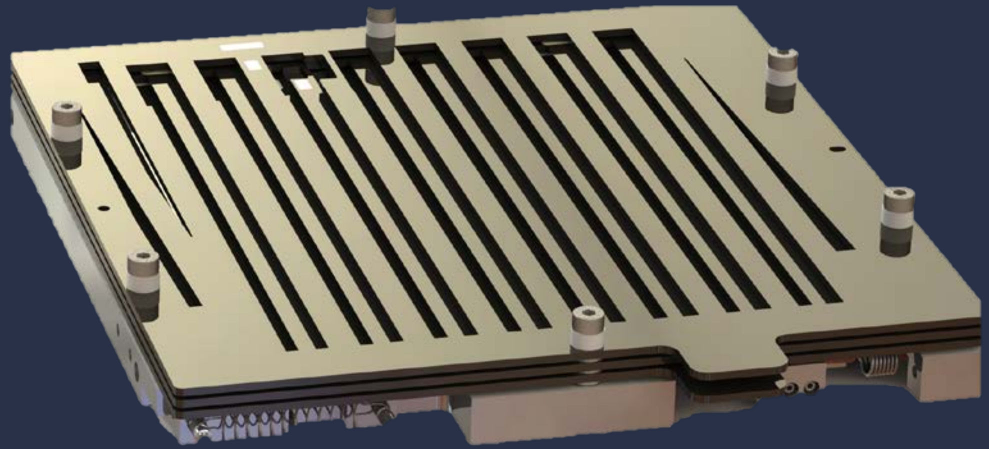
COOLER: A Louvered, Passive Radiator for Cubesats

Final Presentation/Review

December 13, 2022



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"Compact and in-plane opening louver with variable thermo-optical properties"

csem heron ENBIO FOTEC

Outline

- **Overview of critical specifications**
- Concept trade-off & Breadboard selection
- BBM Test results and EM selection for Test campaign
- FEM analysis (Mechanical & Thermal)
- EM Assembly
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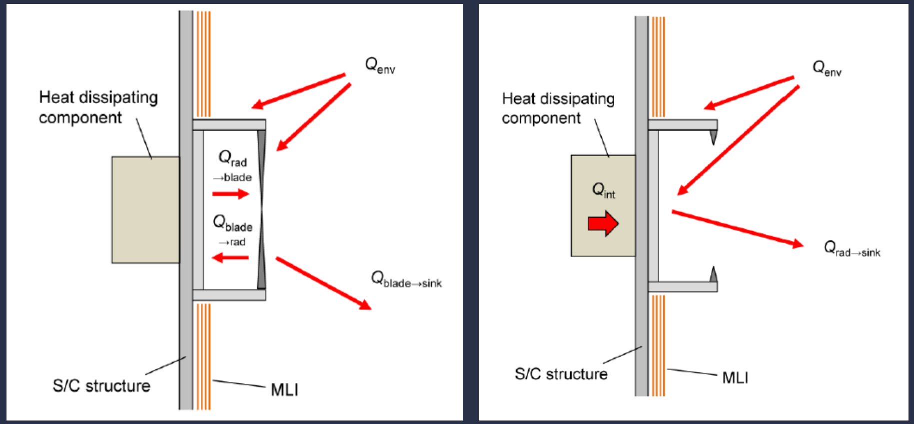
Overview of critical specifications

- Targeted for CubeSats and compact instruments
- Compact radiator design 100mm x 100mm x 30mm
- Heat rejection capability >85% when fully open
- Heat rejection range 0.1W to 10W / device of $1dm^2$
- Friction free
- Single actuator
- Actuator activation requirements
  - Adjustable temp range from -50°C to +90°C
  - Close to open activation temp range of 15° to 20°
- TRL3 (proof of concept)

Closed | Open



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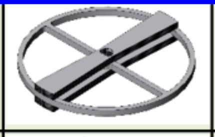
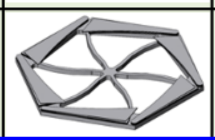
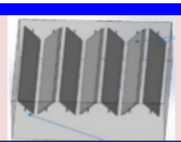
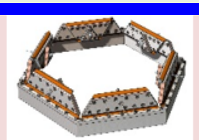
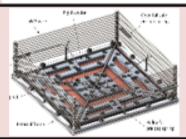
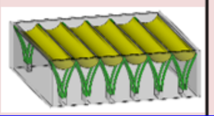
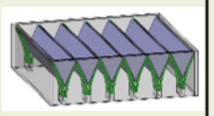
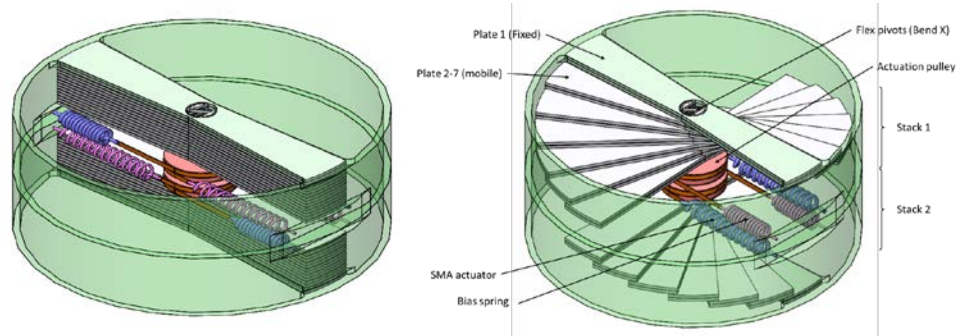
Preliminary conceptual designs and Trade-off

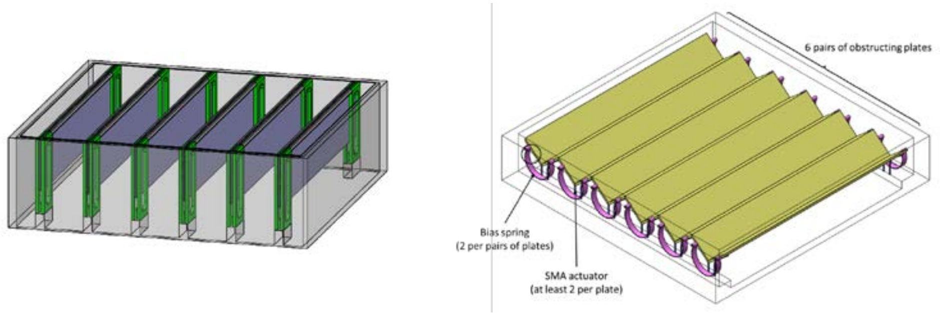
Criterion			In-plane	Heat rejection	Compactness	Comment
Concept	1		Yes	round / average	good	Selected
Concept	2		Yes	hex / average	good	Selected
Concept	3		No	square / average	average	Discarded because it is too similar to existing systems
Concept	4		Yes	square / low	good	Selected
Concept	5		No	hex / good	low	Discarded due to its lack of compactness. Moreover, this concept requires actuation with important strokes not compatible with SMA
Concept	6		No	square / good	low	Discarded due to its lack of compactness. Moreover, this concept requires actuation with important strokes not compatible with SMA
Concept	7		No	square / average	average	Discarded in favor of concept 8 because multi-layer insulant is deemed not resilient enough to folding fatigue.
Concept	8		No	square / average	average	Selected despite the fact that it is not in-plan because of its compatibility with SMA technology and its innovative architecture.

Technical overview Output of Preliminary design and trade-off

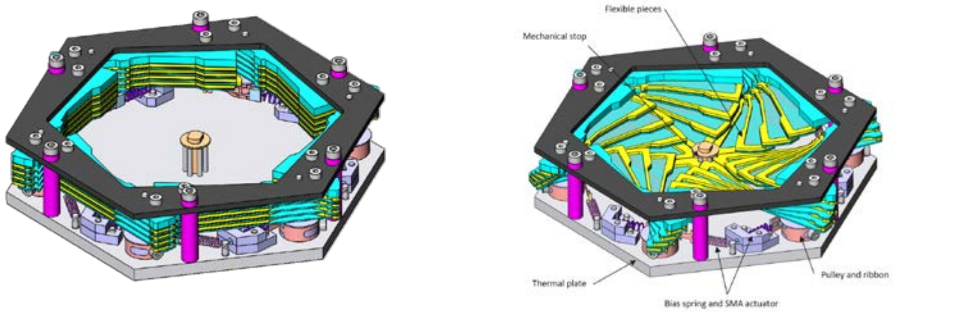
Concept C1 Circular diaphragm



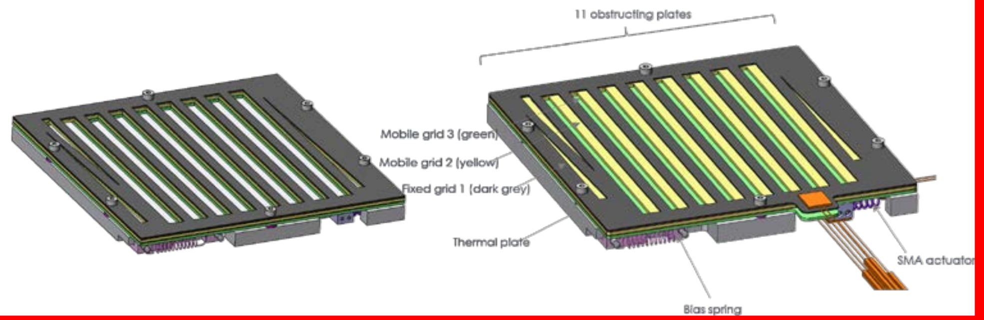
Concept C8 Folded metallic sheets



Concept C2 Hexagonal diaphragm iris



Concept C4 Flexible grids

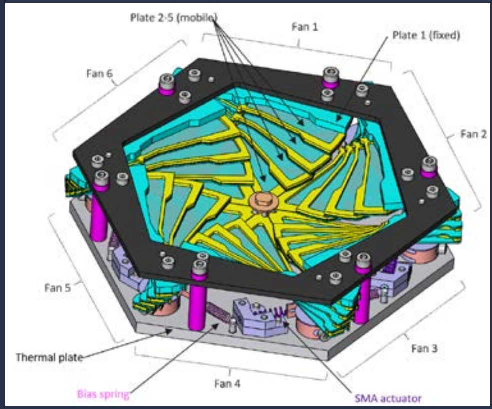


- Actuator technology : SMA from NIMESIS
- Thermo-Optical coatings from ENBIO

Breadboard hardware manufactured for BB Test campaign

Concept 2 Diaphragm iris

Concept 4 Flex grids



Concept 2 (2/6 segments)

Concept 4 (~full mechanism)

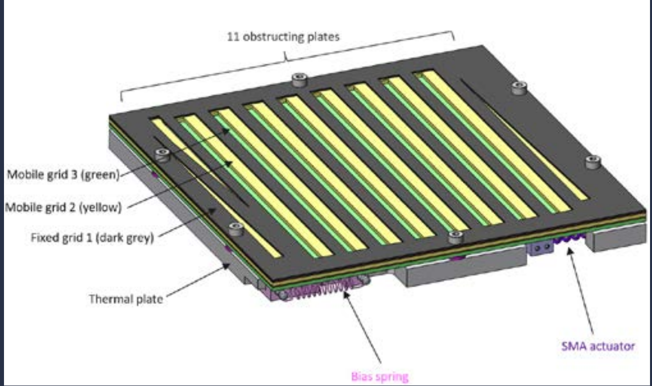
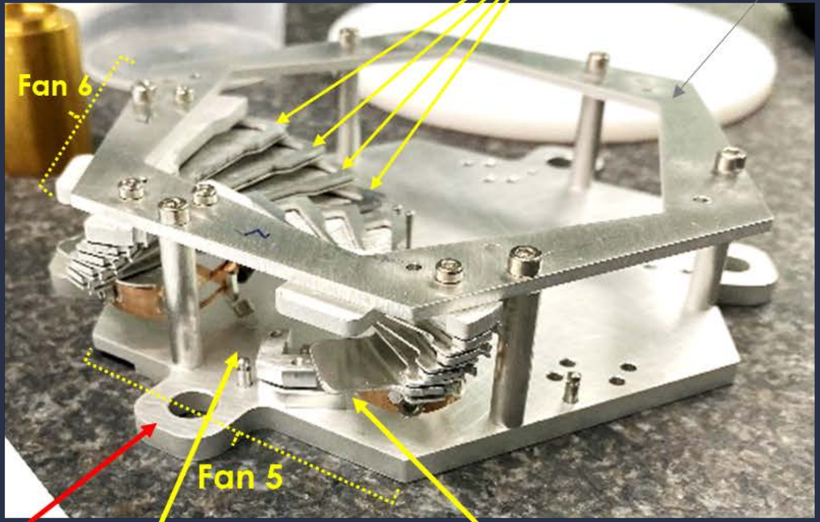


Plate 2-5 (mobile) Plate 1 (fixed)



Thermal plate

Bias spring (not installed)

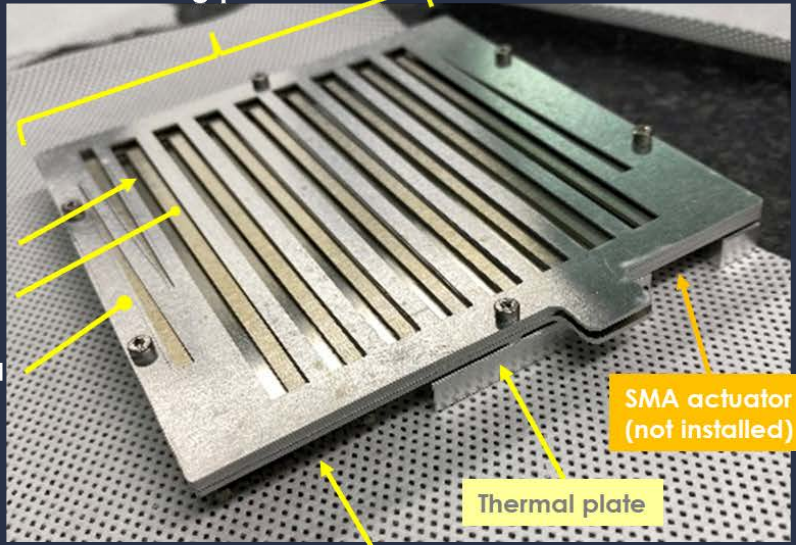
SMA actuator (not installed)

11 obstructing plates

Mobile grid 3

Mobile grid 2

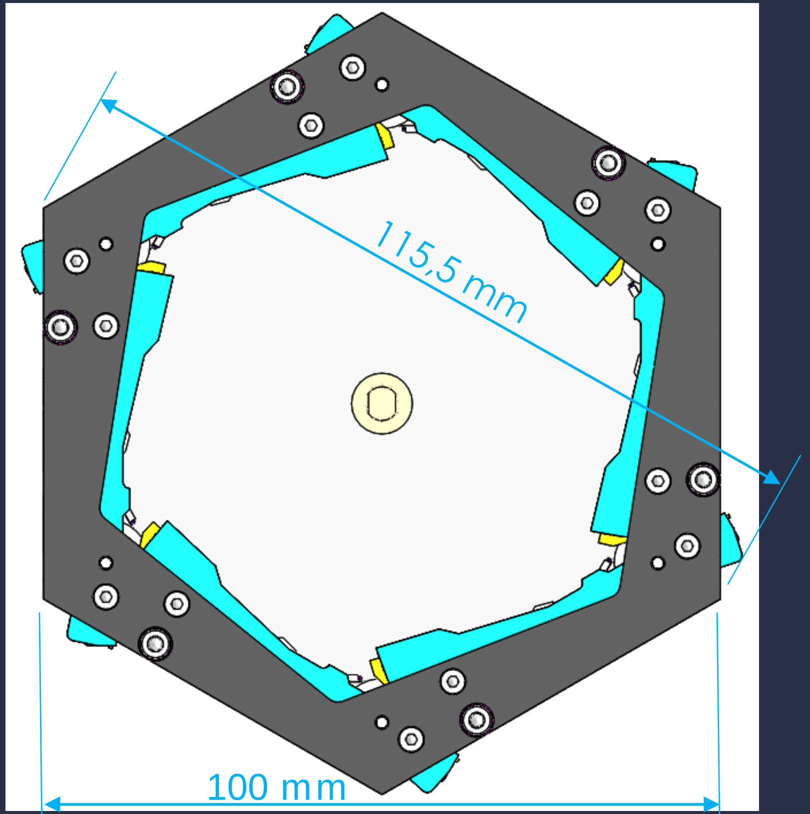
Fixed grid 1



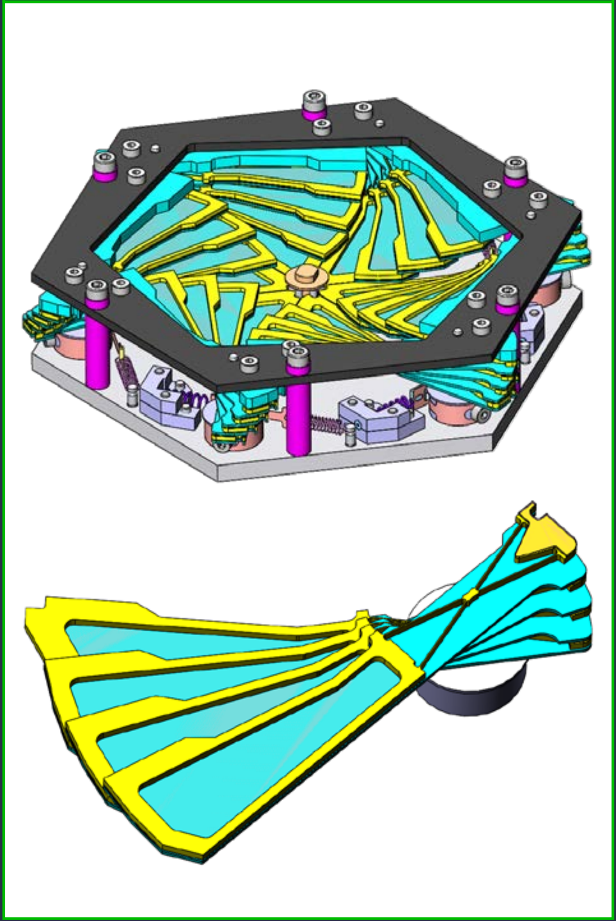
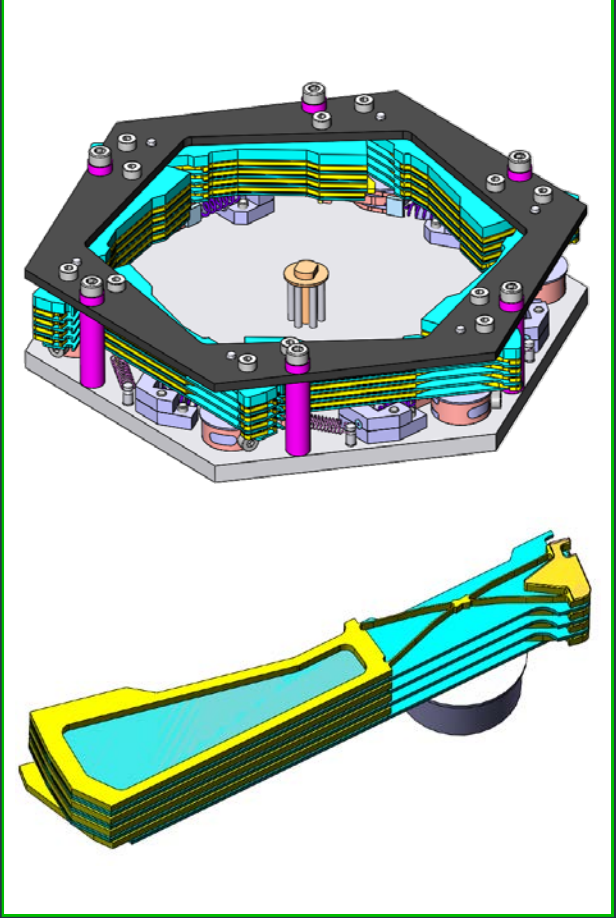
Bias spring (not installed)

Design, sizing and manufacturing – Concept 2: Diaphragm iris

"Concept 2 Top view"

