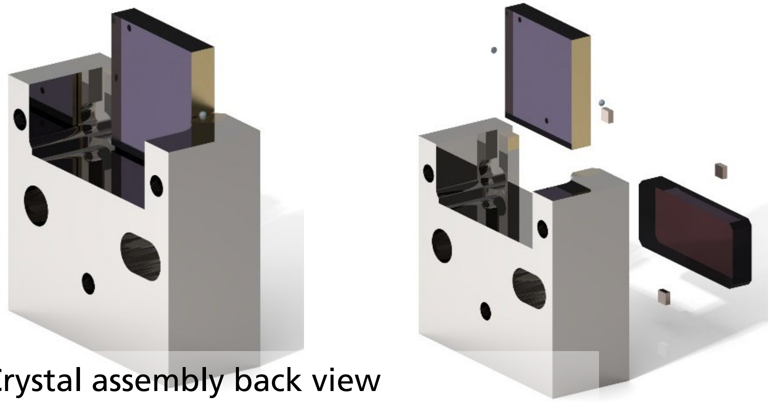
- Flexure on one side integrated
  - Decouple soldering structure from mount
  - Important for thermal load compensation
  - Note: not meant for crystal temperature levelling
- Soldering structure
  - 3x 120° on front surface
  - Designed for mechanical load incl. Marging
    - Note: proved to be not sufficient
- Fiducials
  - Glued into mount
  - Positions defined by mechanical references

Bond-Match

Designs – Laser Crystals



Crystal assembly front view



Crystal assembly back view

- **Flexures 3x120° integrated**
  - Decouple soldering structure from mount
  - Important for thermal load compensation
  - Note: design can be reversed, depending on numerical aperture direction
- **Soldering structure**
  - At both sides
  - Designed for mechanical load incl. marging
    - Note: proved to be not sufficient
- **Fiducials**
  - Glued into mount
  - Positions defined by mechanical references

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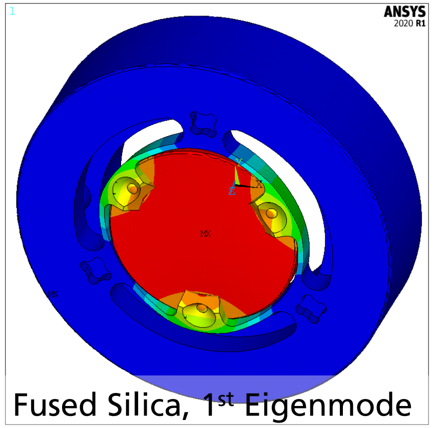
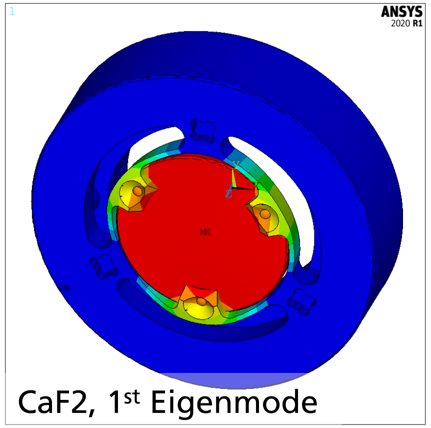
Bond-Match

Designs – Numerical Analysis – Eigenfrequencies Lens Dummy Assemblies



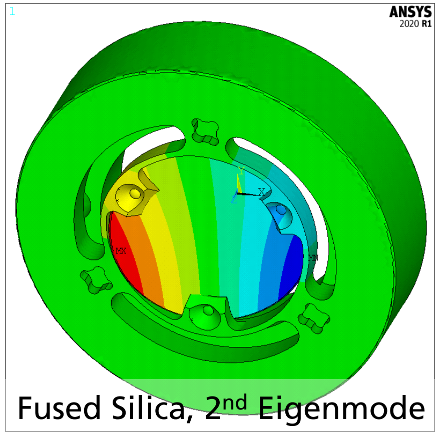
Fused Silica, 1st Eigenmode



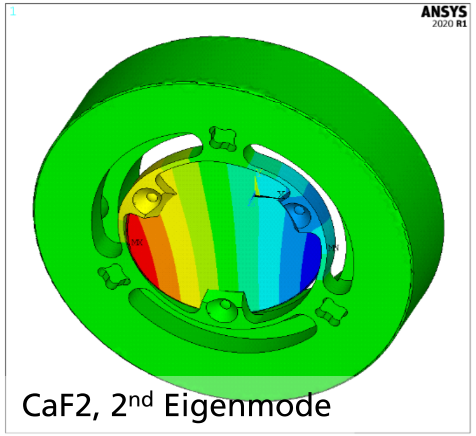
CaF2, 1st Eigenmode

- Eigenfrequencies well above 2 kHz
- Quasi-static system response 133.5 g (3σ rms) for vibrational excitation, 600 g for shock

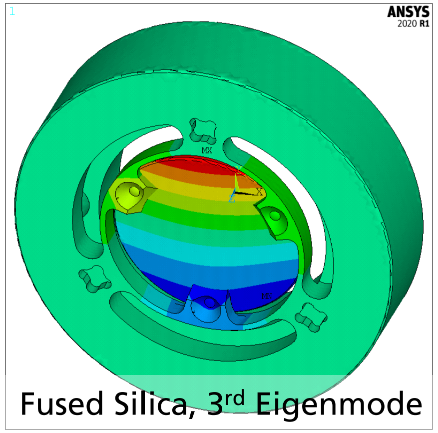
Mode No.	Eigenfrequency [Hz]	
	CaF2	SQ1
1	17671.83	17585.48
2	19231.82	19199.40
3	19242.87	19213.33