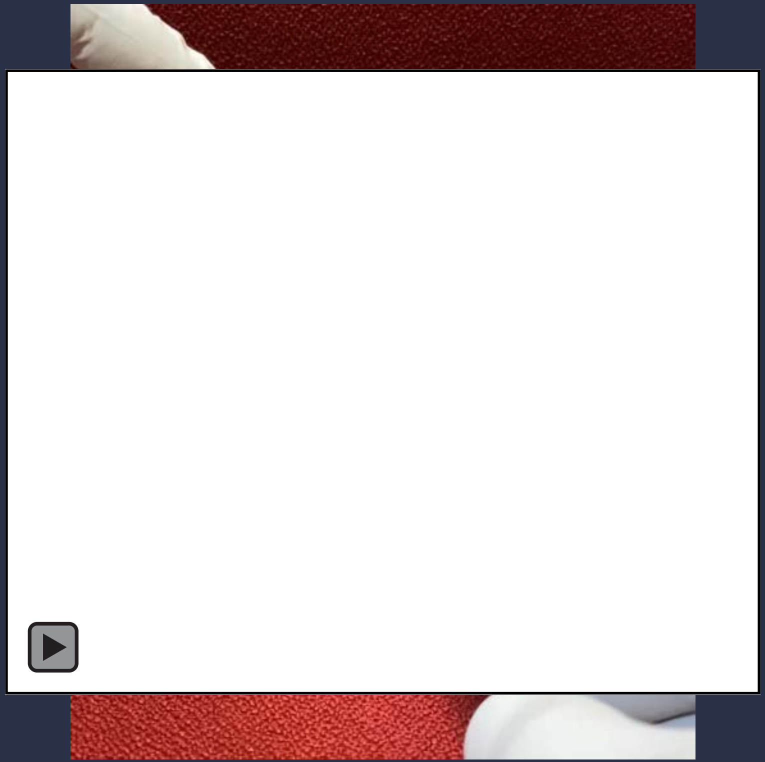


Edge to edge dimension: 100mm
→ does not fit in a 100 x 100 mm area

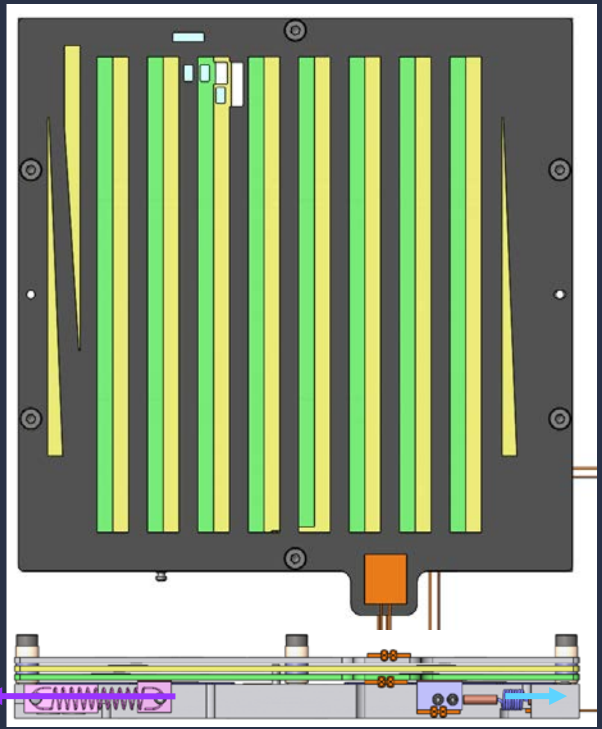
Closed	Open
	

Design, sizing and manufacturing – Concept 4: Flex grids

- 2 flexures actuated with one SMA
- SMA is actuated by a thermal conductivity with the base plate



Cold configuration



Force bias spring + guiding system > Force SMA cold

Hot configuration

Force bias spring + guiding system < **Force SMA hot**

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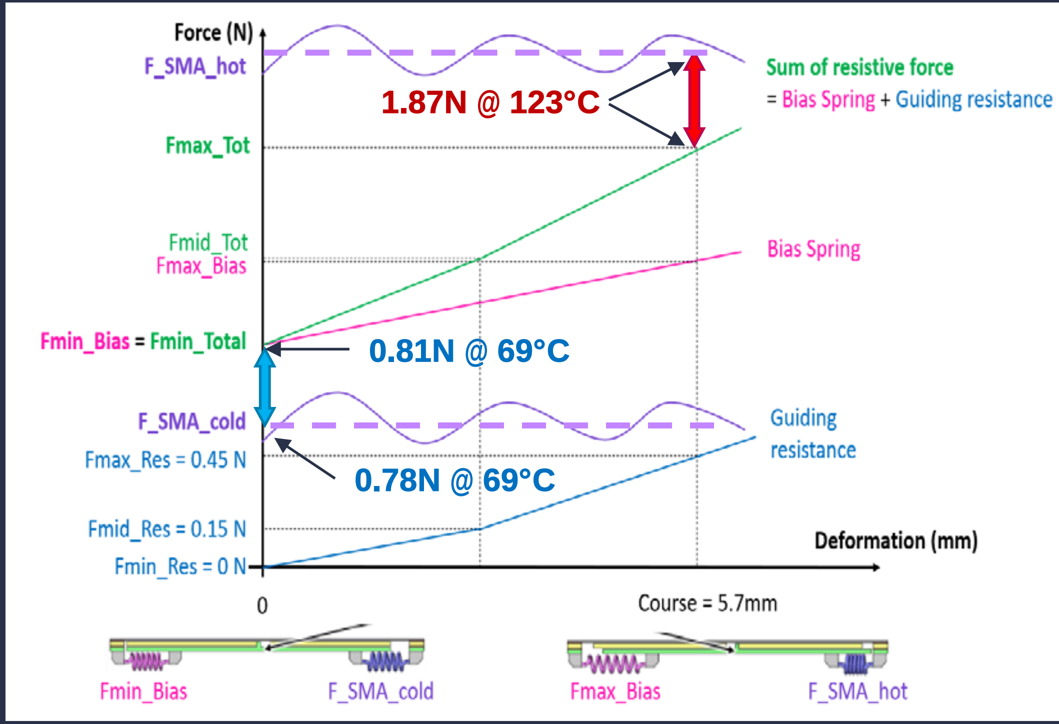
SMA actuator operation and sizing

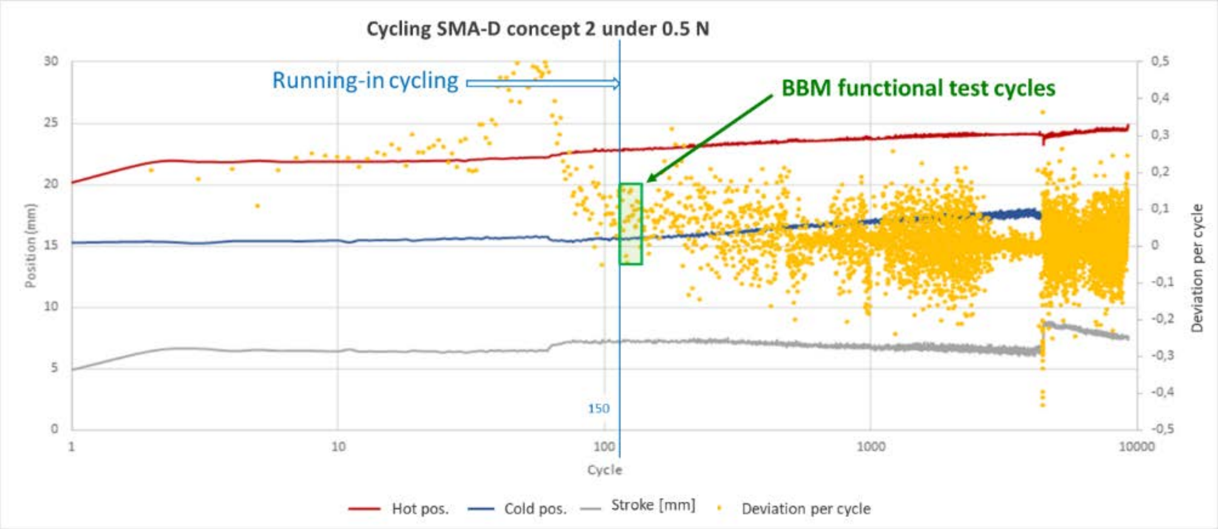
- SMA and bias spring combination does not meet ESA actuation design margins during heating and cooling
- SMA activation temperature range is not compliant to specs, SMA design has to be reviewed in the future



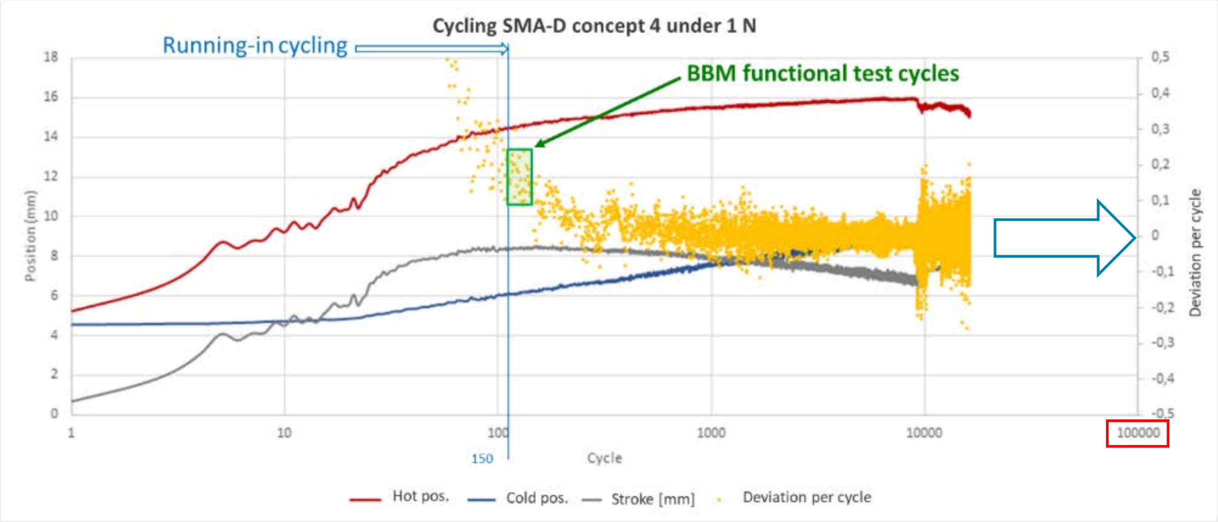
Actuation condition description	Guiding plates + bias spring	SMA		Safety factor
	Worst case sizing force F_{tot} [N]	F_{SMA} [N]	T [°C]	S_{act} [none]
During **heating** → Opening actuation by SMA				
Nominal force condition @ X_{travel} = 0	0.90	0.90	**85**	1
Maximal force condition @ X_{travel} = 0	0.99	0.99	**89**	1
Nominal force condition @ X_{travel} = 5.7mm	1.70	1.70	**117**	1
Maximal force condition @ X_{travel} = 5.7mm	**1.87**	1.87	**123**	1
During **cooling** → Closing actuation by bias spring				
Minimal force condition @ X_{travel} = 0	0.81	0.78	69	**1.04**
Nominal force condition @ X_{travel} = 0	0.90	0.78	69	1.15

NIMESIS SMA-D Actuator Running-in cycling prior to delivery

- SMA-D for Concept 2 :
  - Tested by NIMESIS to achieve 10’000 cycles but failed prematurely at 9’230 cycles (surface defect at change in wire diameter)

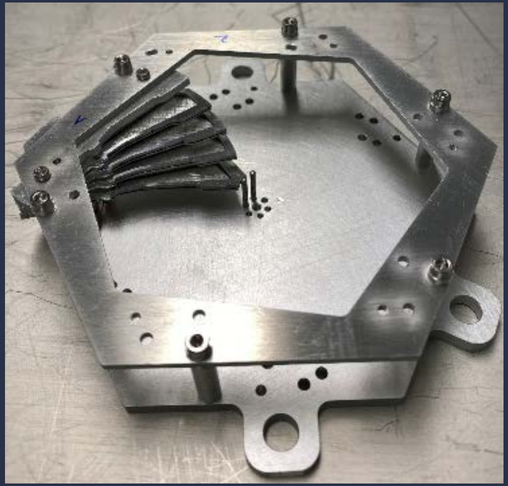


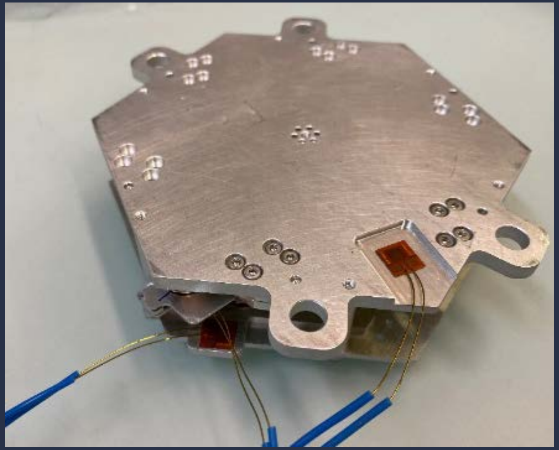
- SMA-D for Concept 4 :
  - Tested by NIMESIS to achieve 10’000 cycles and continued without failure to 300’000 cycles under 1 N load

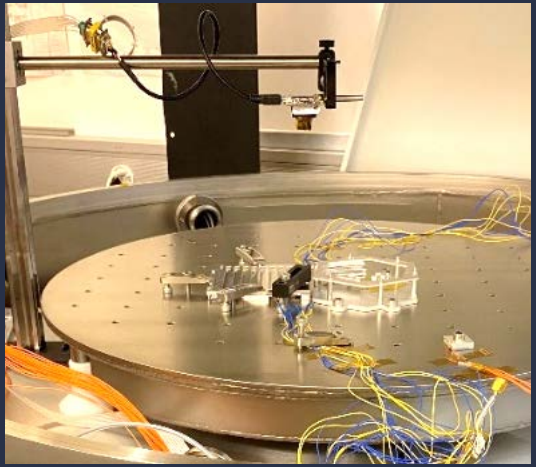


BB Test campaign carried out in parallel with both concepts

Concept 2 Diaphragm iris

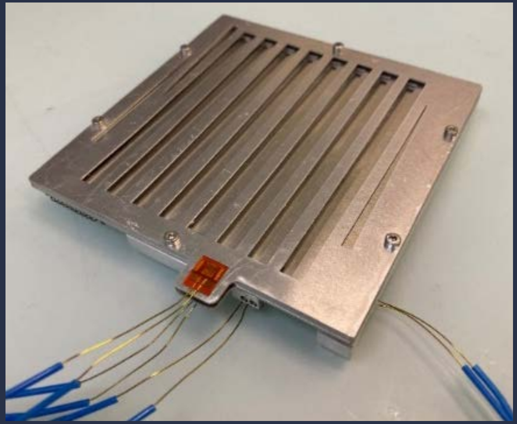


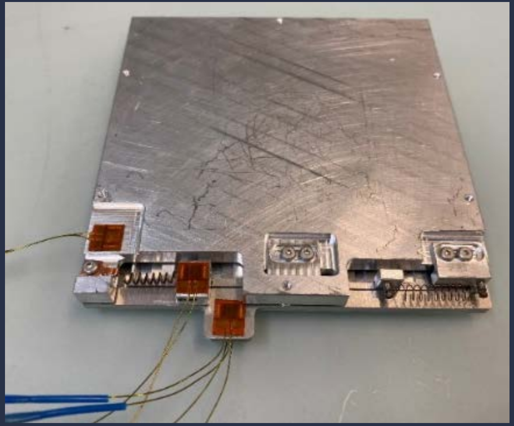




Performance TVAC tests

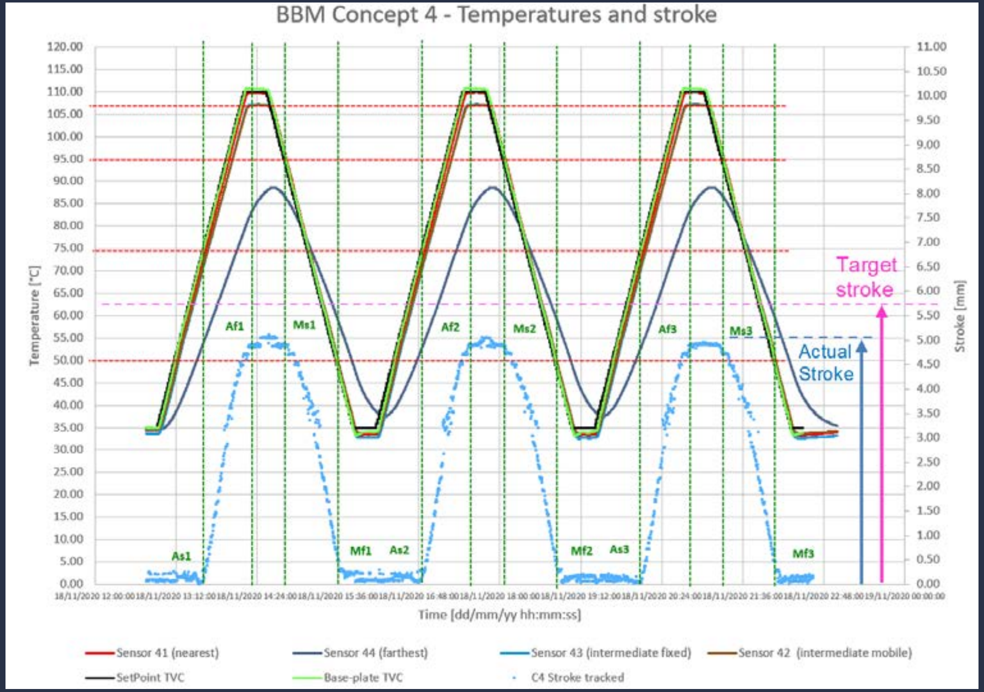
Concept 4 Flex grids





Breadboard Concept 4 Test results

- Breadboard tested in a vacuum of 10^{-6} mbars
- Temperature set point stability <±1°C
- Heating cycle slope = 1°/min
- SMA Sensitivity and Flex grid movement 0.1 mm/°C
- Linear operation **5.0mm** stroke, target 5.7mm (88%)
- SMA material alloy CuAlNi (selected by Nimesis)
  - Adjustment range (closed to open) **75°C to 108°C** (spec: -50°C to +90°C)
  - Activation range (delta between closed to open) **33.5°C** (spec: 15 to 20°C)
- SMA lifetime tests **>300’000 cycles** under 1N load (spec: 20’000 cycles)

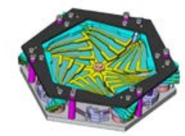
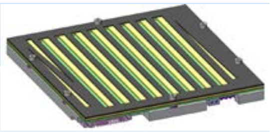


* Mechanical adjustment of springs not optimal

:: csem

Following Breadboard Assembly, Integration & Test

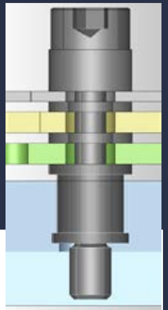
Concept 4 Selected for EM Test Campaign

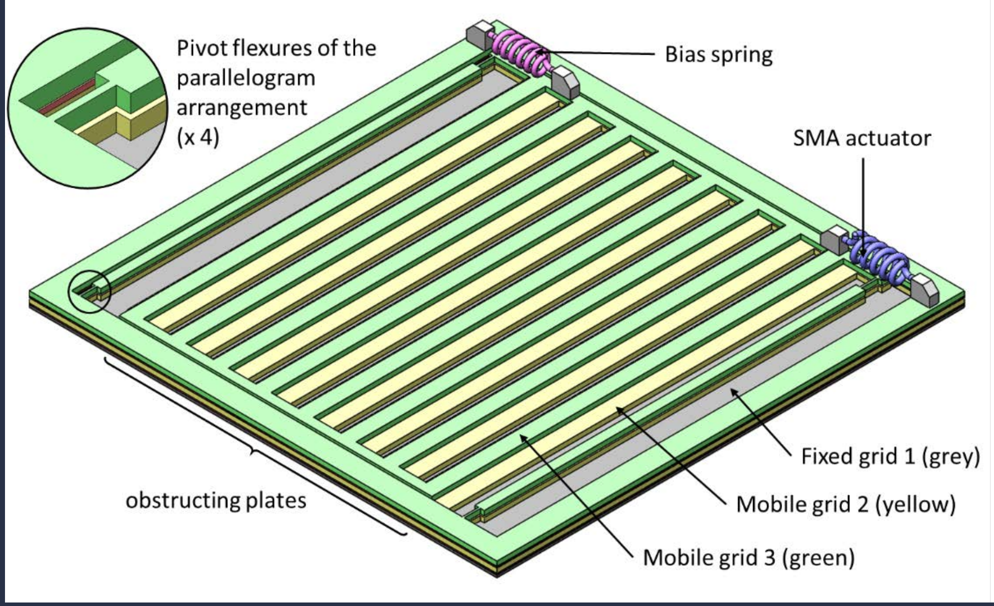
	Concept 2	Concept 4
Guiding type	X pivot 	**Parallelogram** 
Number of actuators	6	**1**
Actuator stroke	47° (~5 mm)	5,7 mm
Actuation force (with margins)	0,85 N	1,83 N
Dissipated power *	**3.3 W**	1.7 W
Weight	195 g	**165 g**
View section area	**4320mm²**	4185 mm²
Dimensions	100 x 116 x 25 mm	100 x 100 x **9 mm**
Number of pieces	189 for 6 segments (77 for 2)	**40**
Delta time for 50°C	~ 11 s	**~ 7 s**

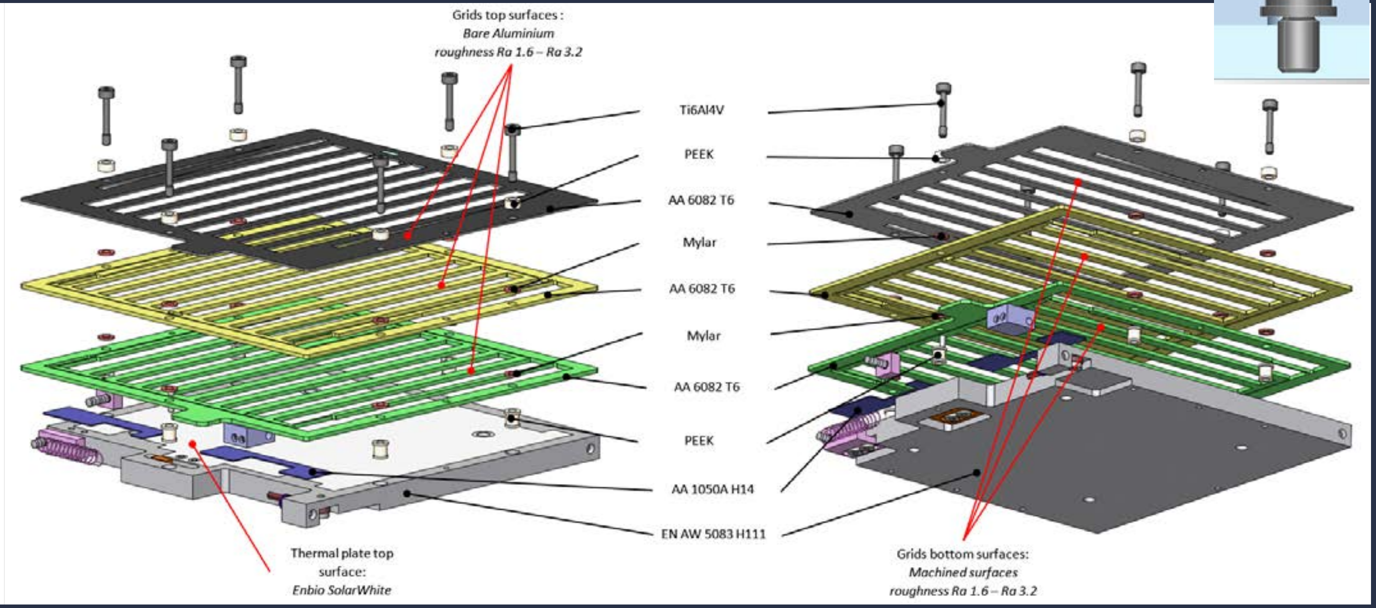
*Preliminary Radiating surface x View Factor computation (ignoring radiation from top cover)

COOLER Concept 4 Flex Grid : EM Design selection

- Chosen based on updated trade-off tables and the BBM TVC performance tests
- Actuator technology confirmed: **CuAlNi** Shape Memory Alloy (SMA) from Nimesis
- Coating technologies: ENBIO SolarBlack and **SolarWhite** thermo-optical coating
- Implemented modifications from test campaign and prelim FEM results
- Improved thermal isolation between top fixed grid and baseplate







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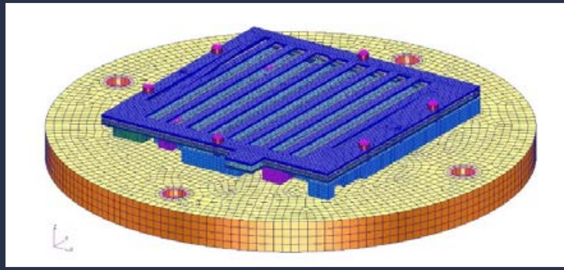
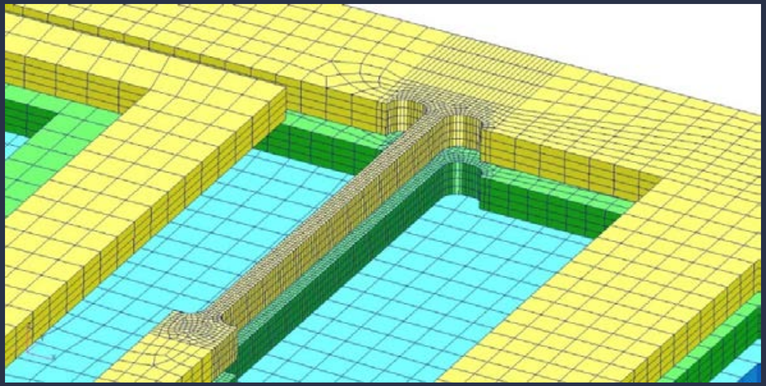
Heron Engineering – FEM Vibration Analysis

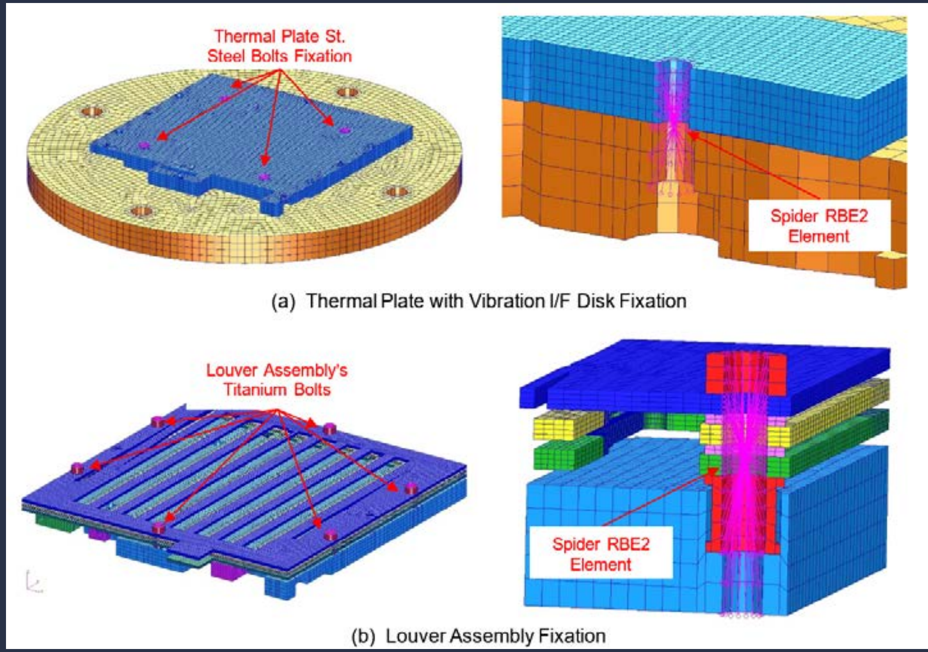
- FEM Model description
  - CAD model clean-up
  - Reviewed meshing
  - Assembly/bolt fixation conditions
  - LLD clamping conditions

Mechanism with shaker I/F

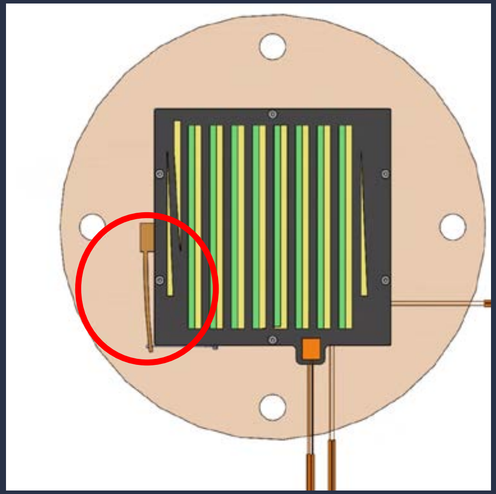




Fine meshed flexure blades



Model fixation elements



With spring-loaded dummy LLD

Heron – Static Analysis considers spacers limiting vertical motion

- High stresses were rechecked by performing static analysis taking into account that the 0.4 mm gap between the grids → applied 0.5mm

In the following tables the calculated MoS from the dynamic and static analysis are presented.

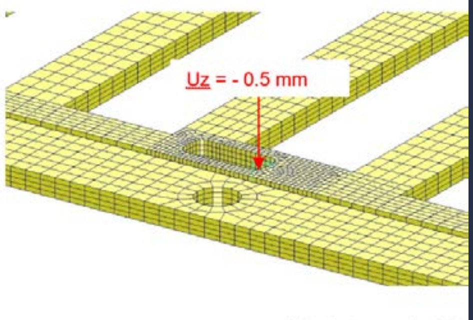
Analysis Type	S (MPa)	MoSY	MoSU	Comments
Sine Vibration - X	681.00	-0.769	-0.757	Covered by Static LC1
Sine Vibration - Y	167.00	-0.056	-0.010	Covered by Static LC2
Sine Vibration - Z	10700.00	-0.985	-0.985	Covered by Static LC3 (& LC4)
Random Vibration - X	161.94	-0.027	0.021	Covered by Static LC1
Random Vibration - Y	133.38	0.181	0.240	Grids 3 sigma
Random Vibration - Z	356.10	-0.557	-0.536	Covered by Static LC4 (& LC3)
	103.50	0.522	0.597	Top Cover, 3 sigma

Table 6-7: Dynamic Analyses Results

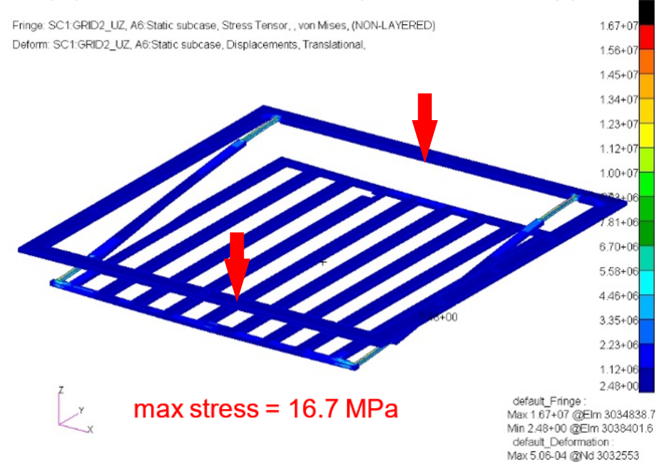
Analysis Type	S (MPa)	MoSY	MoSU	Comments
Static- LC1	13.00	11.121	11.718	Rotation along Y, 1st Grid
Static- LC2	9.40	15.763	16.589	Rotation along X, 1st Grid
Static- LC3	16.20	8.727	9.206	Displacement Z, 1st Grid
Static- LC4	16.70	8.436	8.900	Displacement Z, 2nd Grid

Table 6-8: Static Analyses Results

Low stresses from vertical displacement acceptable



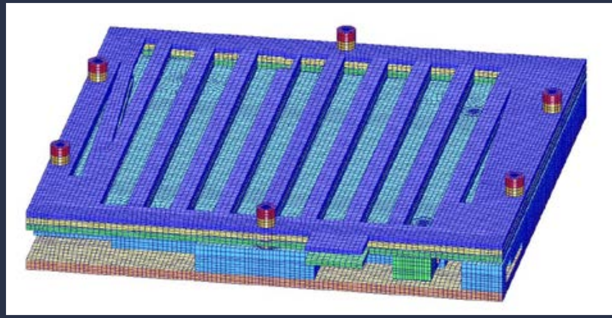
(a) Subcase LC41

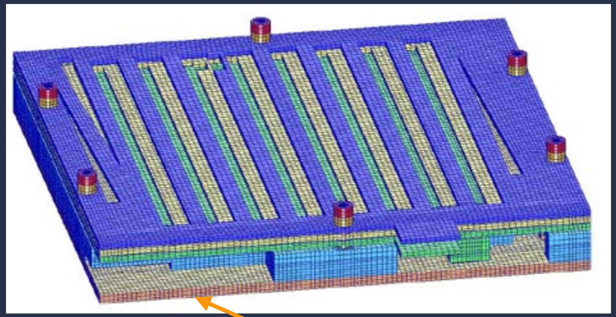


(c) Subcase LC43 – Apply LC41 & LC42 simultanuesly

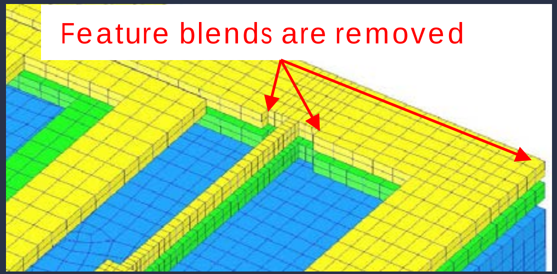
Figure 6-21: LC4 – Displacements Z of 2nd Grid

Heron Heron Engineering – FEM Thermal Analysis





- Both open and closed configuration were modelled
- A copper plate of 2mm thickness beneath the thermal plate was also modelled (test config)
- Only the parts that mainly participate in the heat transfer mechanism are modelled
- Load Cases:
  - Four different load cases were examined Two for each louver configuration
  - The heat is applied uniformly at the bottom surface of the copper plate
  - Different emissivity values for different surfaces used from samples test results and literature



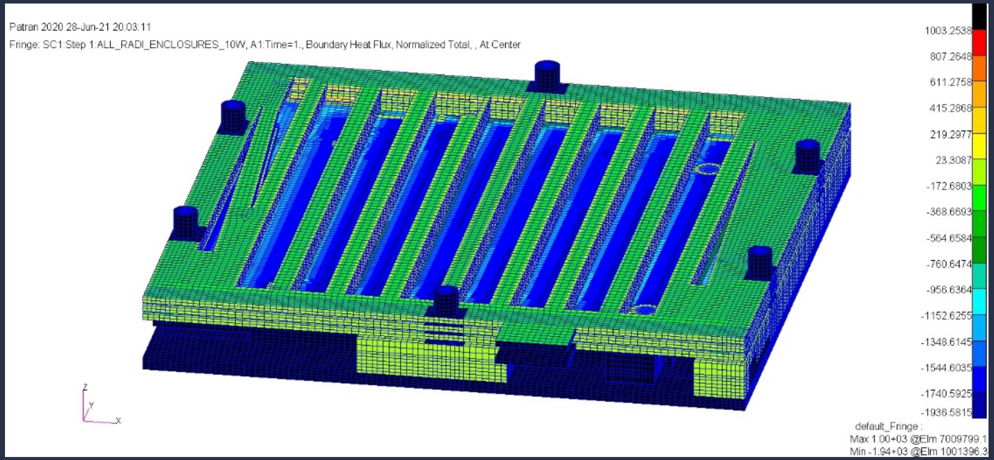
Load Case	Configuration	Applied Heat (W)	Ambient Temperature (C)
LC1.1	Open	10	20
LC1.2	Open	10	-273.15
LC2.1	Closed	0.1	20
LC2.2	Closed	0.1	-273.15

Heron – FEM Thermal Analysis Results

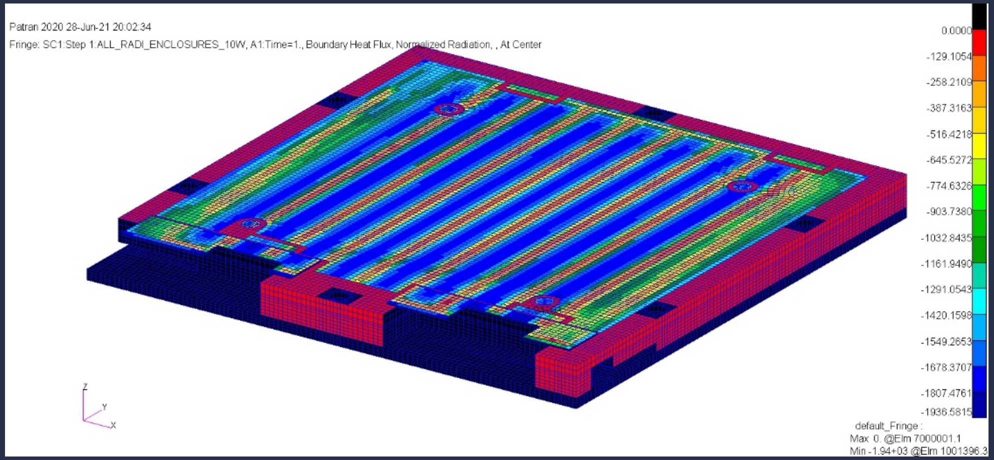
LC1.1 **OPEN** Configuration: 10 W @ 20°C ambient temperature

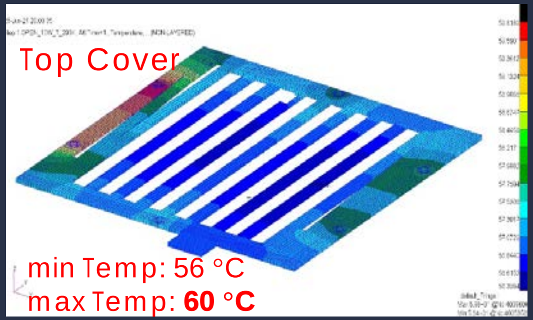
SolarBlack coating on grids

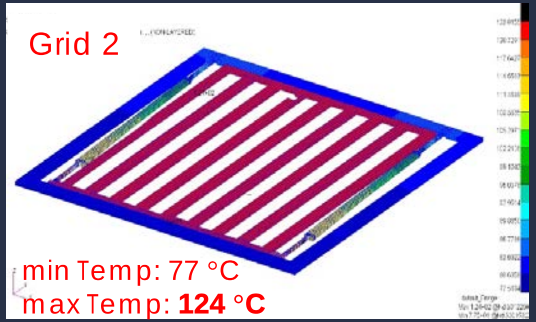
Total Heat Flux

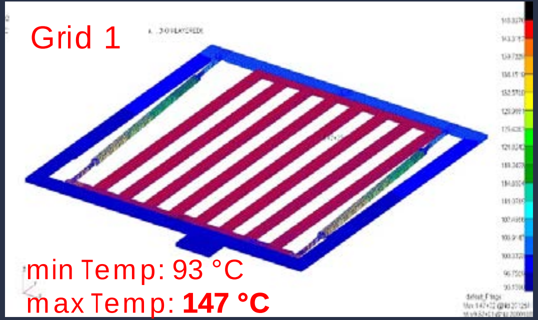


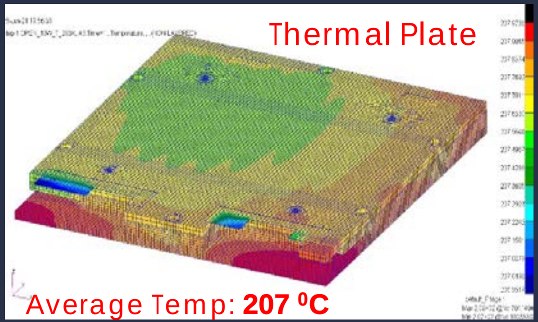
Thermal Plate
Radiation Heat Flux









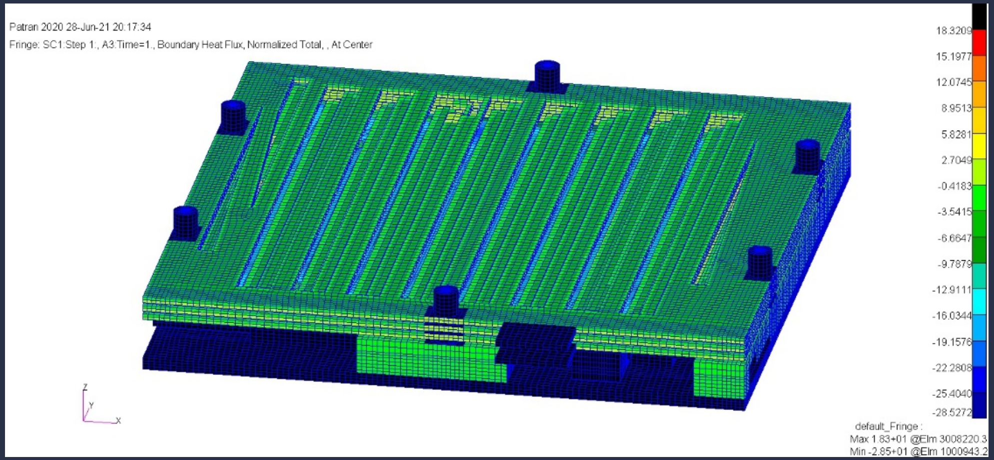


Heron – FEM Thermal Analysis Results

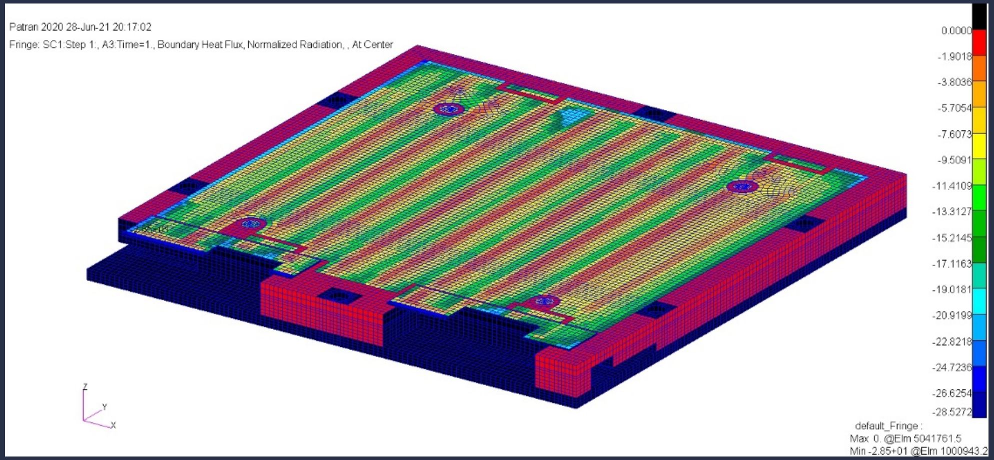
LC2.1 **CLOSED** Configuration: 0.1 W @ 20°C ambient temperature