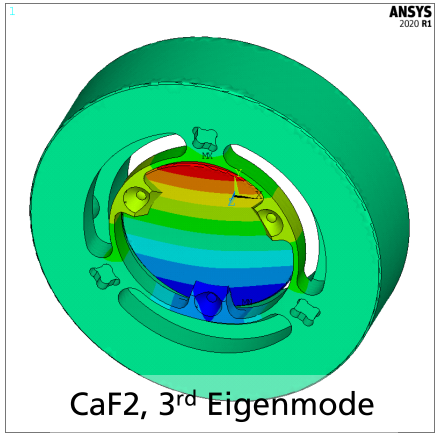
Fused Silica, 2nd Eigenmode



CaF2, 2nd Eigenmode



Fused Silica, 3rd Eigenmode



CaF2, 3rd Eigenmode

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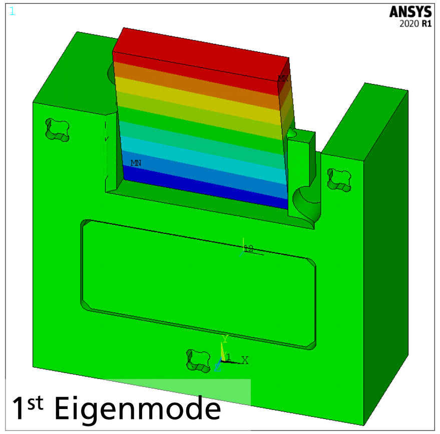
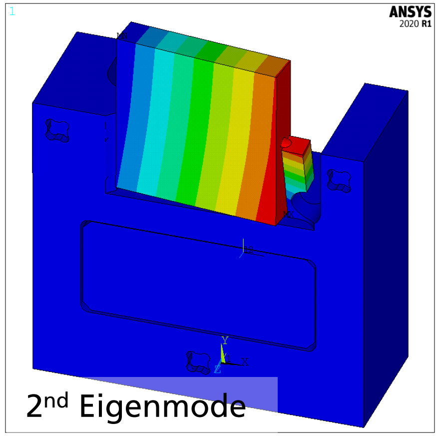
Bond-Match

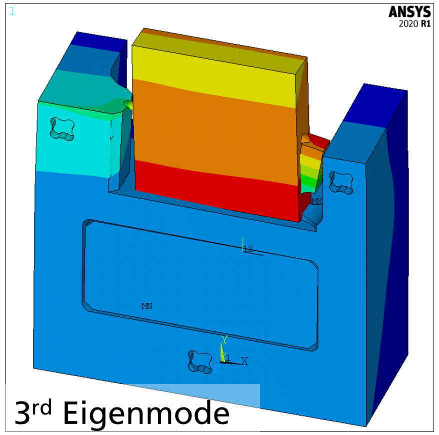
Designs – Numerical Analysis – Eigenfrequencies Laser Crystal Assemblies



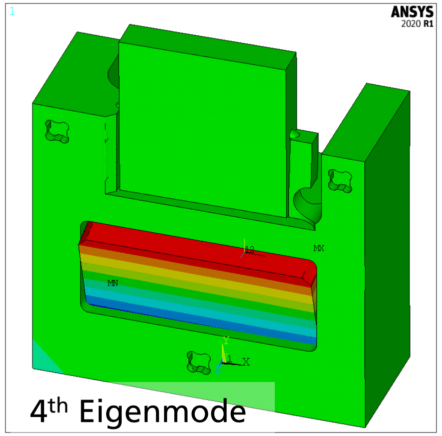
1st Eigenmode



2nd Eigenmode



3rd Eigenmode



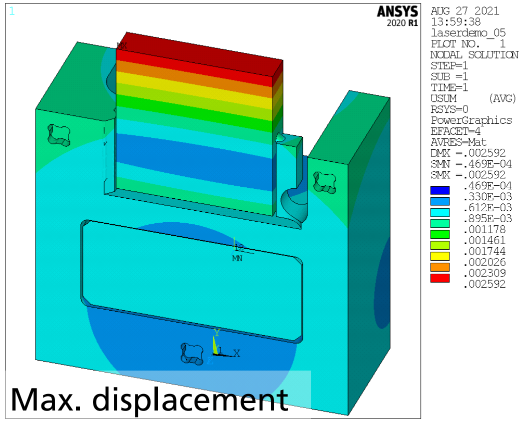
4th Eigenmode

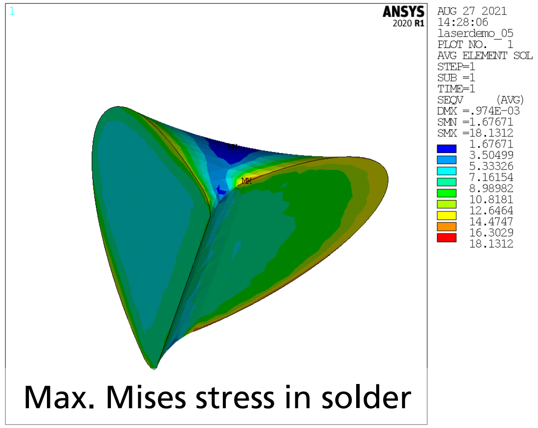
- 1st Eigenfrequencies at 1.4 kHz
- Fundamental mode = rX, effective masses of this mode wrt. linear vibrations are negligible
- Next mode starts at 4.1 kHz
- Quasi-static system response @ 4.1 kHz 133.5 g (3σ rms) for vibrational excitation, 600 g for shock

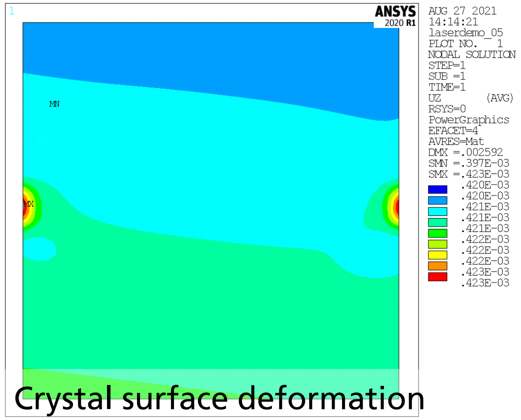
Mode No.	Frequency [Hz]
1	1442.340
2	4073.033
3	11969.34
4	13961.02
5	14326.72
6	15843.62