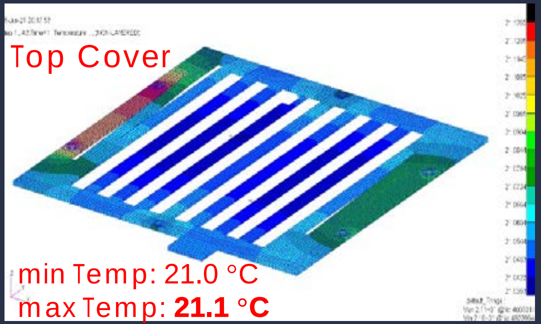
SolarBlack coating on grids

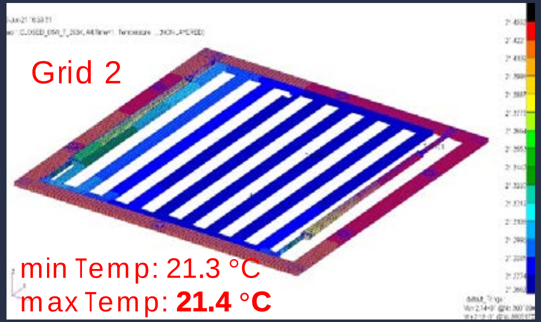
Total Heat Flux

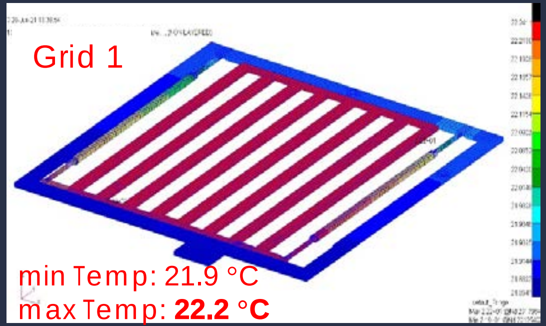


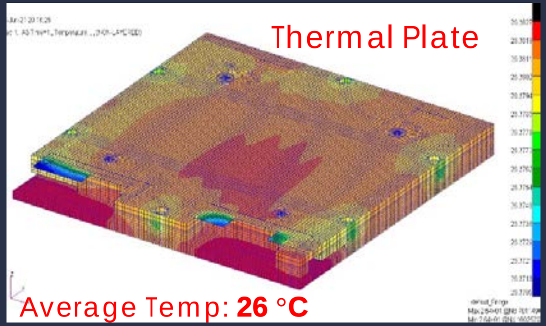
Thermal Plate
Radiation Heat Flux





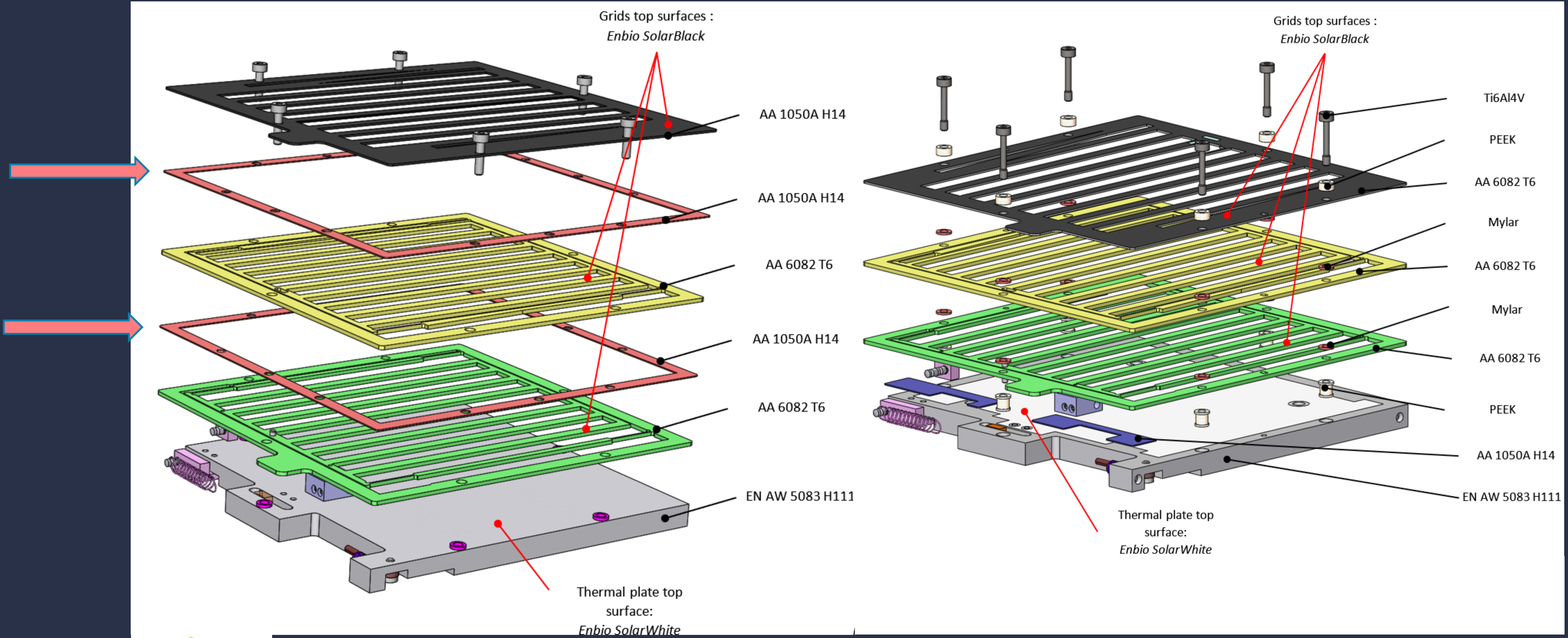






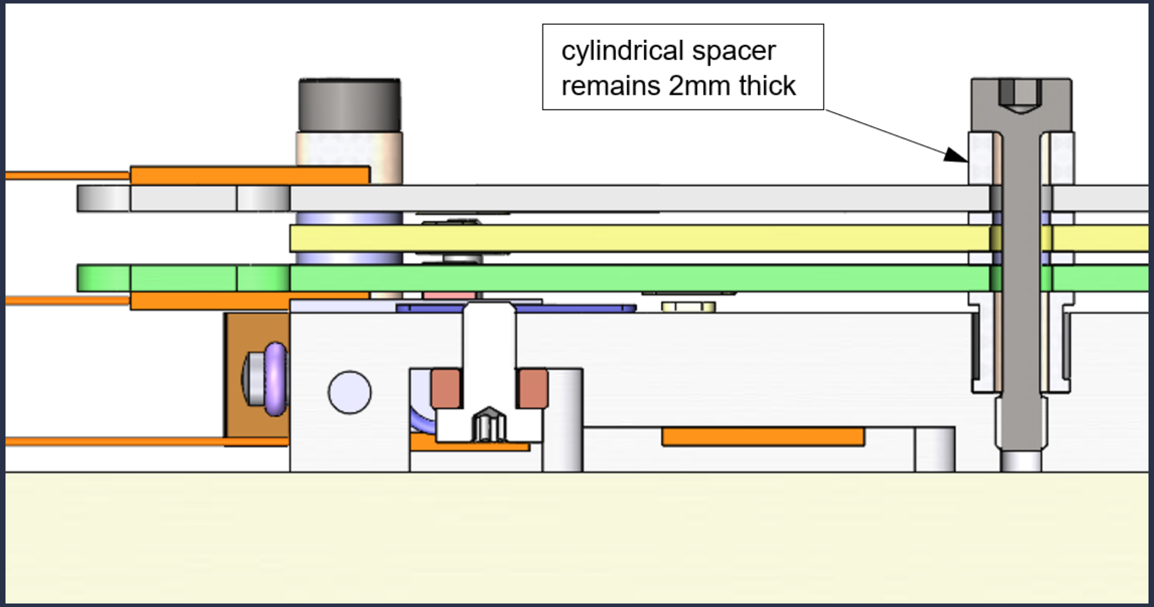
Heron – FEM Thermal Analysis Design recommendations

- Heron recommandations to design :
  To improve thermal isolation between top fixed grid and baseplate



Heron – FEM Thermal Analysis Design recommendations

- Design update from Heron – Preliminary Thermal Network Analysis
  - Change bolts from stainless steel to Titanium
  - Replaced frame spacer by individual thermal insulation around Titanium bolts
    - Mylar washers
    - PEEK spacers/bushings



BBM+ (EM) Test configuration recommendation

- Based on the detailed FEM analysis, recommendation was **to remove SolarBlack** from mobile and fixed flex grid elements

- Conclusion: **no coating** (bare aluminium metal)
  - ➔ In open configuration: slightly degraded emissivity
  - ➔ In closed configuration: greatly improved insulation

Baseplate with SolarWhite and masking pattern

Heron – FEM Thermal Analysis Results [FROM CDR July 20,2021]

Effective Emissivity

Compare tables which one is valid?

Table below WITH coatings on flex grids

- The effective emissivity is calculated by the following formula.

$$\varepsilon_{eff} = \frac{Q}{\sigma * A * VF * (T_{bp}^4 - T_{ambient}^4)}$$

- Where: σ = 5.669E-8 (W/m²K), A = 0.01 m2 , View Factor VF = 1.
- Q is the applied heat, T_{bp} is the temperature of the base plate and $T_{ambient}$ is the ambient temperature.

Configuration	Applied Heat (W)	Ambient Temperature (C)	Thermal Plate Temperature (C)	Effective emissivity
Open	10	20	207.5	0.384
Open	10	-273.15	188.9	0.387
Closed	0.1	20	26.4	0.265
Closed	0.1	-273.15	-141.7	0.591

Thermal analysis results without SolarBlack [FROM ESMATS Sept,2021]

- The properties of Concept 4 lead to low effective emissivity in the open configuration at 10 W and 0 K, and to a very high effective emissivity in the closed configuration at 0.1 W and 0 K.
- No coatings bring down the effective emissivity for the open configuration to 0.319 and the closed configuration to 0.128

With SolarBlack on grids

Load Case	Configuration	Applied Heat (W)	Ambient Temperature (^{0}C)	Thermal Plate Temperature (^{0}C)	Effective Emissivity
LC 1.1	Open	10	20	207.5	**0.384**
LC 2.1	Closed	0.1	20	26.4	**0.265**

No coating on grids

Load Case	Configuration	Applied Heat (W)	Ambient Temperature (^{0}C)	Thermal Plate Temperature (^{0}C)	Effective Emissivity
LC 1.1	Open	10	20	227.1	**0.319**
LC 2.1	Closed	0.1	20	33	**0.128**

In the open configuration, the current design has a power dissipation to deep space (5K) when the radiator is at 90°C of 3.2 W.

Resume of implemented design changes from BB to BBM+

- Identified design upgrades following Breadboard Test Campaign
- The BB+ became BBM+ (recuperated certain H/W from BB) & used as part of the EM test campaign
- EM2 is a future EM with more fundamental design changes not possible to implement in BBM+

	COOLER Design implementations for EM mechanism	BB+	EM2
	Points identified during PM4 (MN-013)		
1	The SMA should be insulated from space temperature. (local MLI around SMA)	X	
2	The SMA fixation parts should be insulated from the parts which are directly in contact with the space temperature (local MLI around SMA) Covers added	X	
3	SMA alloy needs to be selected accordingly to meet the specification activation range of 50 to 90°C → Already implemented as part of SMA design iteration SMA-D (alloy CuAlNi 39 to 69°C)	X	
	Points identified during BBM test campaign		
4	Implement a larger stroke adjustment range for the SMA		X
5	Increase the negative stroke adjustment against the end-stops in the open position		X
6	Review sizing/stiffness of grid flexure to avoid contact between plates when horizontal (against gravity)		X
7	Physical targets should be engraved on the fixed and flexible grids to simplify and increase the quality of tracking since the grid stroke during TVC testing is measured using video tracking software	X	
8	A graduated system should be engraved on the BBM fixed grid to read the grid positions easily and without a tracking software.		X
9	Review mechanical interface of mechanism (for vibration & thermal tests)	X	

	COOLER Design implementations for EM mechanism	BB+	EM2
	Points identified during BBM→ EM (PSc internal design review WP31)		
10	Launch Locking Design not included in budget or tasks (SMA & Bias springs cannot maintain mobile stage against end-stop) Dummy LLD Mobile stage bound to endstop	X	
11	LLD: Analyse sizing of current springs (bias and SMA) to block during vibrations	X	
12	LLD: Vertical direction (between plates) protection spacers (coated metallic shims or scotch tape)	X	
13	PT100 Cable routing and envelope to be discussed with FOTEC (TVAC chamber)	X	
14	Grid not fully closed (small gap visible) when viewed from the side in 1 of 2 directions		X
14.1	Application of solar black & white surface coating (masking of coatings defined)	X	
	Points identified during PDR		
15	SMA integration in structure and protection against external environment (Thermal disturbance, ATOX) → Nimesis has no information on effect of ATOX. This point may need to be addressed in a long-term context out of the scope of the current project.		X
16	ESA points out that in previous experience during vibration tests, SMA had activated. Point to be discussed with Nimesis → Subject discussed with Nimesis. See section "Nimesis open questions" addressed on previous page.	X	
	Points identified during Preliminary Thermal Analysis (Heron/CSEM)		
	Titanium bolts for low conductivity	X	
	Mylar washers replacing spacing frame between flex grids	X	
	PEEK thermal isolation bushing between bolts and baseplate	X	
	Eyebolts for Thermal Balance Test wire suspension (GSE)	X	
	M4 bolts for fixation vibration baseplate and thermal heaters plate (Cu) GSE	X	
	Zones defined for masking of SolarWhite and SolarBlack thermo-optical coatings	X	

Outline

- Overview of critical specifications
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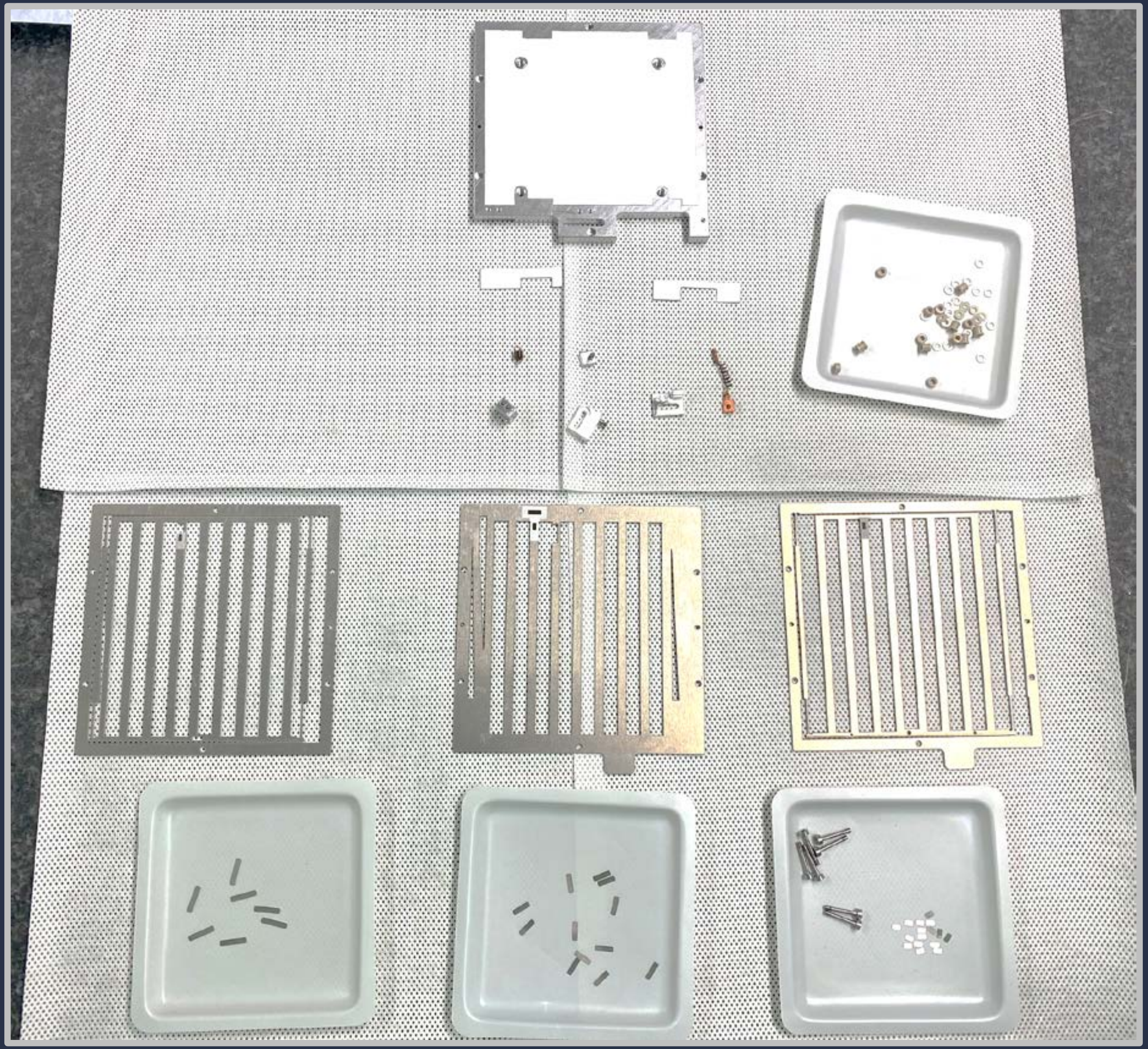
- FEM analysis (Mechanical & Thermal)
- **EM Assembly**
- EM Test campaign
- EM Correlation

EM (BBM+) Hardware prior to assembly

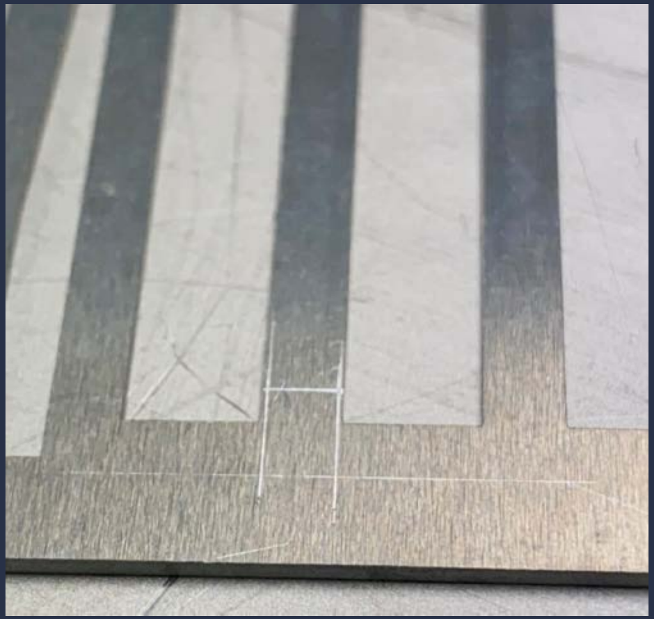
Packaged hardware from ENBIO

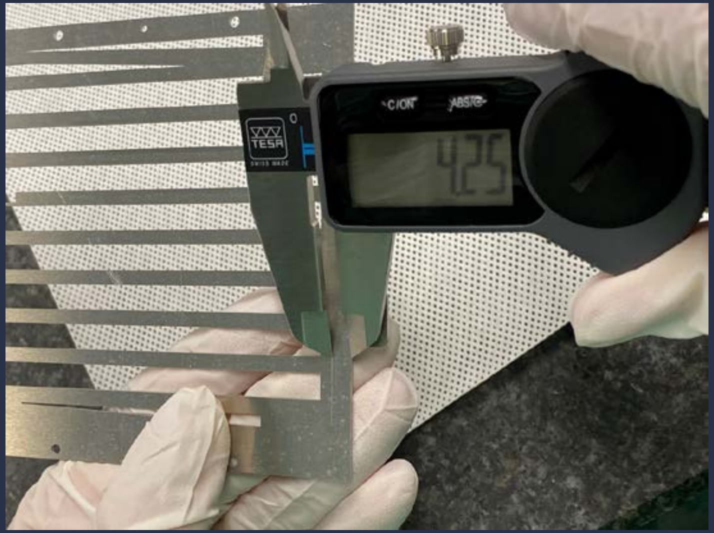


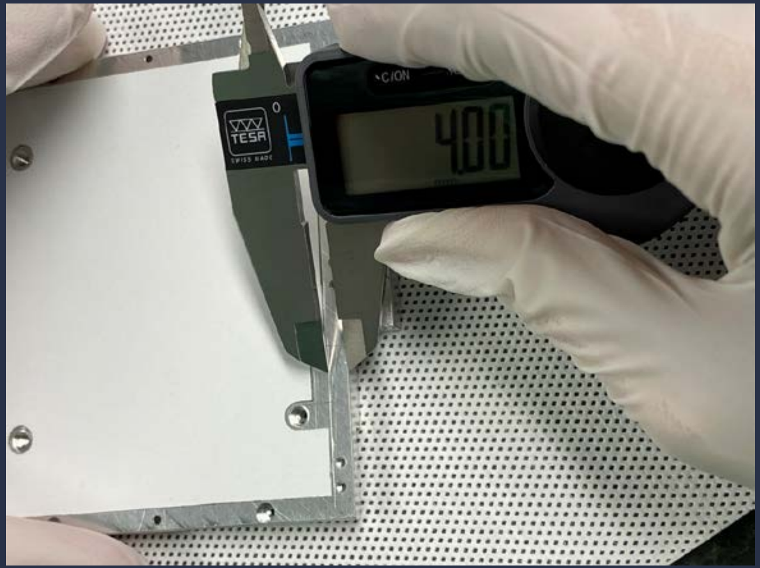
EM (BBM+) Gluing operations on grids

Vertical gap spacers

- Areas to be glued were measured and scribe marks made
- Surrounding area masked off with tape (0.05mm thick)