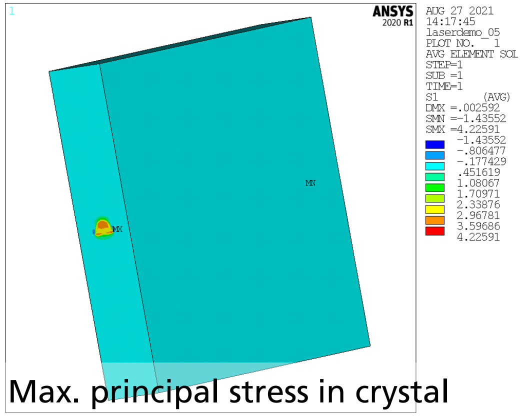
Bond-Match

Designs – Numerical Analysis – Example thermal Load


Max. displacement


Max. Mises stress in solder


Crystal surface deformation


Max. principal stress in crystal

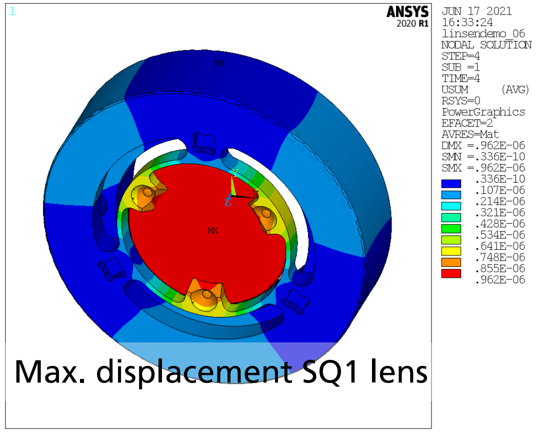
- FEM done @ 10K for BBO
- Linear extrapolation to Δ60K (Ambient .. -40° C)

Component	Maximum stress at -40 °C [MPa]
Optical element	48
Mount	237
Solder	**109**

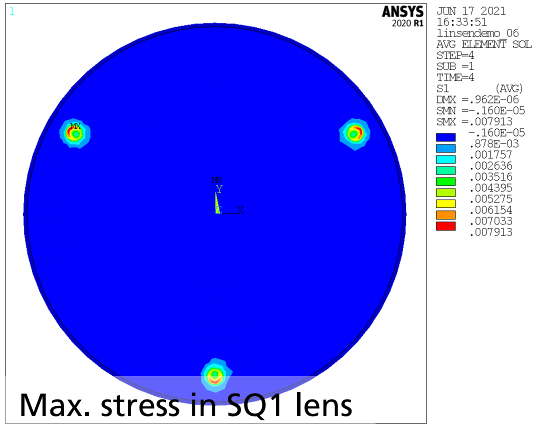
- 109 MPa = artifacts, real stress ca. 0.13 MPa

Bond-Match

Designs – Numerical Analysis – Example mechanical Load



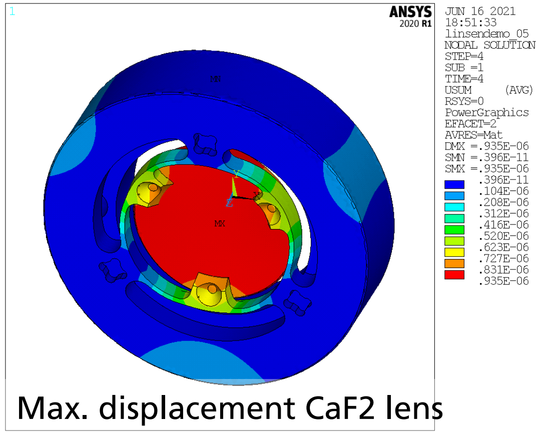
Max. displacement SQ1 lens



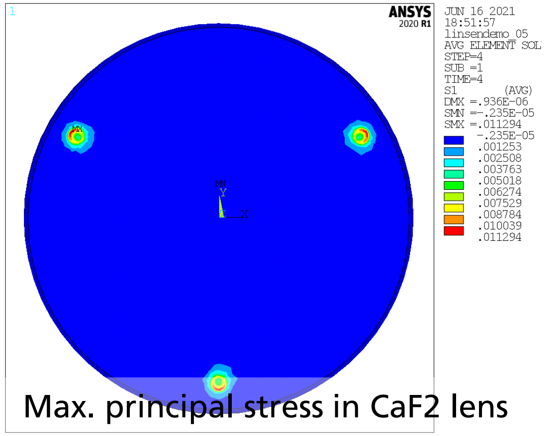
Max. stress in SQ1 lens

- FEM done @ 1g in Z direction
- Linear extrapolation to 600g

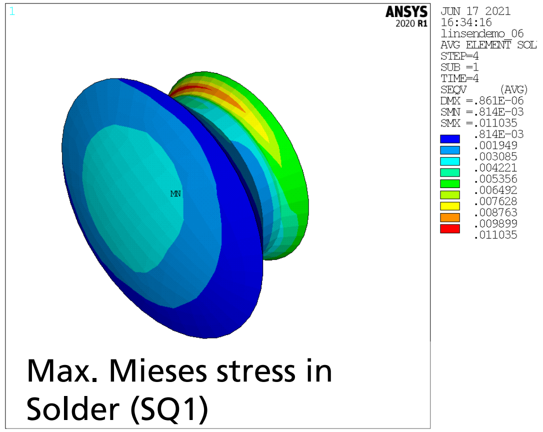
Component	Maximum stress at 600 g in Z [MPa]	
	CaF2	SQ1
Optical element	6.78	4.75
Mount ring	109	67.8
Solder	9.66	6.60



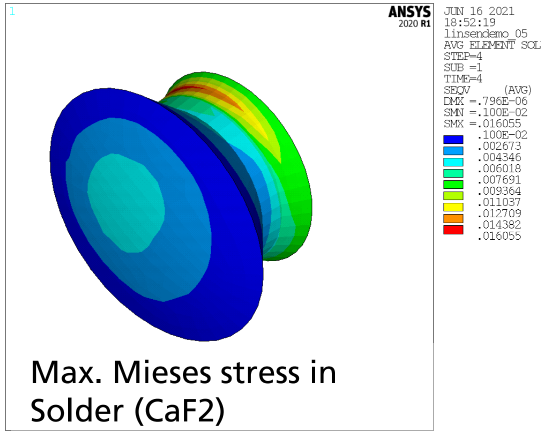
Max. displacement CaF2 lens



Max. principal stress in CaF2 lens



Max. Mieses stress in Solder (SQ1)