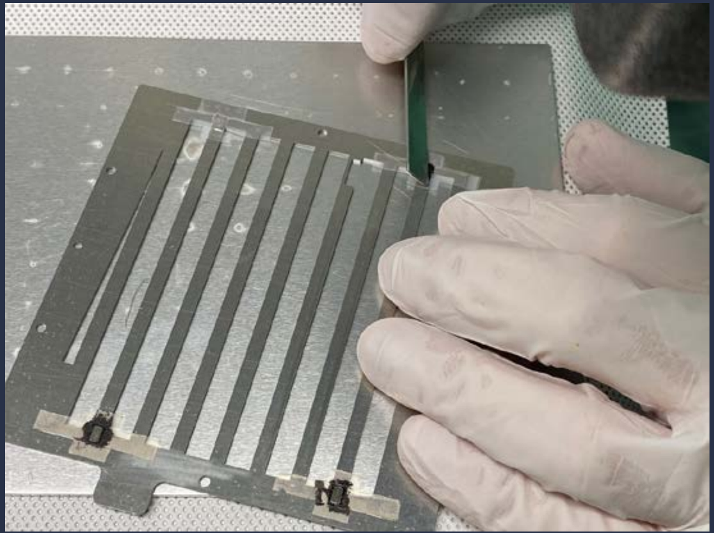




EM (BBM+) Gluing operations on grids

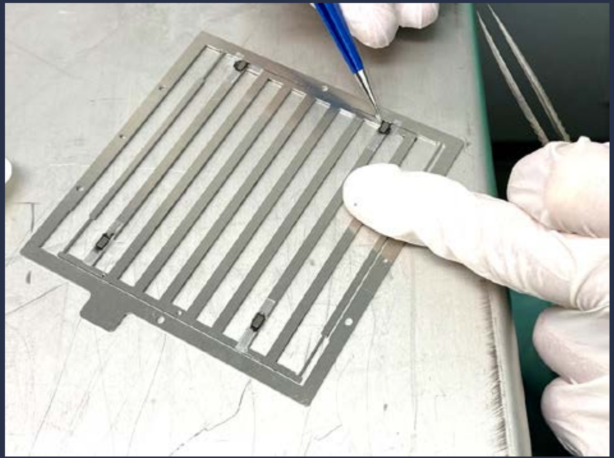
Preparation of epoxy
Stycast 2850 FT + cat. 9

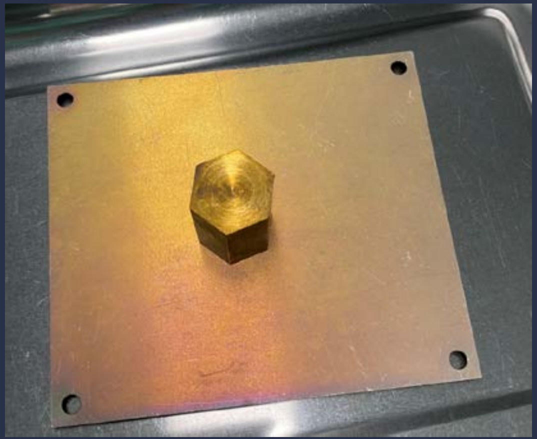
Application of epoxy in designated areas



Application of spacer on epoxy

Removal of tape around spacers

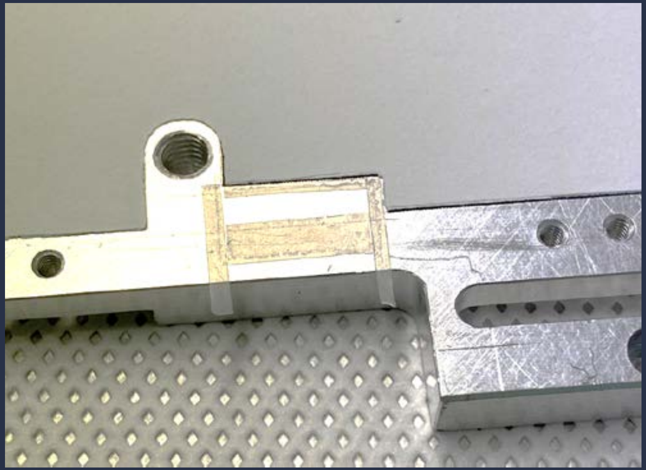




Weighted plate placed on spacers and cured in over 1h at 65°

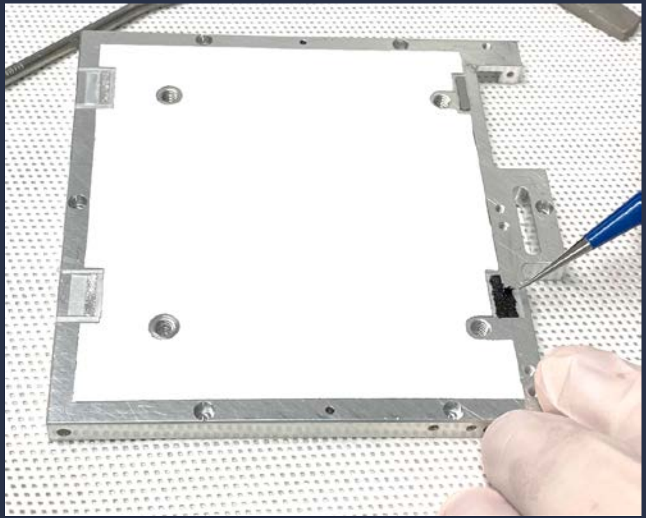
EM (BBM+) Gluing operations on Baseplate

Masking areas with tape

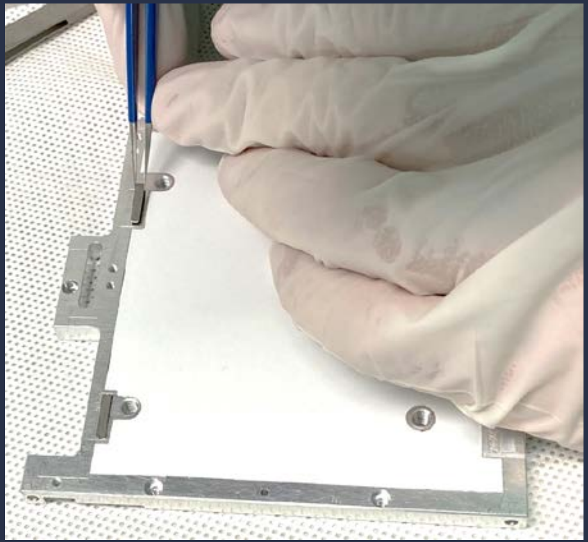


Epoxy surface scribed for better adhesion

Application of epoxy in designated areas

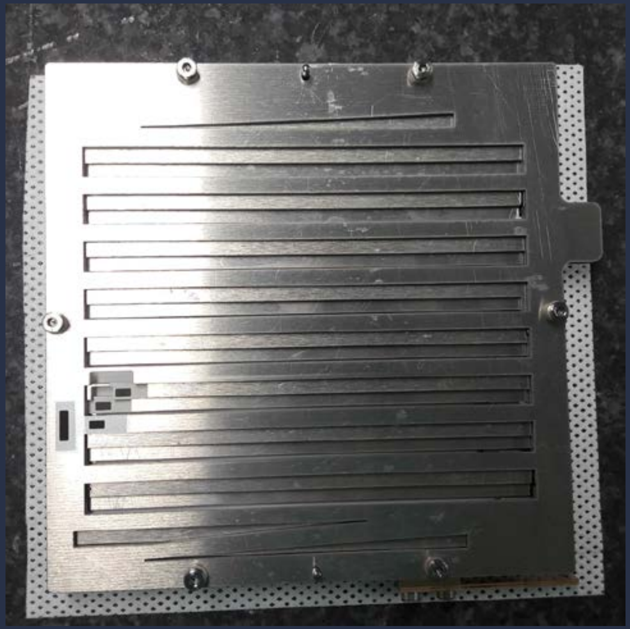


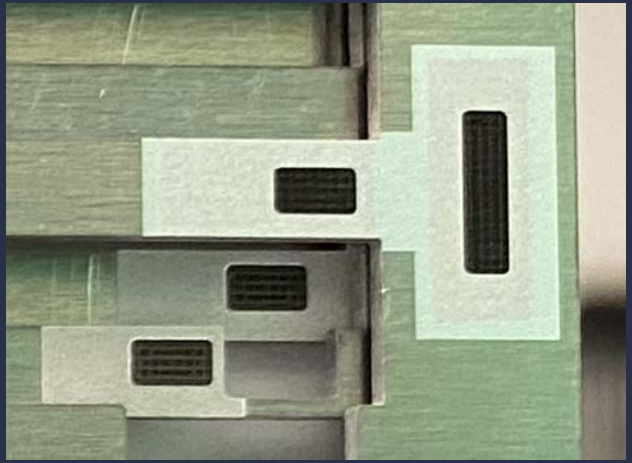
Removal of tape around epoxy and application of spacers

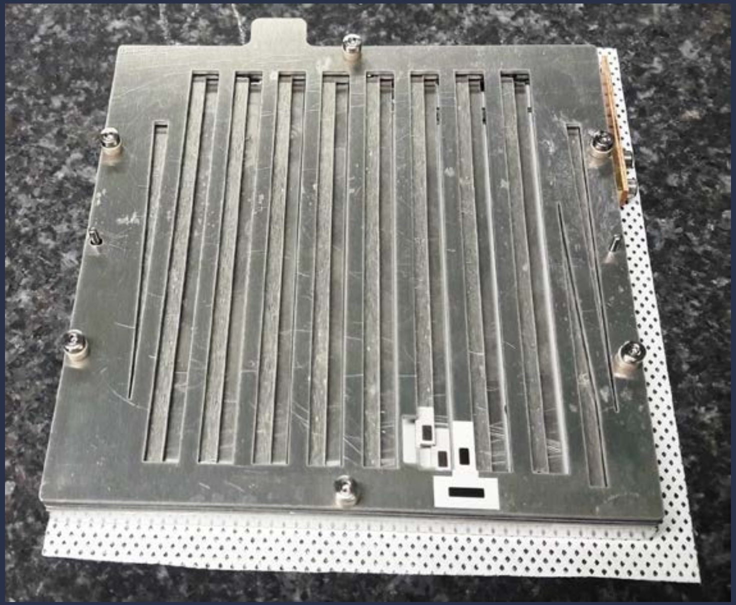


EM (BBM+) Targets on grids

- With the decision to maintain grids with bare Aluminium, targets for video tracking slightly modified.
- ENBIO applied a SolarBlack base coat, then a SolarWhite coating on a slightly over-sized region on each of these grids
- EFJ subco then laser etched targets to the exact correct size/shape with SolarBlack exposed against the white regions





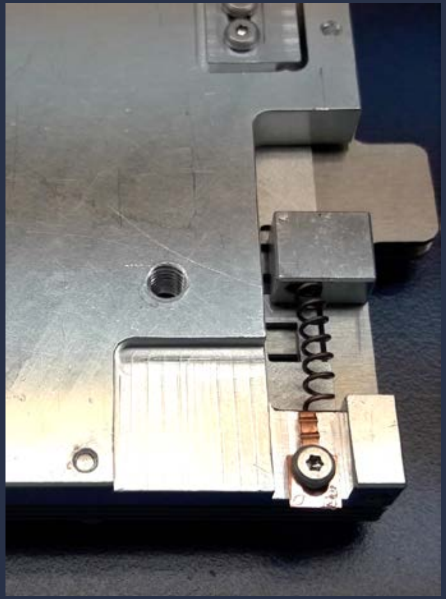


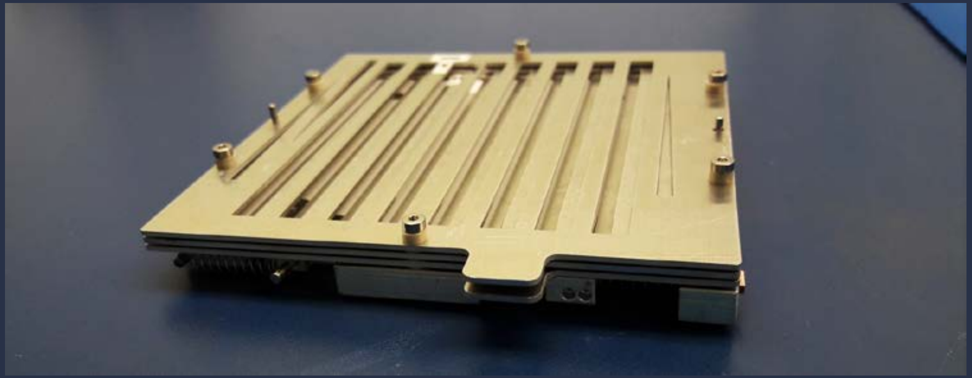
EM (BBM+) Final assembly steps

- Adjustment of SMA position and spring forces









BBM+ assembled

Outline

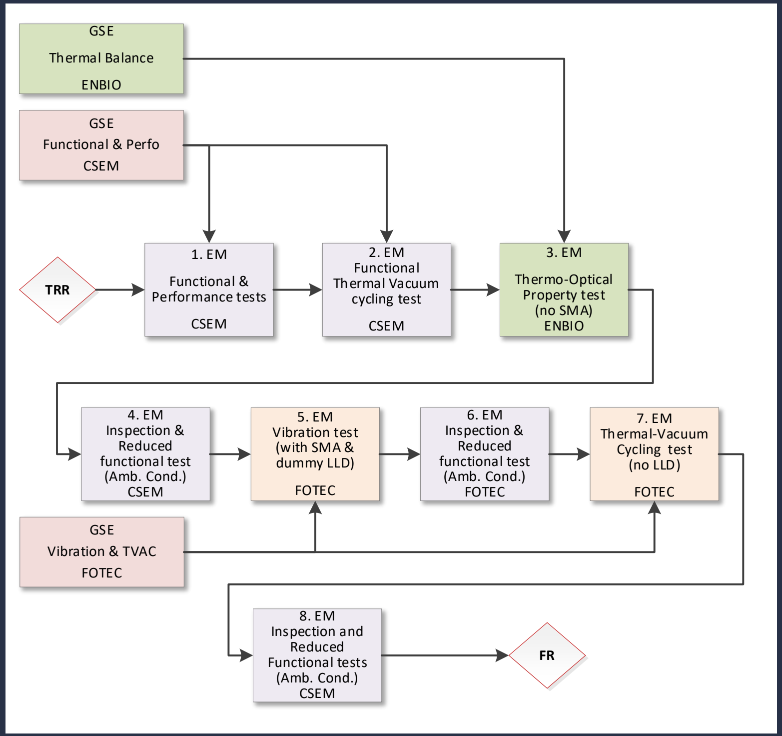
- Overview of critical specifications
- Concept trade-off & Breadboard selection
- BBM Test results and EM (BBM+) selection for Test campaign
- FEM analysis (Mechanical & Thermal)
- EM Assembly
- **EM Test campaign**
- EM Correlation

EM (BBM+) Test campaign

- Functional tests in vacuum (CSEM)
  - Repetition of BBM tests

- Thermal balance tests (ENBIO)
  - Mechanism suspended by 4 stainless steel wires
  - Foil heaters on Cu plate behind baseplate
  - Effective Emissivity will be derived by temp measurements
  - Correlation of simulation model with test results

- Environmental tests (FOTEC)
  - Mechanical vibration (Sine & Random)
  - Thermal vacuum cycling (8 x -60°/+100°C)

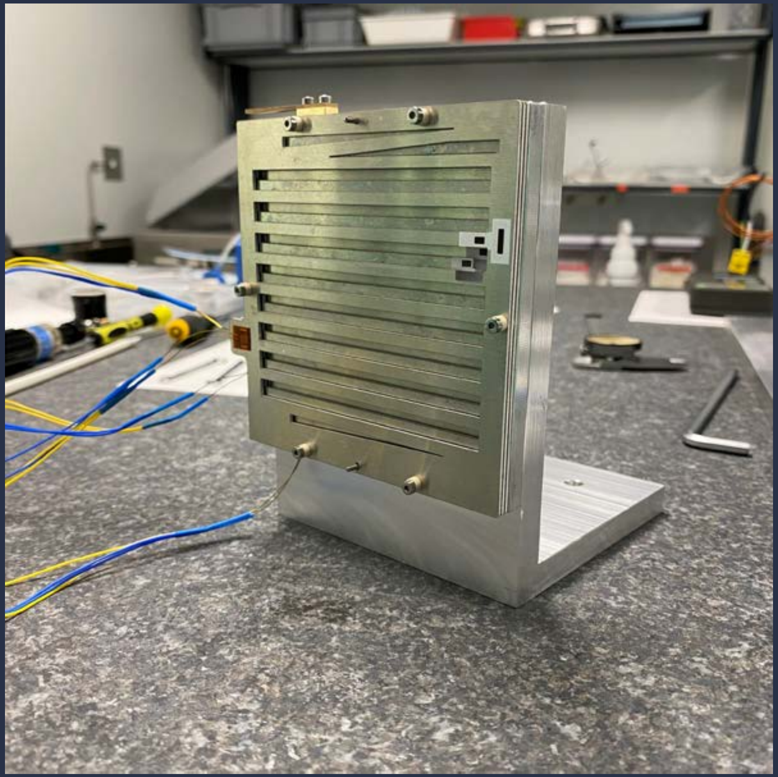


csem

EM (BBM+) validation – Functional tests at ambient atmosphere

- SMA actuator is activated with a hot air gun.
- The mechanism was tested in different orientations (vertical, horizontal, etc.)

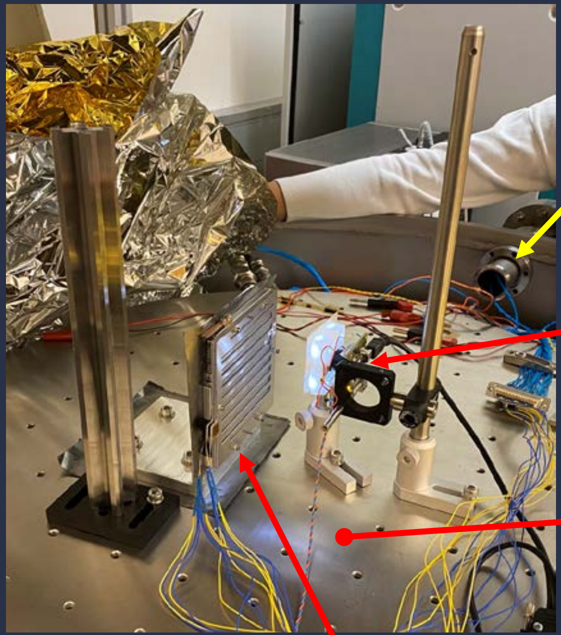
Vertical orientation (gravity along +X)



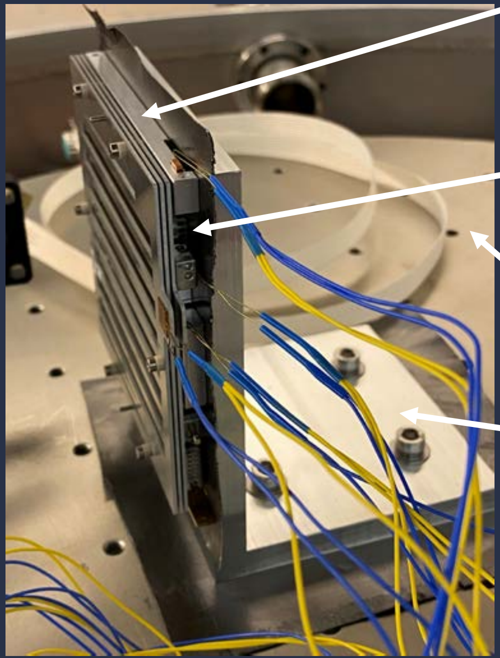
Functional tests performed using hot air gun.
Setting 130° = 120°C ±10° Stroke=5.7mm

EM (BBM+) validation – Functional tests in TVC

- Test under vacuum
- SMA actuator is activated by conductivity through the TVC's base plate then the louver base plate
- The mechanism was tested in different orientations (horizontal & vertical)

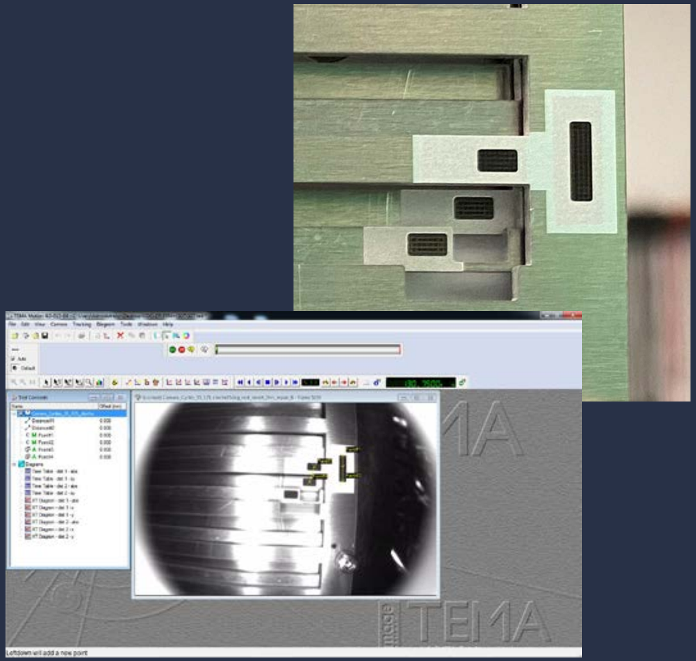


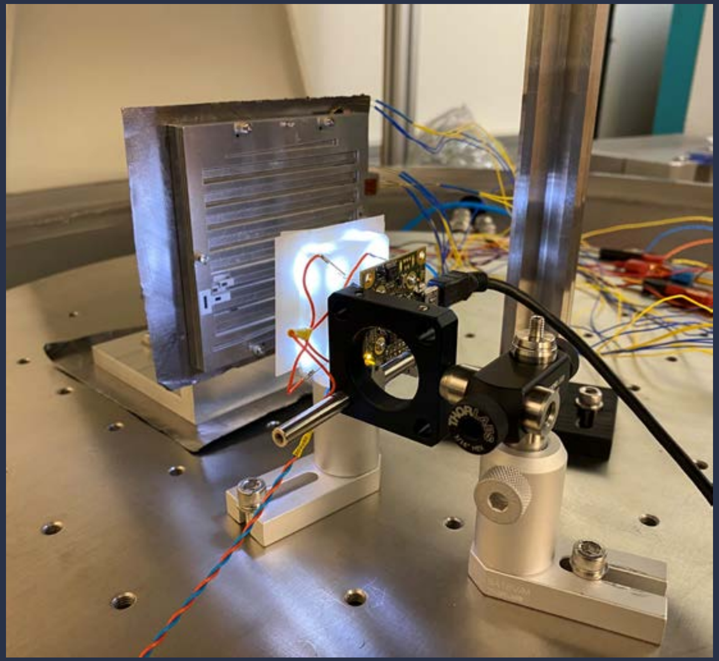
TVAC chamber

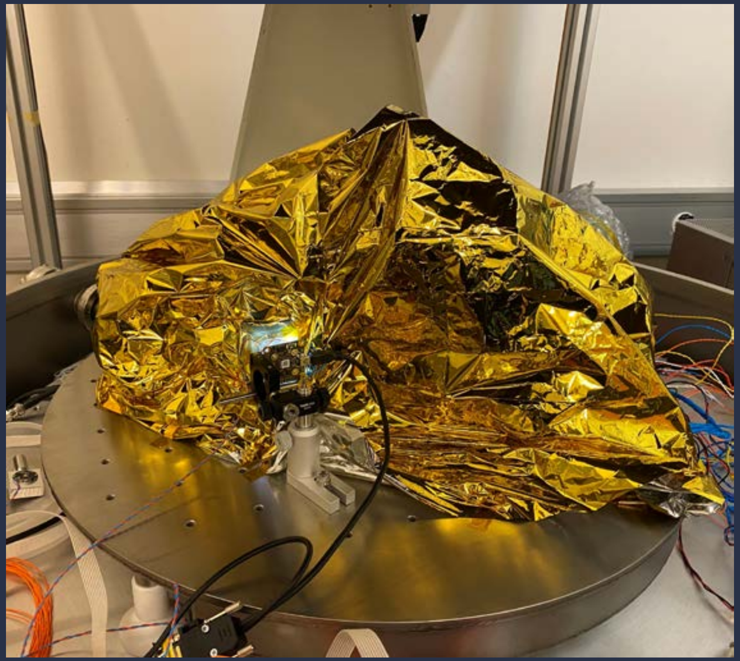


EM (BBM+) validation – Functional tests in TVC

- Thermal sensors for thermal monitoring
- Targets on flexible grids for motion tracking
- MLI blanket to insulate the SMA actuator from TVC housing radiation



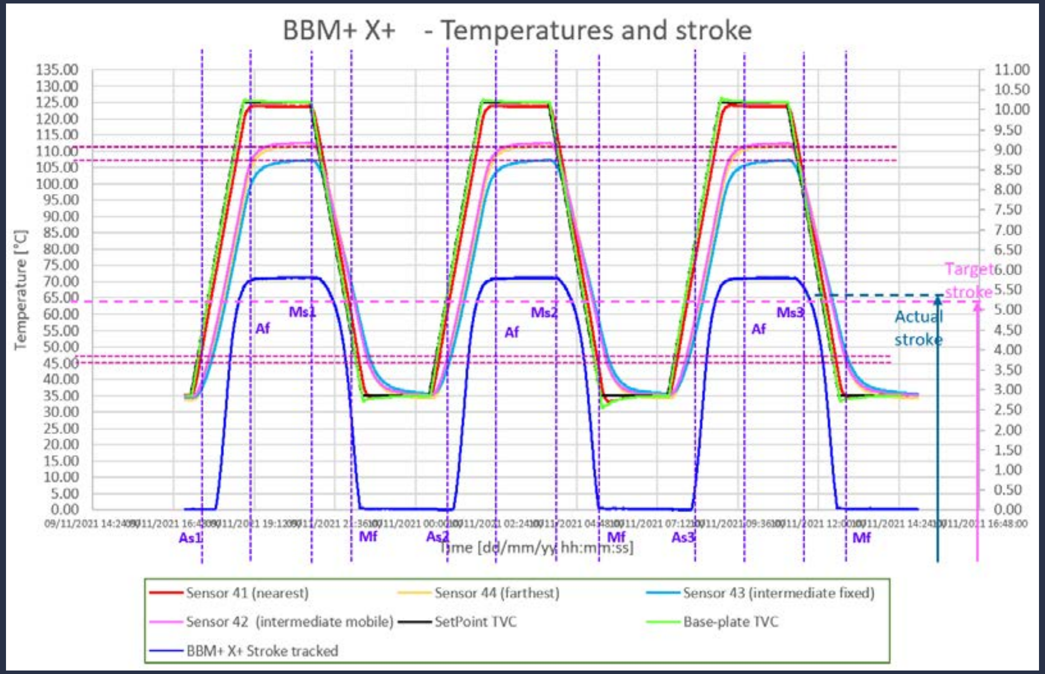




Camera mounted looking in horizontal direction

EM (BBM+) validation – Functional tests in TVC

- Video during TVC tests and graphics
- Reactivity of the SMA is dependent on the rate of change of the heat source.



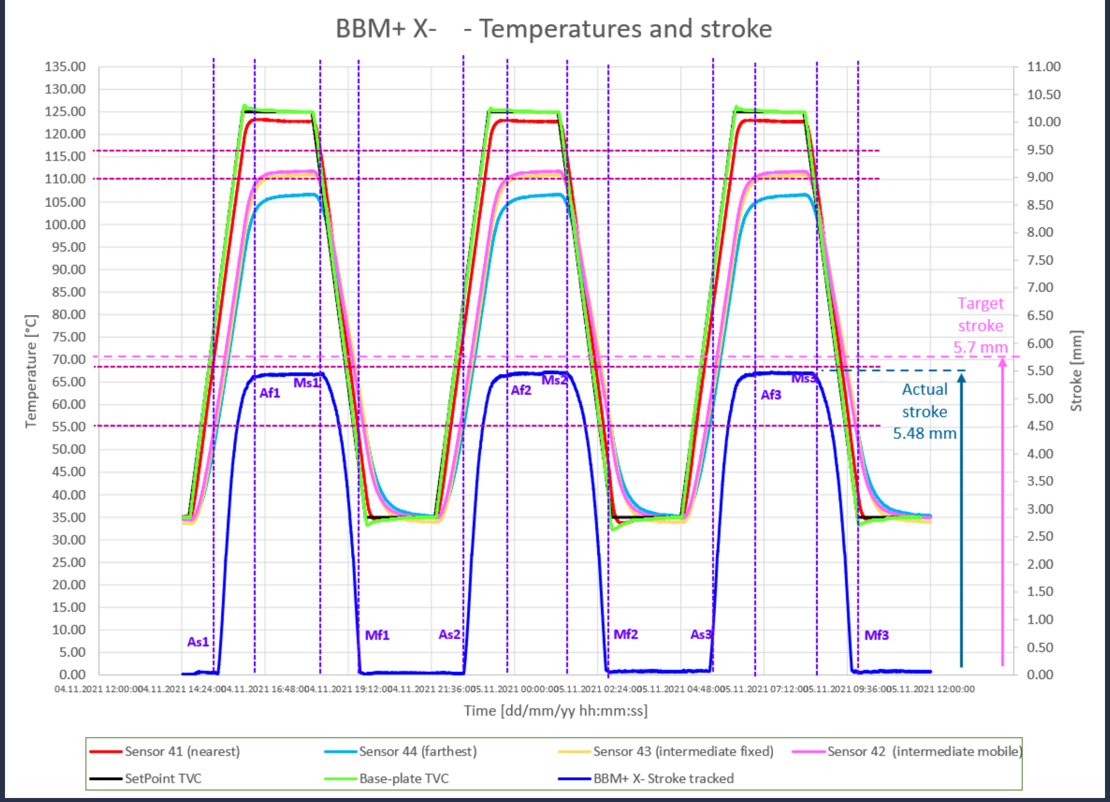
Upper temperature and plateau duration (125°C / 2h)

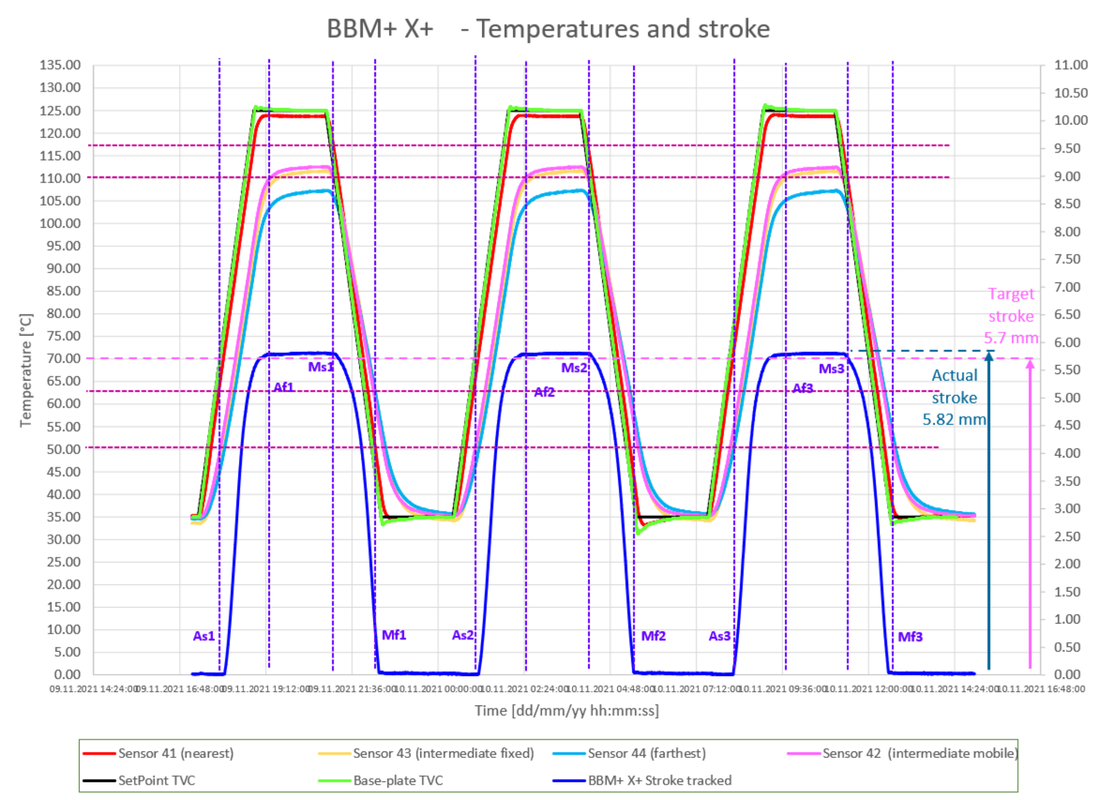
BBM+ EM test – Opening/closing temp. set points

FPR6	Stability of the opening and closing set points shall be +/- 1°C.

Conclusion:

- Stability of the opening and closing set points shall be <±1°C.





BBM+ EM test – Opening/closing temp. set points

FPR6	Stability of the opening and closing set points shall be +/- 1°C.

Conclusion:

- Stability of the opening and closing set points shall be <±1°C.
- Set point temperatures achieves stability with max deviation of **0.8°C.**

	Set points' temperatures from TVC test [°C]			
	Gravity along X- direction		Gravity along X+ direction	
As_l	68.63	+0.27 -0.28	63.33	+0.62 -0.38
Af_l	116.43	+0.47 **-0.78**	117.50	+0.35 -0.20
Ms_l	110.30	**+0.80** -0.70	110.47	+0.58 -0.32
Mf_l	54.92	+0.18 -0.22	50.00	+0.15 -0.10

BBM+ EM test – Opening/ closing temp. range (15 to 20°C)

IR4	The COOLER concept properties shall have a full closed to full open temperature range of 15°C to 20°C and be selected/adjusted within the range -50°C to 90°C.

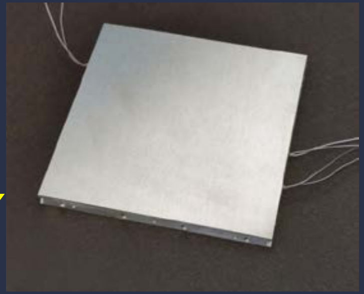
Conclusion:

- BBM+ (EM) with modifications and in vertical configuration

	BBM+ (EM)		BBM+ (EM)		(BBM)	
	Gravity along –X dir		Gravity along +X dir		Gravity along –Z dir	
Heating range	47.80	+0.45 -0.50	54.17	+0.58 -0.82	34.38	+0.52 -0.98
Cooling range	55.38	+0.77 -0.88	60.47	+0.43 -0.22	46.37	+0.28 -0.42

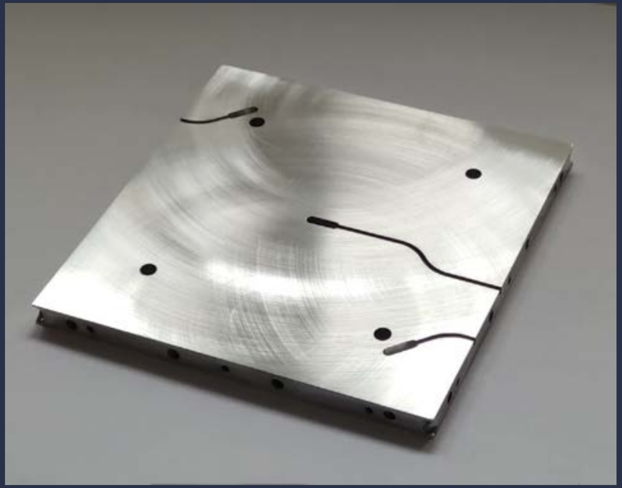
ENBIO Thermal Balance tests

- Vacuum thermal balance test was performed where results would be correlated to the thermal model analysis and derive the emissivity and absorptivity values for the mechanism
- The following hardware and configurations were tested:

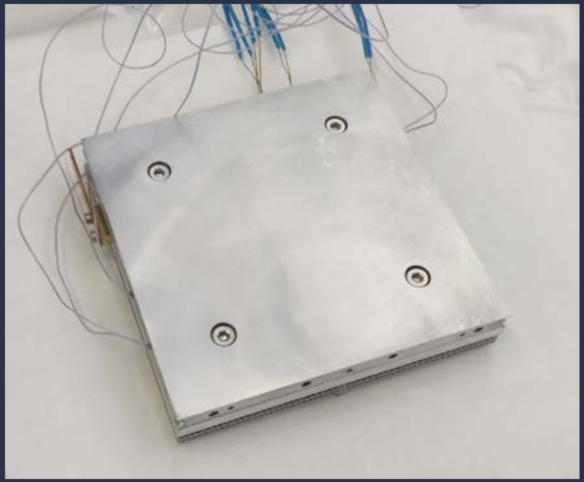


  - Step 1 Sample with SolarBlack coating
  - Step 2 Sample with Polished Al (no coating)
  - Step 3 EM Closed configuration
  - Step 4 EM Open configuration

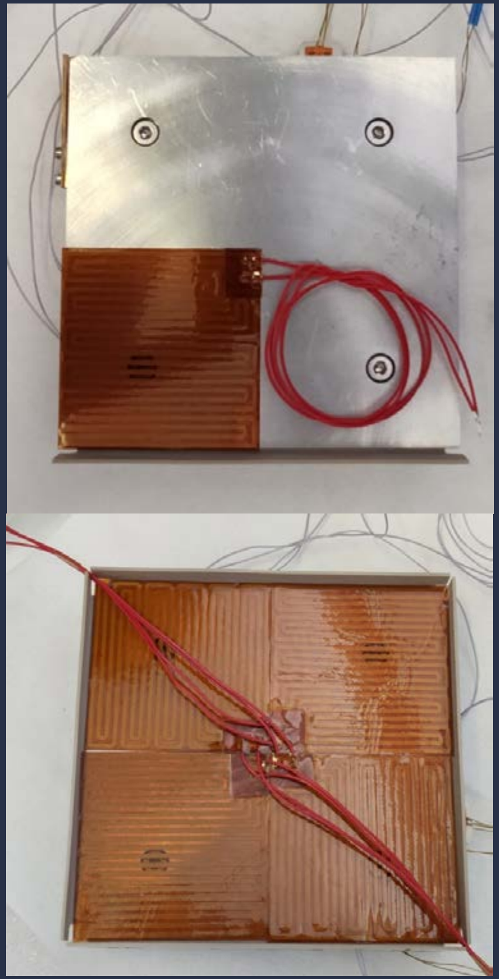
ENBIO Thermal balance test setup and instrumentation



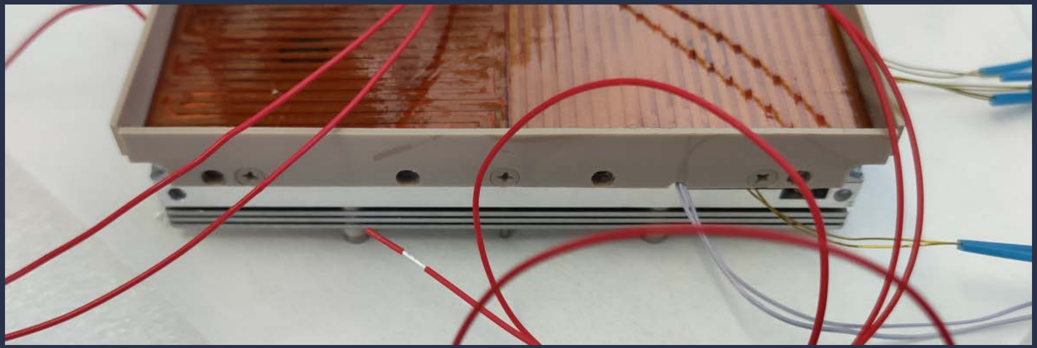
6 type E thermocouples embedded in the baseplate



Baseplate attached to COOLER device.



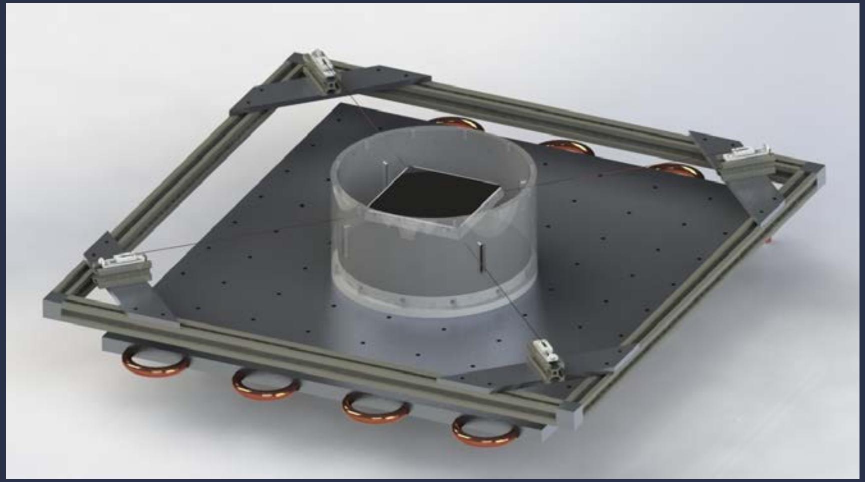
Kapton foil heaters attached to baseplate



Attachment of PEEK side panels to avoid direct contact between heaters and MLI

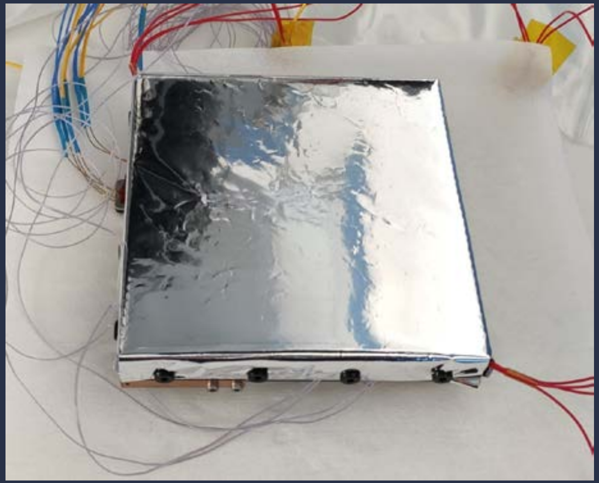
ENBIO Vacuum chamber test setup

ENBIO T2 test facility used for thermal-vacuum cycling testing



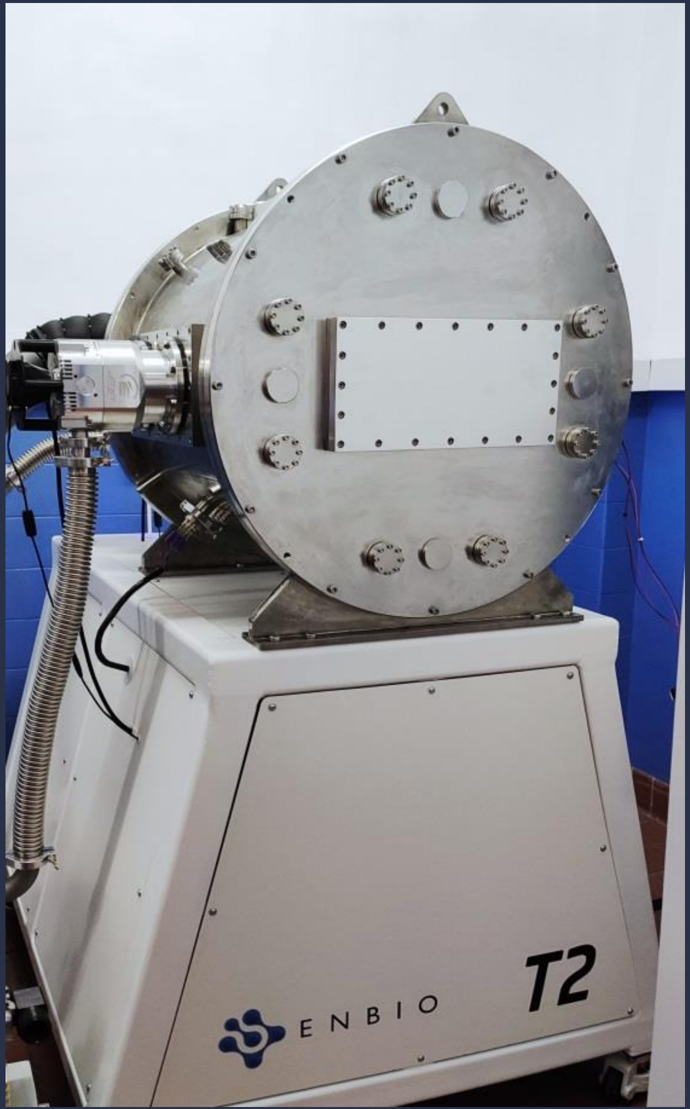
Conceptual illustration of the test configuration

COOLER device in the closed configuration mounted inside the thermal shroud, suspended by stainless steel wires



MLI attached to the thermal baseplate to minimise heat leakage

ENBIO Test Parameters



- Adapter plate held at 20 °C
- Power to heaters stepped by 0.2 W until device reaches 90 °C
- Dwell periods of 7-12 h at each step (total duration ~ 1 week)
- Power then set to 0 W; data recorded during cooling
- Finally, one step change to the power setting required to reach 90 °C, giving a clean temperature profile for thermal modelling.