Max. Mieses stress in Solder (CaF2)

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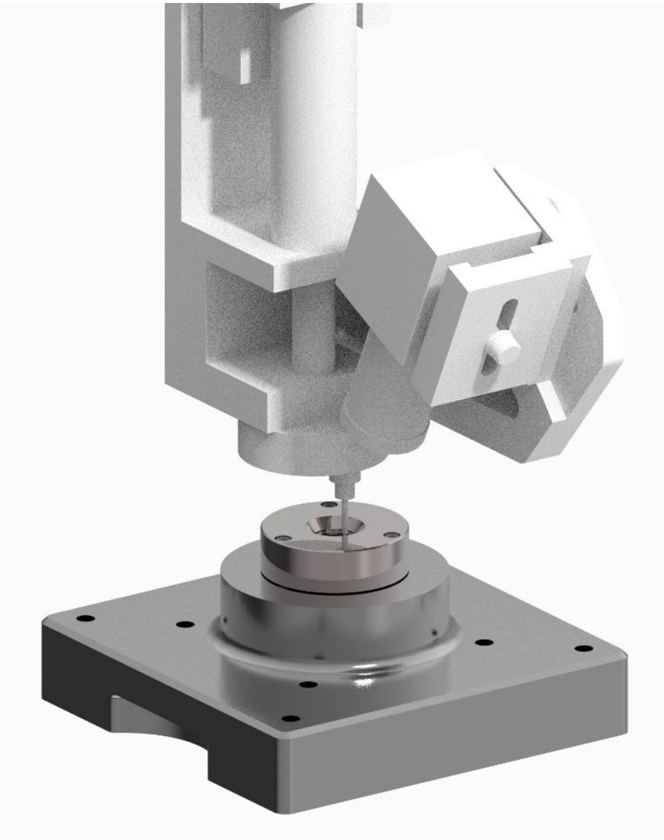
Designs – Numerical Analysis – Summary

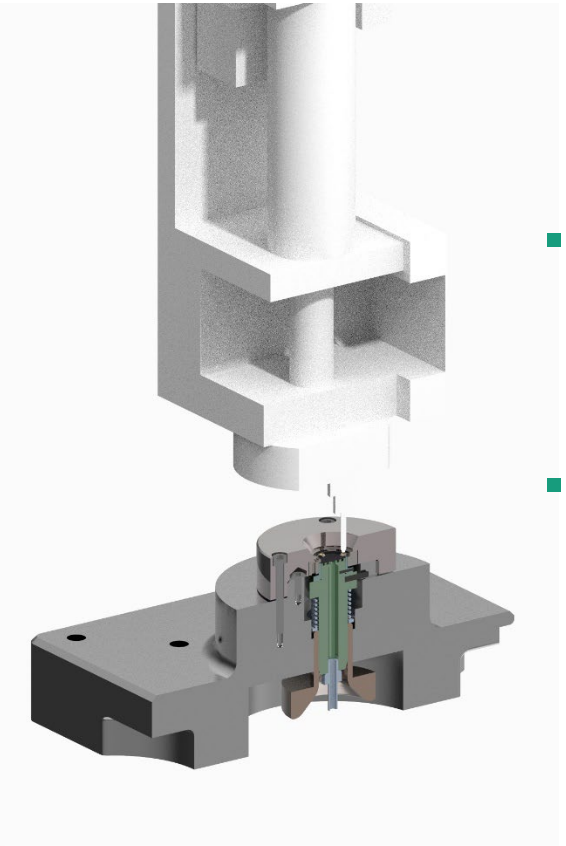
- **Demonstrators will survive the respective environmental loads (∆60K, 600g)**
  - Note: Critical statement!
- **Excessive stresses occur locally at singular points of the solder interface**
  - However, total joint forces will remain below critical value
- **Laser crystal demonstrator has a first Eigenfrequency below 2 kHz**
  - However, the respective effective masses are very small
  - This mode will have negligible influence on the vibration response

Bond-Match

Designs – Assembly and Test Environment – Lens Dummy Assemblies



Lens assembly setup



Setup cross-section

- Passive alignment lens vs. mount
  - Lens vacuum gripper
  - Mount clamp
- Lens clamped vs. mount by adjustable spring force