TC Placement:

6 embedded in baseplate

2 embedded in adapter plate (+ 1 RTD for closed-loop control)

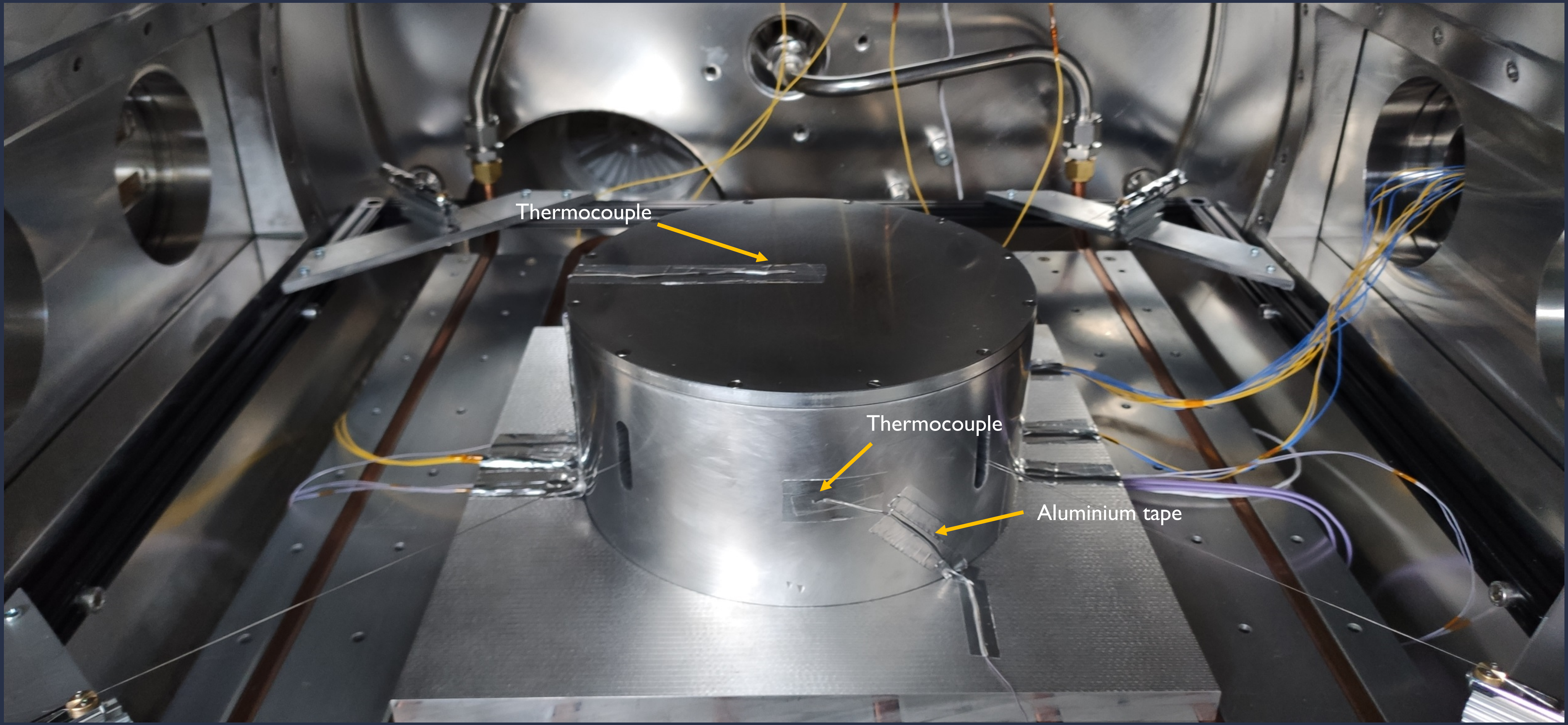
1 on shroud tube at half-height

1 on top of tube lid

Recording 4x COOLER device RTDs

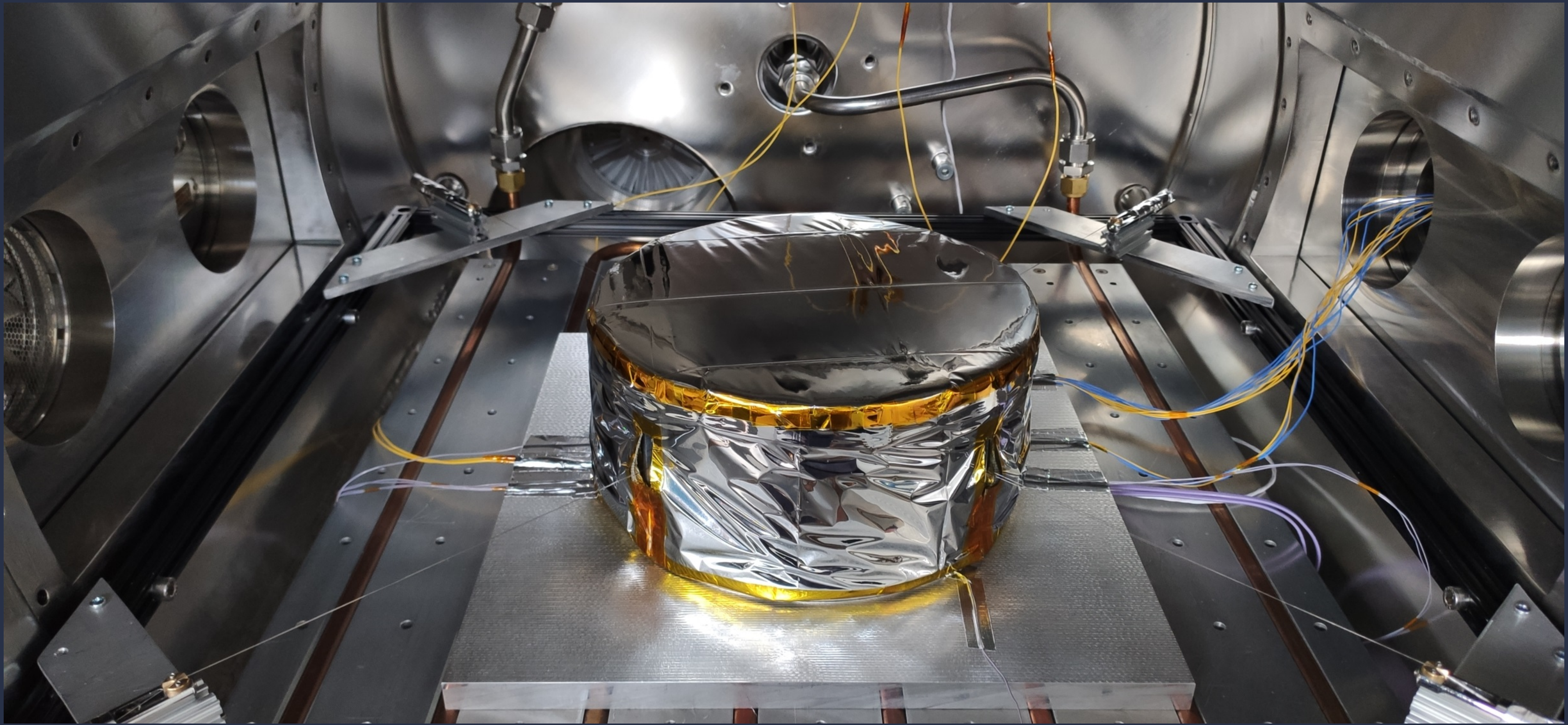
Recording voltage and current supplied to heaters

ENBIO Test Setup



With lid in place.

ENBIO Test Setup



With MLI in place.

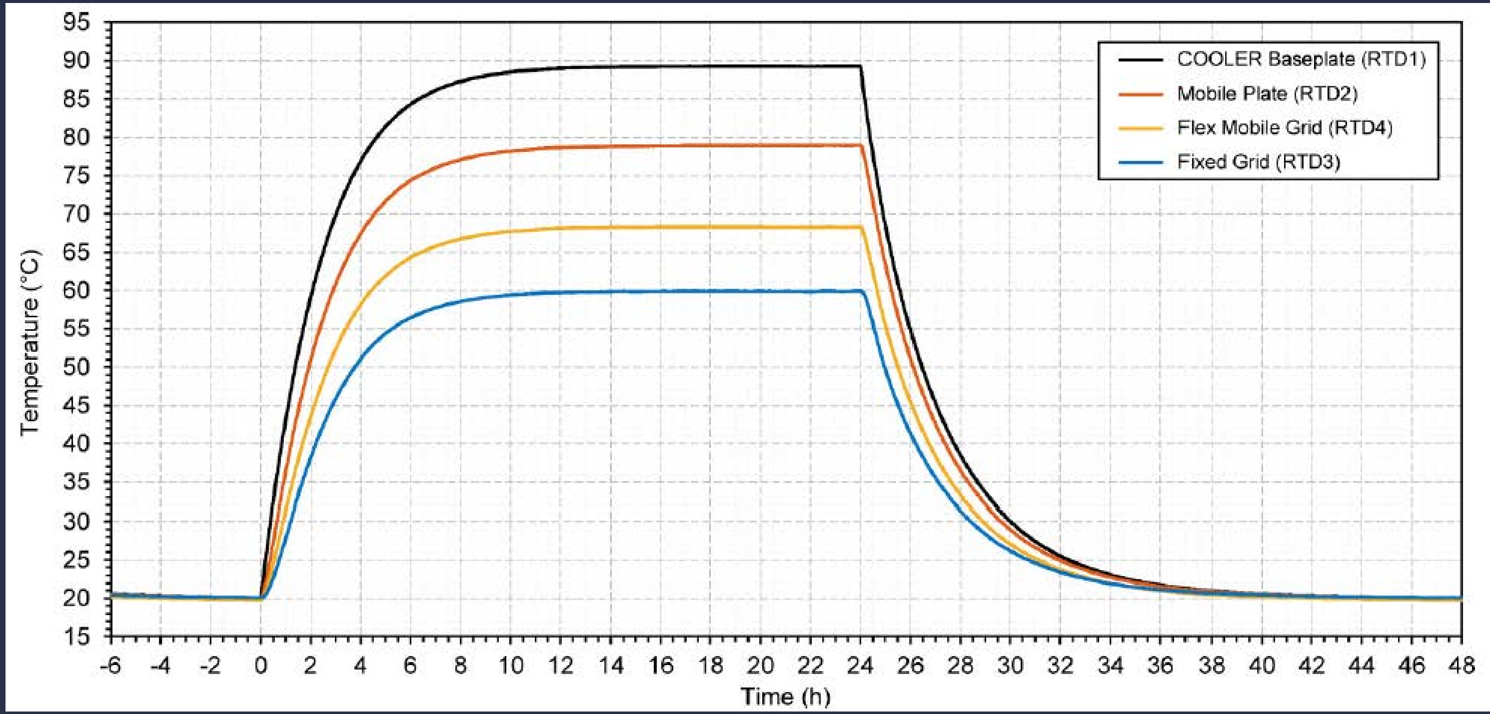
ENBIO Results

- A bare aluminium baseplate and a baseplate coated with a black thermo-optical coating (ENBIO SolarBlack) were tested in order to allow for correlation of data with a thermal model. The thermal emittance of the bare aluminium surface and SolarBlack surface were measured using an FTIR spectrometer.

Surface	Thermal Emittance (%)
Bare aluminium	6.4
ENBIO Solar Black	79.4

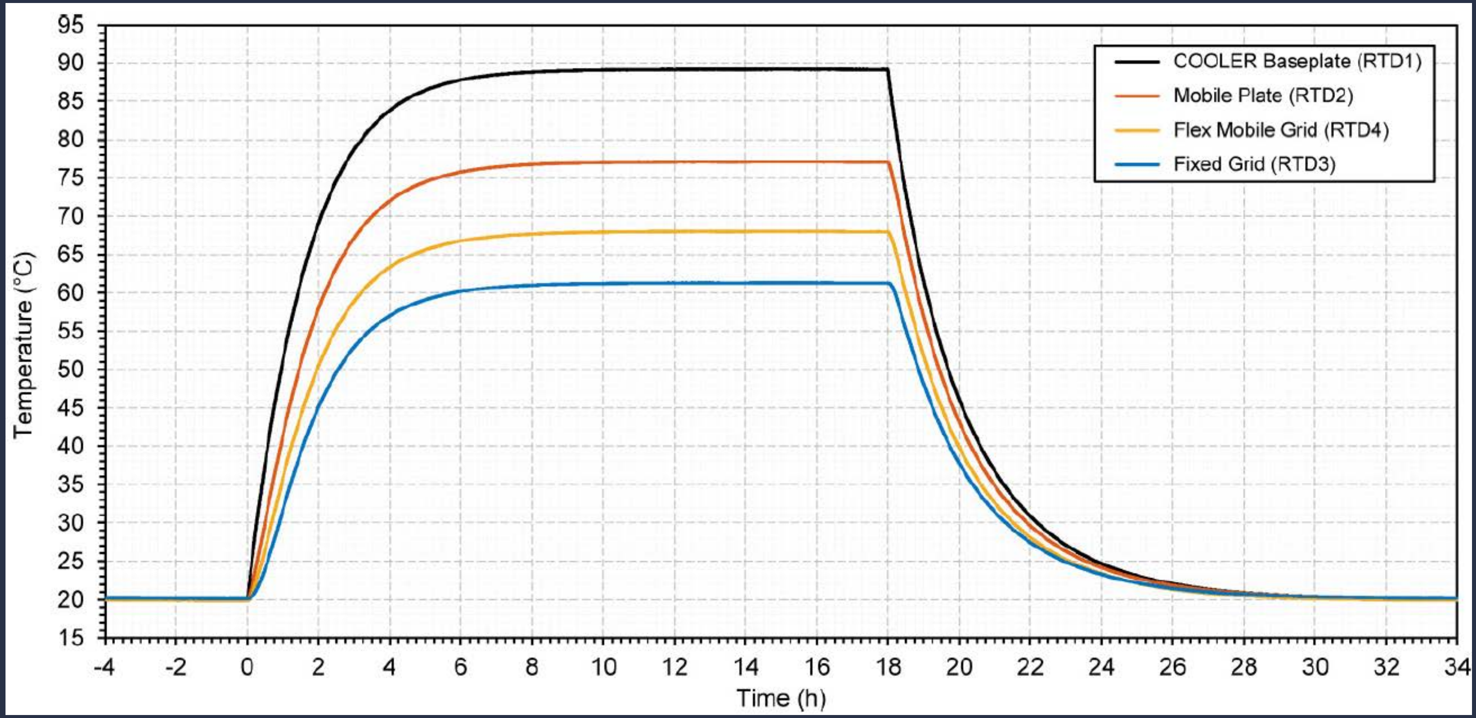
ENBIO Thermal Balance test results: Closed Configuration

- Single-step test, an average heater power of 2.34 W yielded an average thermal baseplate temperature of 89.9°C.



ENBIO Thermal Balance test results: Open Configuration

- Single-step test, an average heater power of 3.40 W yielded an average thermal baseplate temperature of 90°C.



ENBIO Thermal Balance test results: Resume

- Thermal balance tests were conducted for the COOLER device in the open and closed configurations, a bare aluminium baseplate, and a black coated baseplate
- Heater power levels, and equilibrium temperatures reached during the single-step tests

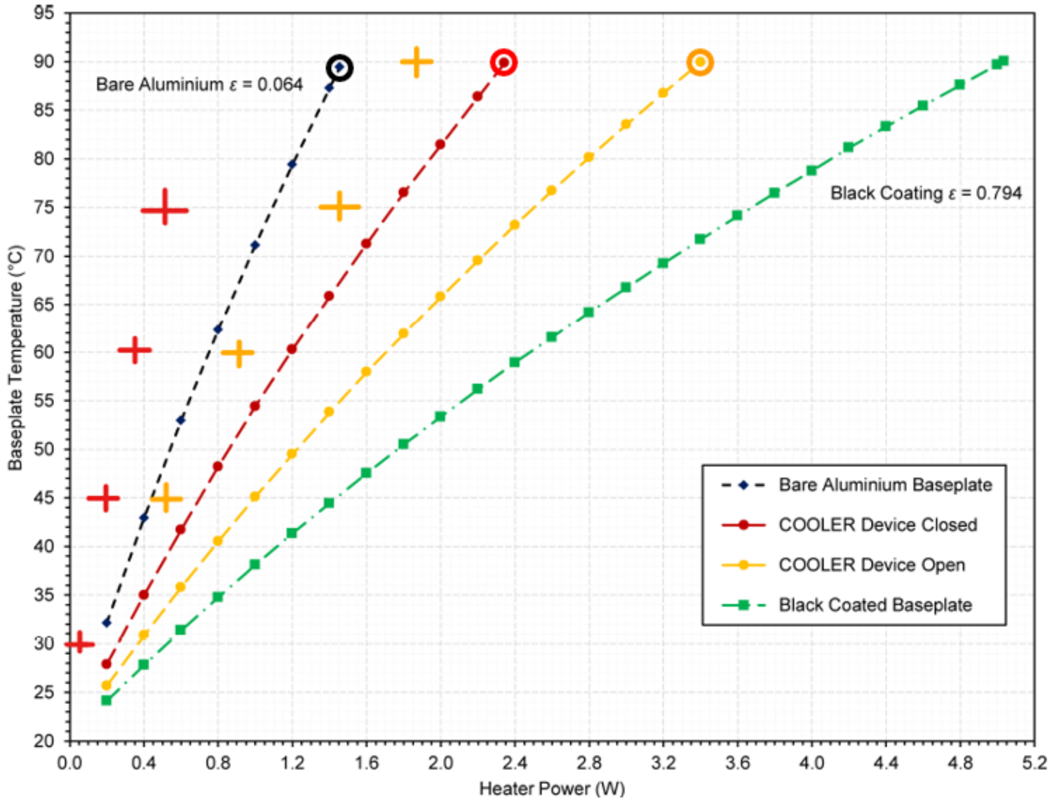
Test Article	Power (W)	Baseplate Temperature (°C)
COOLER closed configuration	2.344	89.98
COOLER open configuration	3.400	90.01
Bare aluminium baseplate	1.455	89.57
Black coated baseplate	5.035	90.06

- Note: Predicted ~1.44 W for plain aluminium plate to reach 90°C

ENBIO Thermal Balance test results: Resume

The average thermal baseplate temperature (arithmetic average of the 6 thermocouples embedded in the baseplate) is plotted in Figure 7-25 as a function of heater power during the **multi-step test** for the two COOLER configurations and tests of the bare aluminium baseplate and black coated baseplate.