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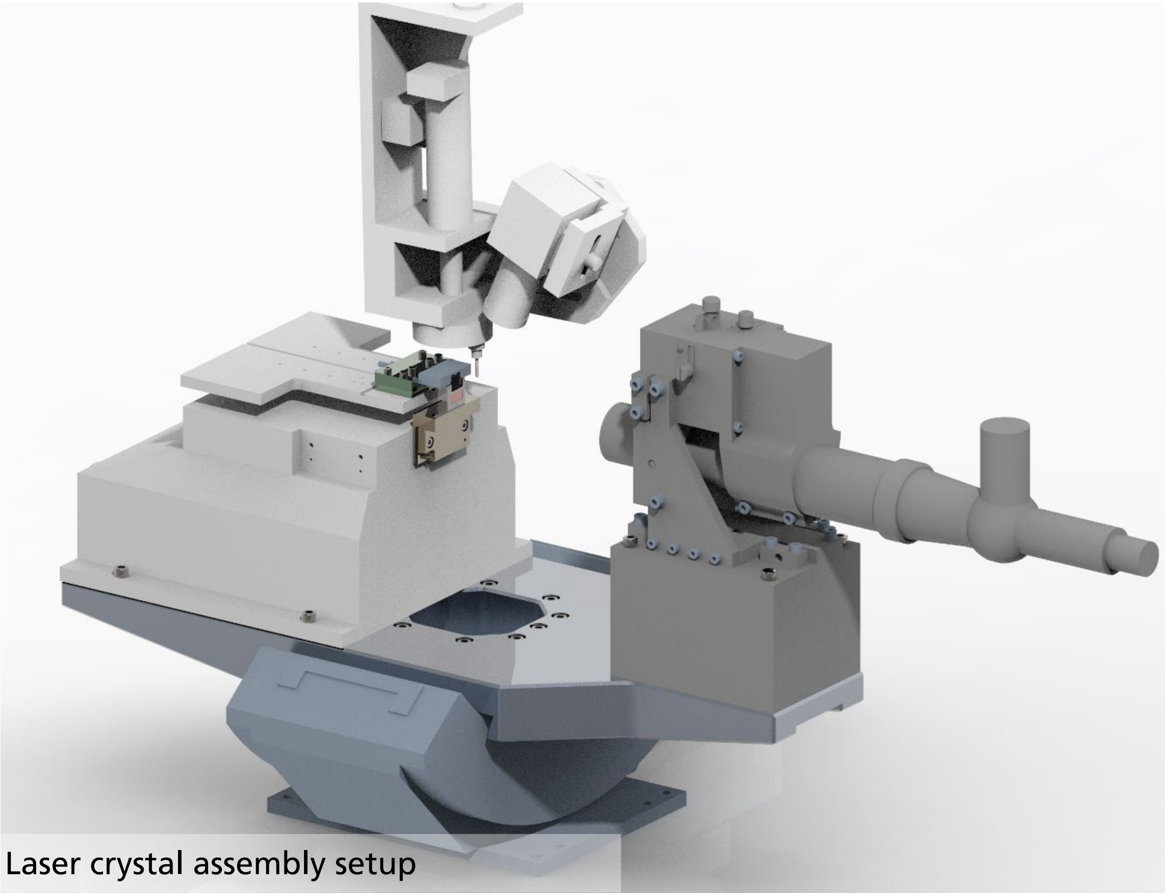
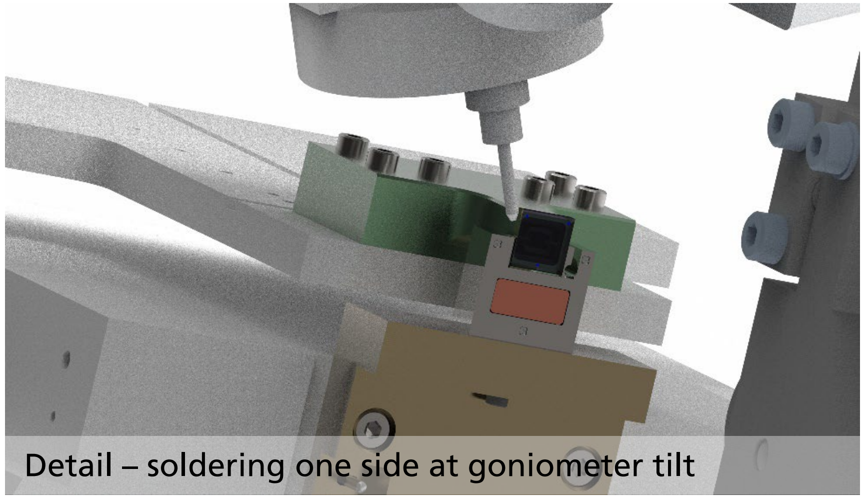
Designs – Assembly and Test Environment – Laser Crystal Assemblies


Laser crystal assembly setup

- Hexapod and vacuum gripper for mirror
  - Tip/tilt alignment crystal vs. mount
- Autocollimation telescope
  - Measurement of tip/tilt alignment
- Goniometer for soldering on both sides


Detail – soldering one side at goniometer tilt

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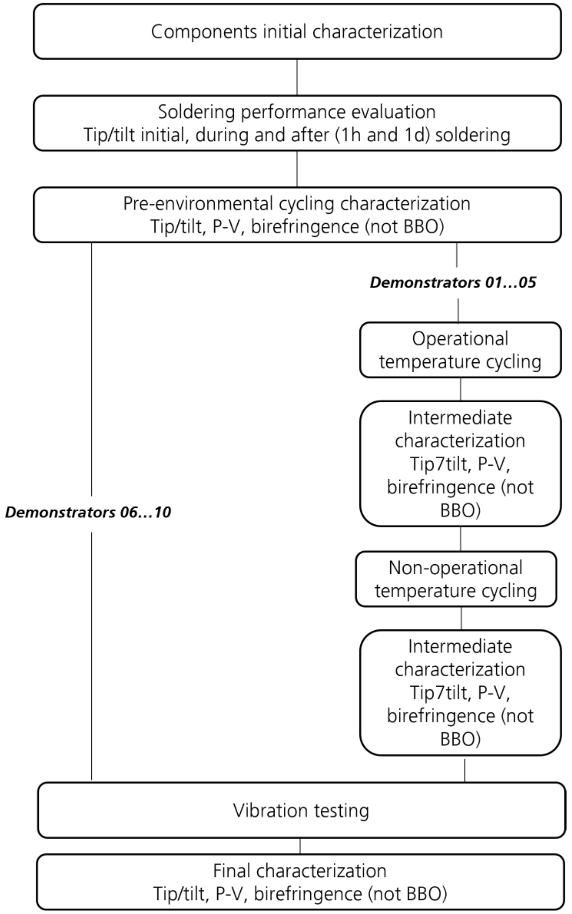
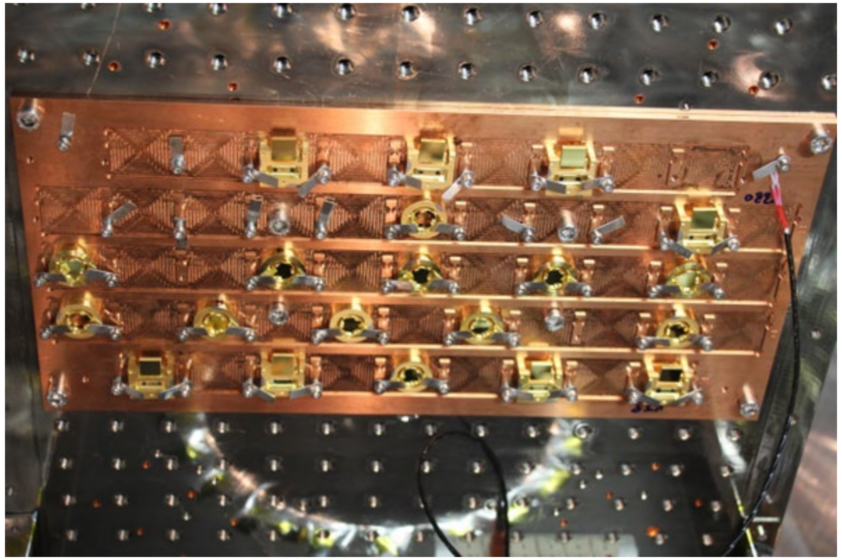
Test Approach, Procedures and Equipment

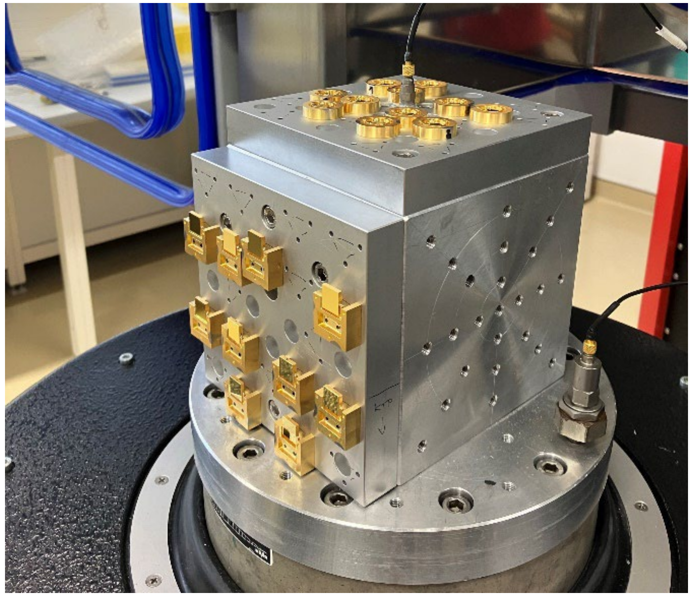


Initially derived test plan



Assemblies within Thermal Vacuum chamber @ F-IOF

- Used measurement equipment
  - Autocollimator
  - Interferometer
  - Polarimeter



Assemblies on shaker @ F-ENAS

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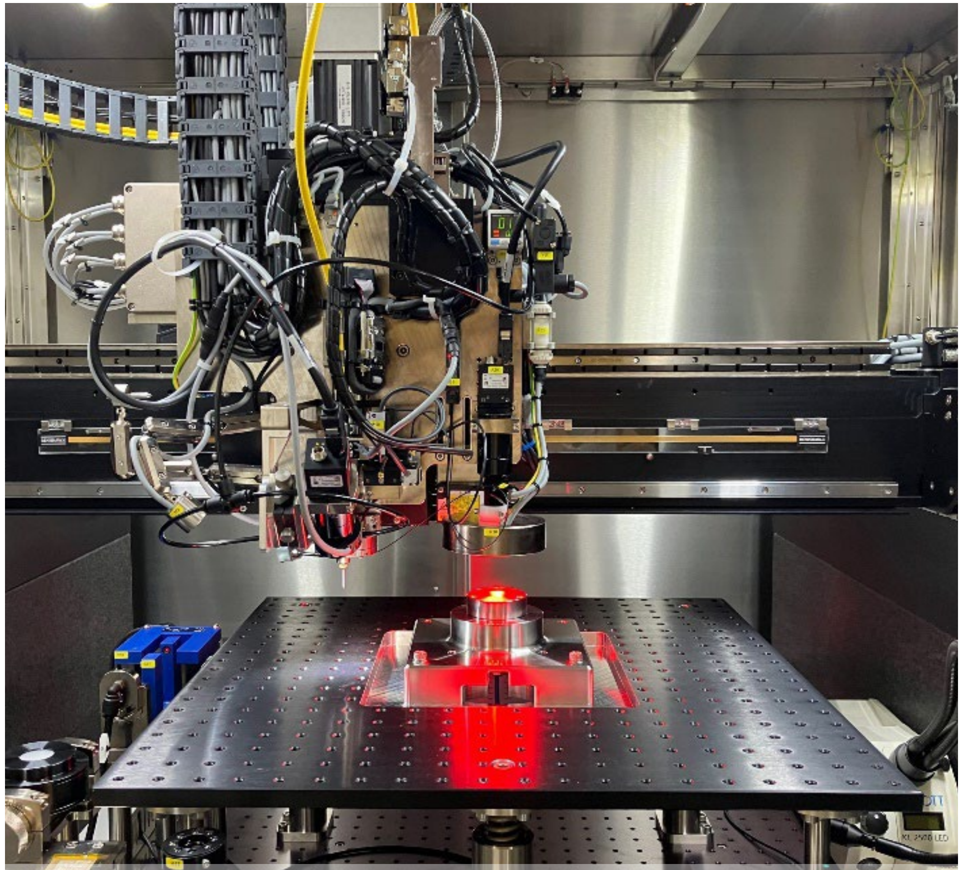
Demonstrator Assembly



Lens dummy assembly environment, gantry-guided SJB tool

Laser crystal assembly environment, robot-guided SJB tool

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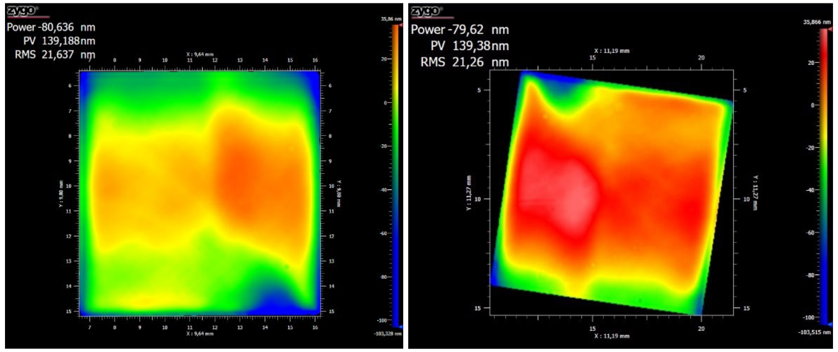
Demonstrator Assembly Results – Initial Measurements vs. Post-Soldering Measurements

- **SQ1 Lens Dummy (n=10)**
  - ΔP-V 26 nm ± 53 nm (3σ)
- **CaF2 Lens Dummy (n=14)**
  - ΔP-V 87 nm ± 205 nm (3σ)
- **BBO Laser Crystal (n=14)**
  - Tip/Tilt 264 µrad ± 1253 µrad (3σ), ΔP-V 30 nm ± 93 nm (3σ)
  - 5 broken or out of range
- **KTP Laser Crystal (n=12)**
  - Tip/Tilt 386 µrad ± 1529 µrad (3σ), ΔP-V 5 nm ± 14 nm (3σ)
  - 3 broken



KTP laser crystal before and after soldering

Poor survival rate!

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Demonstrator Assembly Results – Initial Birefringence Measurements after Soldering

Demonstrator Type	Material	Component No.	Material	Mount No.	Name	Birefringence [nm]
Lens	SQ1	11	INVAR	11	1128-001-10-02_SQ_Test01	15
		12		12	1128-001-10-02_SQ_Test02	11

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Demonstrator Testing Results – Initial Measurements vs. Post-Vibration

- SQ1 Lens Dummy (n=10)
  - ΔP-V 29 nm ± 90 nm (3σ)
  - 3 broken
- CaF2 Lens Dummy (n=14)
  - ΔP-V 91 nm ± 217 nm (3σ)
  - 7 broken
- BBO Laser Crystal (n=14)
  - Tip/Tilt 157 µrad ± 514 µrad (3σ), ΔP-V 29 nm ± 90 nm (3σ)
  - 5 broken or out of range
- KTP Laser Crystal (n=12)
  - Tip/Tilt 812 µrad ± 2632 µrad (3σ), ΔP-V 5 nm ± 14 nm (3σ)
  - 7 broken

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Demonstrator Testing Results – Final Birefringence Measurement

Demonstrator Type	Material	Component No.	Material	Mount No.	Name	Birefringence [nm]	ΔBirefringence Final – Post Soldering [nm]
Lens	SQ1	11	INVAR	11	1128-001-10-02_SQ_Test01	13	2
		12		12	1128-001-10-02_SQ_Test02	12	1

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Demonstrator Assembly and Testing Conclusions I

- **Demonstrator Lens, SQ1 component, INVAR mount**
  - 3 out 10 assemblies broke during the complete test campaign, the surviving 7 assemblies were used for P-V measurements,
    - Mean change in PV was 29 nm, at a 3σ of 90 nm,
  - The surviving 7 assemblies were not used for tip/tilt measurements, due to the lack of sufficient reference surfaces on the mount for autocollimation,
  - 2 additional assemblies were used for birefringence measurements,
    - The mean change in birefringence was 2 nm,
  - 2 more additional assemblies were used for testing purposes.

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Demonstrator Assembly and Testing Conclusions II

- **Demonstrator Lens, CaF2 component, Stainless Steel mount**
  - 7 out 14 assemblies broke during the complete test campaign, the surviving 7 assemblies were used for P-V measurements,
    - Mean change in PV was 91 nm, at a 3σ of 217 nm,
  - The surviving 7 assemblies were not used for tip/tilt measurements, due to the lack of sufficient reference surfaces on the mount for autocollimation,
  - None of the assemblies were used for birefringence measurements,
  - 4 additional assemblies were used for testing purposes, and broke during the testing campaign.

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Demonstrator Assembly and Testing Conclusions III

- **Demonstrator Laser Crystal, BBO component, KOVAR mount**
  - 5 out 14 assemblies broke during the complete test campaign, the surviving 7 assemblies were used for P-V measurements,
    - Mean change in PV was 15 nm, at a 3σ of 36 nm,
  - Surviving 7 assemblies were used for tip/tilt measurements,
    - Mean tip in Rx was 155 µrad, at a 3σ of 51 µrad (goal: <5..20 µrad),
    - Mean tip in Ry was 200 µrad, at a 3σ of 145 µrad (goal: <5..20 µrad),
  - None of the assemblies were used for birefringence measurements,
  - 2 more additional assemblies were used for testing purposes.

Bond-Match

Demonstrator Assembly and Testing Conclusions IV

- **Demonstrator Laser Crystal, KTP component, Super INVAR mount**
  - 7 out 12 assemblies broke during the complete test campaign, the surviving 5 assemblies were used for P-V measurements,
    - Mean change in PV was 21 nm, at a 3σ of 24 nm,
  - The surviving 5 assemblies were used for tip/tilt measurements,
    - One assembly could not be measured at all (out of range),
    - One other assembly could only be measured in tip, while tilt was out of range,
    - The mean tip in Rx was 244 µrad, at a 3σ of 520 µrad (goal: <5..20 µrad),
    - The mean tip in Ry was 847 µrad, at a 3σ of 2035 µrad (goal: <5..20 µrad),
  - None of the assemblies were used for birefringence measurements.

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Final Compliance Statement I

- **Requirements - Materials and Dimensions**
  - Coated, uncoated and encapsulated optical components, component’s diameters and lenghts up to 10 mm, material CaF2, MgF2, rad hard (e.g. BK7), non-linear (e.g. LBO), active medium (e.g. YAG), and CTE-matched substrates
  - Adjustment range +/- 1° (rotation in Z axis), best resolution <0.3 mrad
  - Initial compliance: Y, Final compliance: Y, Comments:
    - Soldering on coatings not advised, but in principle possible
    - Experimentally tested materials: CaF2, Fused Silica, BBO, KTP
    - Matched mount materials: 1.4301, INVAR, KOVAR

Bond-Match

Final Compliance Statement II

- **Requirements - Design**
  - Cleanliness according to ESA ECSS-Q-70-01A rev.1, space-worthy materials selection wrt flammability, outgassing, susceptibility to stress corrosion etc., operational lifetime ca. 4 years (reliability >0.97) for in-orbit operation
  - Initial compliance: Y, Final compliance: Y, Comments:
    - Laser-based soldering process is inherently clean, no use of flux nor other organics
    - Used SAC305 bonding medium used in many space applications for electronics and opto-electronics already, at high lifetimes

Bond-Match

Final Compliance Statement III

- **Requirements – Environmental stability**
  - Alignment stability 5..20 µrad vs thermal cycling, survival acceleration, vibration, and shock.
  - Initial compliance: Y, Final compliance: N, Comments:
    - Stability considered by design, only thermal cycling and vibration experimentally conducted.
    - 1..2 order of magnitude higher de-alignment than required
    - Low principle survival rate
      - In-sufficient design of bonding geometries wrt accuracy and strength, compared to heritage ☹

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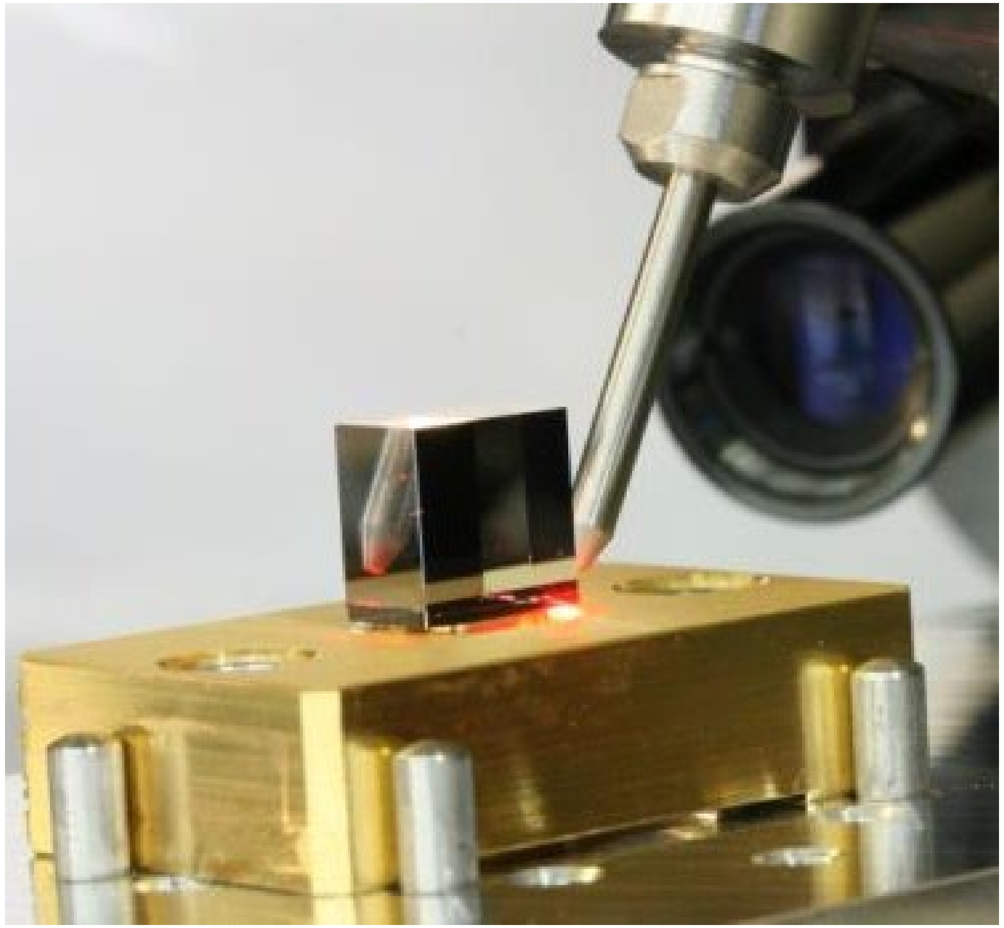
Final Compliance Statement III – comparable Heritage*



	IOF-1-4		IOF-2-9		IOF-3-8		IOF-3-9		IOF-4-4		
	rot X	rot Y	rot X	rot Y	rot X	rot Y	rot X	rot Y	rot X	rot Y	
Δ M R2 to M R1 [arc sec]	2	2.5	1.9	2.3	4.6	0.8	3.0	-0.7	5.5	-2.7	Vacuum
Δ M R2a to M R2 [arc sec]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Δ M R3 to M R2a [arc sec] [1]	1.9	-1.6	0.4	-2.4	3.1	0.9	2.1	-3.0	-0.9	-0.8	full non-op
Δ M R4 to M R3 [arc sec]	1.0	2.0	2.8	2.5	0.0	3.2	3.5	0.2	0.6	2.2	
Δ M R5 to M R4 [arc sec]	0.3	-0.5	-1.2	0.5	-1.9	-1.0	-3.9	0.8	-3.9	-0.5	↑
Δ M R6 to M R5 [arc sec]	-0.2	0.3	1.1	-0.3	-0.1	-10.4	3.2	-1.3	0.3	0.2	
Δ M R7 to M R6 [arc sec]	0.2	-0.2	-1.1	0.2	0.5	10.6	0.1	-0.1	2.3	-1.3	op
Δ M R8 to M R7 [arc sec]	-0.4	0.3	0.9	-0.2	1.5	0.3	-0.3	0.4	-0.4	1.8	
Δ M R9 to M R8 [arc sec]	0.4	-0.3	-0.8	0.2	-1.8	-0.7	-1.4	-1.1	-1.8	-0.4	
Δ M R10 to M R9 [arc sec]	-0.4	0.3	0.8	-0.2	1.8	0.5	1.8	1.0	1.9	0.6	↓
Δ M R11 - M R10 [arc sec]	-2.4	0.0	0.6	-0.6	0.6	-0.3	-0.6	-0.4	0.3	-1.4	spec.non-op
Δ M R12 - M R11 [arc sec]	-0.7	-0.5	-2.0	-0.1	-0.3	-0.1	1.0	1.4	3.0	0.6	Vibr.
Δ M R12 - M R2 [arc sec]	-0.4	-0.3	1.4	-0.5	3.3	3.0	5.6	-2.3	1.5	0.8	

*ESA-project: Space-Mount

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Main Findings and Lessons learned

1. **Avoid soldering close to edges of components**
   - Micro-cracks from component's manufacturing processes are critical for mechanical stability

2. **Avoid complicated, tiny bonding geometries**
   - Difficult to clean, results in metallization adhesion problems

3. **Design for accuracy AND strength**
   - Larger margin of safety required, consider solder volume contracting during process

4. **Lots of staff changes during the duration of the project**

Thank you for your attention.

Questions?

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