- For closed configuration, ~2.34 W to reach 90°C **Point O in graph**
- For open configuration, ~3.40 W to reach 90°C **Point O in graph**
- Plain aluminium plate ~1.44 W to reach 90°C **Point O in graph**



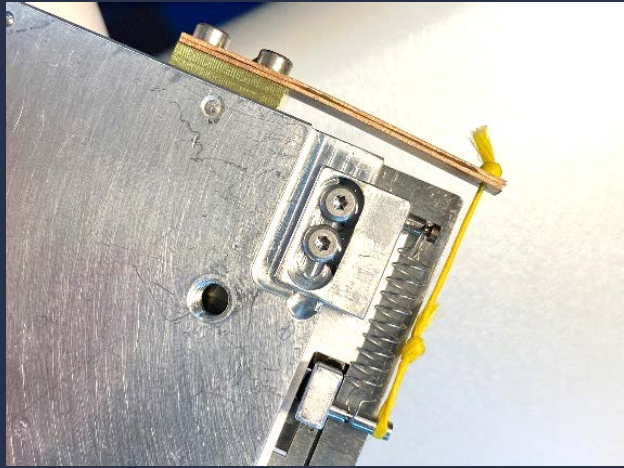
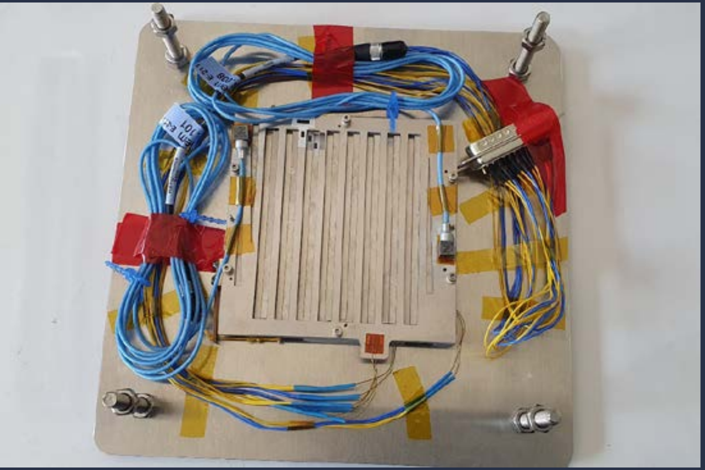
+ HERON simulation prediction data for Cooler device CLOSED (ref, COOLER-CSE-TN-06, p.67)
+ HERON simulation prediction data for Cooler device OPEN (ref, COOLER-CSE-TN-06, p.67)

EM (BBM+) Preparation for vibration tests at FOTEC

- Dummy launch locking device, all bolts locked with EC2216





Packaging for shipment

Verification of launch locking force

EM (BBM+) Vibration test instrumentation

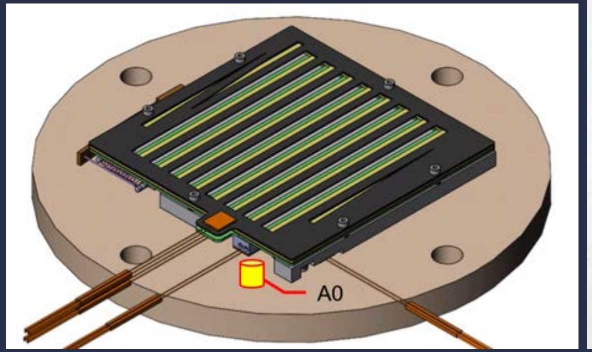
- **Control** Accelerometer:

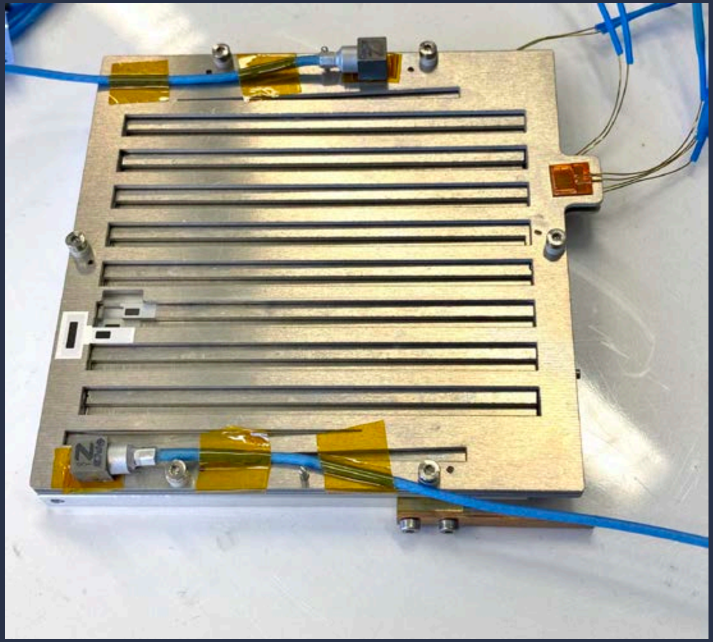
  A0 (baseplate) B&K 4535 from FOTEC
- **Mobile grid** Accelerometers

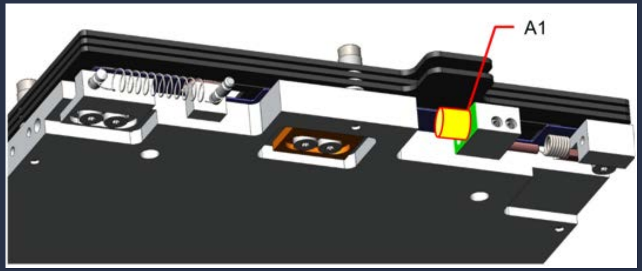
  A1 Endevco Isotron Model 35B from FOTEC
- **Fixed grid** Accelerometers:

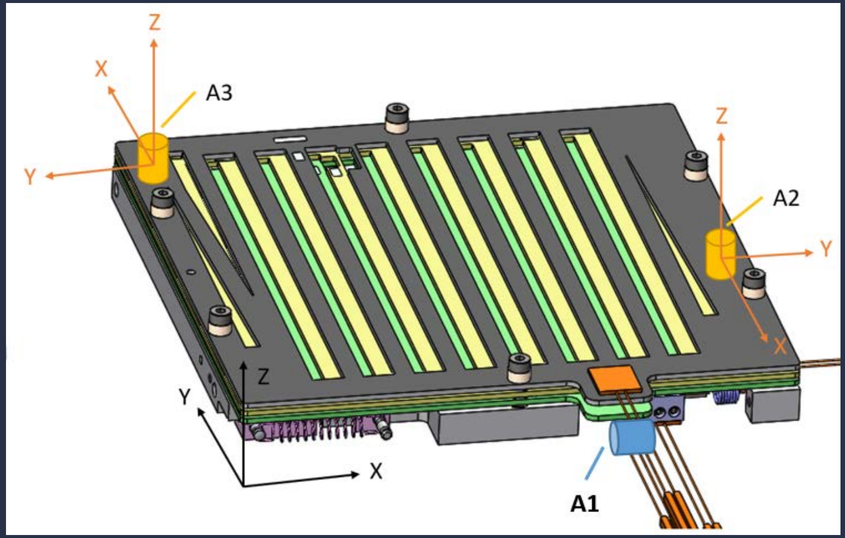
  A2 PCB 356A04 from CSEM SN 324996 NI : IKB.008

  A3 PCB 356A04 from CSEM SN 324997 NI : IF0.101





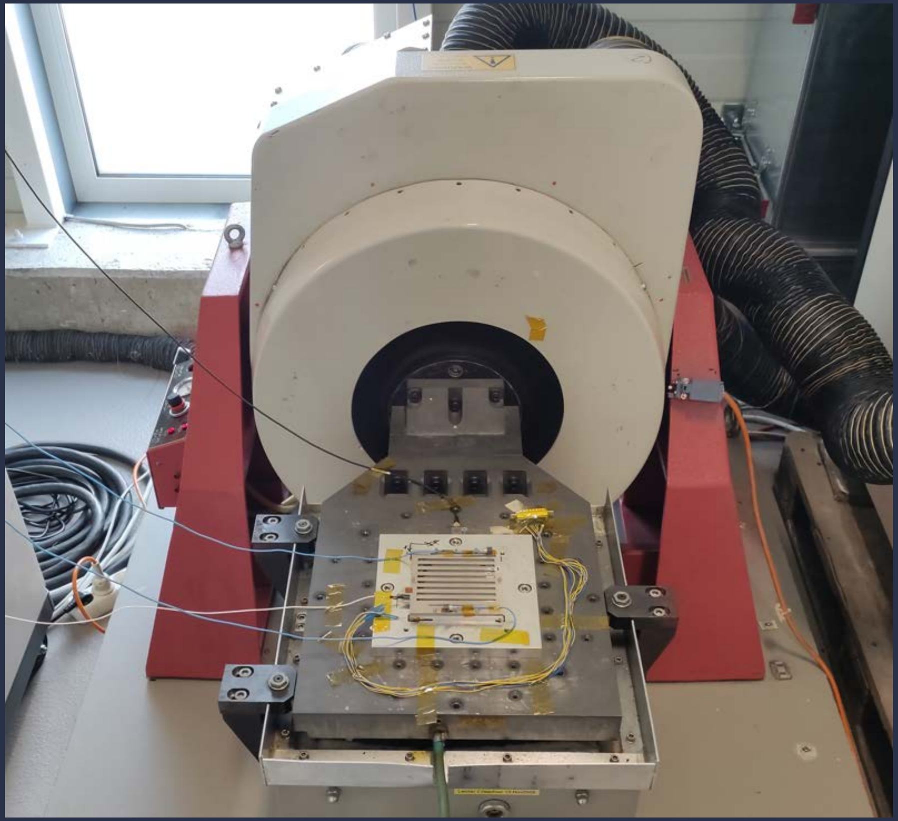


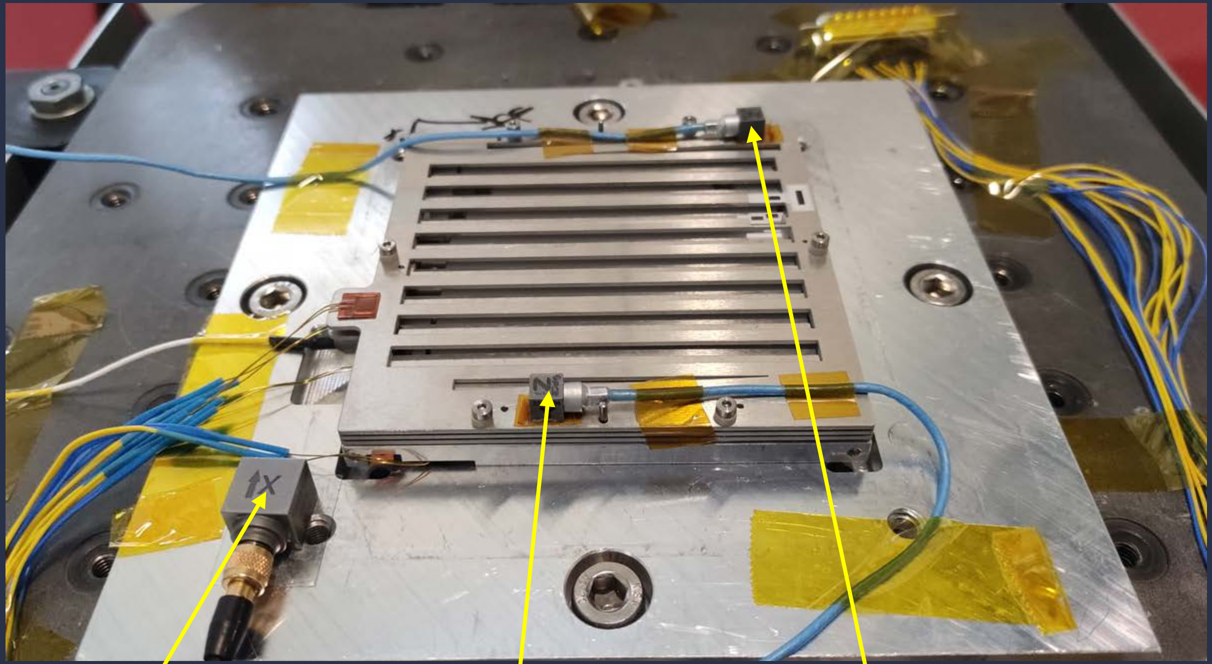


csem FOTEC

EM (BBM+) validation – Environmental vibration tests

- Mounting onto the vibration test device (Example: Y-axis)





Accelerometer A0 (Reference)

Accelerometer A2

Accelerometer A3

EM (BBM+) validation – Environmental vibration tests

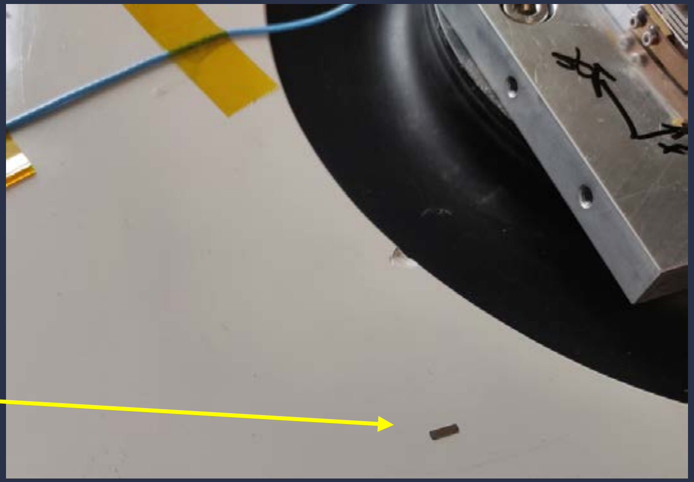
- Conclusion
  - During the preparation of the vibration test, a few minor issues were observed, and a solution implemented by machining a slot in the baseplate to allow room for the A1 accelerometer.
  - The vibration tests (Sine and Random) in the X and Y direction were performed successfully as planned. A verification of the sine sweeps with the modal analysis showed frequencies corresponding very well with the simulations.
  - For the vibration tests in the Z-direction, the A1 sensor became detached and had to be re-glued. At the end, the full level 0dB random vibration test was performed successfully.
  - The A1 sensor did not stay attached throughout the entire test sequence. The before/after sine sweep was performed by comparing the A2 and A3 sensors which showed no significant frequency shifts.

Conclusion

- The main areas to be pursued in the future to increase the difference of effective emissivity between OPEN/CLOSED configurations are:
  - Increase the number of slots from (e.g. 8 →10)
  - Review the number of movable grids (currently 2) to 3 or 4 which would reduce the area of the obstructing grids in the open configuration
  - Review and adapt coating baselines for grids as a function of envisioned application environment and operating conditions
  - Proof of concept project will allow us to evaluate impact and balance between thermal and mechanical requirements → useful for the future

Conclusion – Functional test after vibration tests

- After the vibration test campaign FOTEC performed a visual inspection and the reduced functional test
  - No damage observed except for two spacer elements during visual inspection
  - Functional test with hot air gun was successful except of unsteady movement of the louver



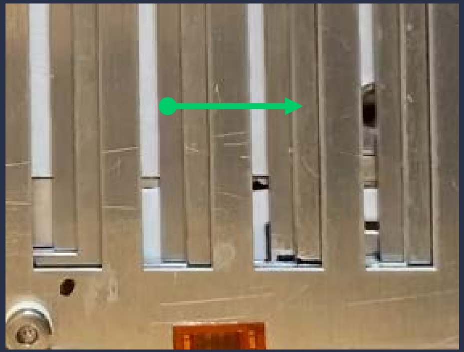
Found spacer after random vibration (Z-axis)

FOTEC video vs CSEM video (Horizontal config) - Opening

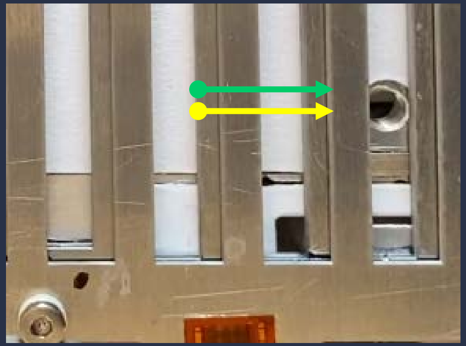
CSEM

BBM+ (EM) fully closed

Smooth single movement



Superposition of grids + Smooth simultaneous movement



BBM+ (EM) fully open

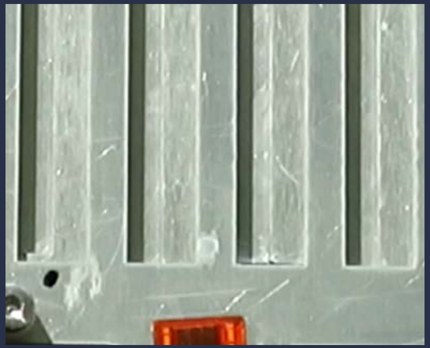
Top grid

Bottom grid

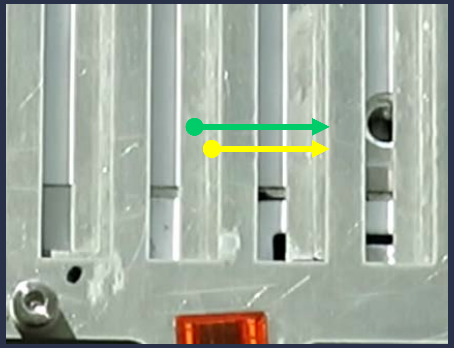
Ambient temperature → >110°C

FOTEC

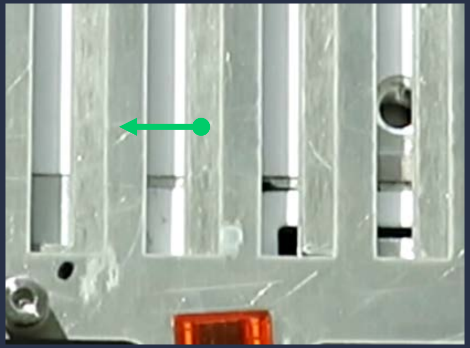
BBM+ (EM) fully closed



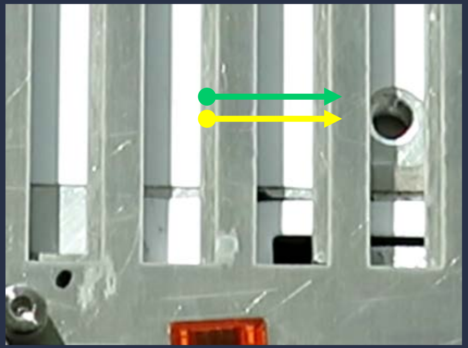
Smooth **simultaneous** movement



Back jump of **top grid** at ~ mid-stroke + superposition of grids



Smooth simultaneous movement



BBM+ (EM) fully open

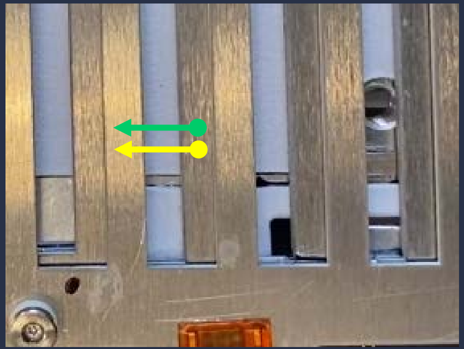
csem

FOTEC video vs CSEM video (Horizontal config) - Closing

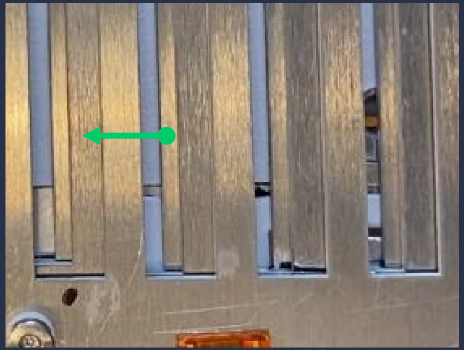
CSEM

BBM+ (EM) fully open

Superposition of grids + Smooth simultaneous movement



Jerky single movement



BBM+ (EM) fully open

Top grid

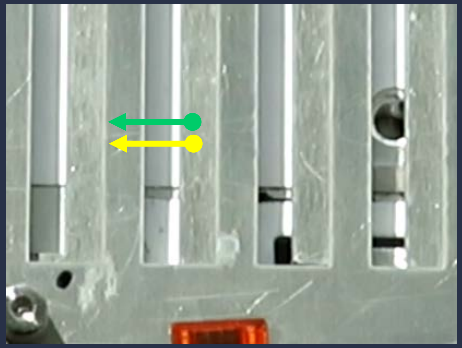
Bottom grid

>110°C — Ambient temperature

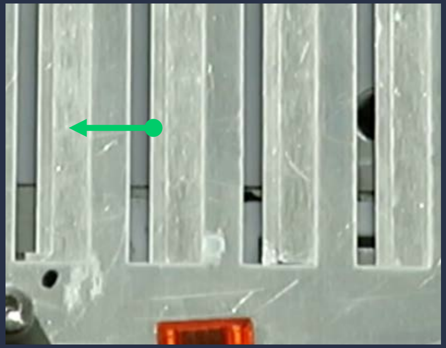
FOTEC

BBM+ (EM) fully open

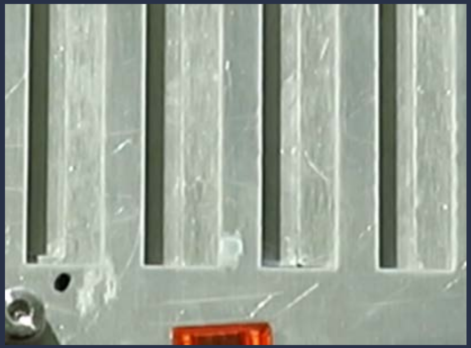
Superposition of grids + Smooth simultaneous movement



Jerky single movement



BBM+ (EM) fully open



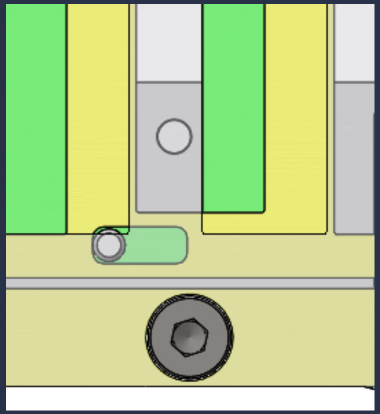
FOTEC video vs CSEM video (Horizontal config) - Conclusion

First conclusion after FOTEC vibration tests:

- Mechanism **closing** seems to work correctly
- Mechanism **opening** does not seem to work correctly.

First hypothesis:

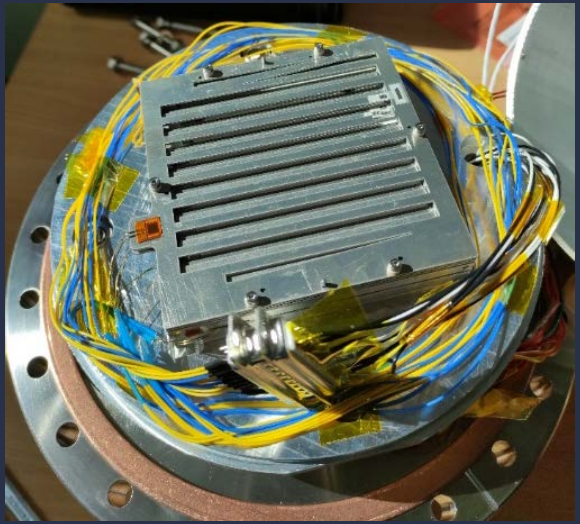
1. Friction between flexible grids (caused by vibration tests).
2. Misalignment between the actuation pin and the groove



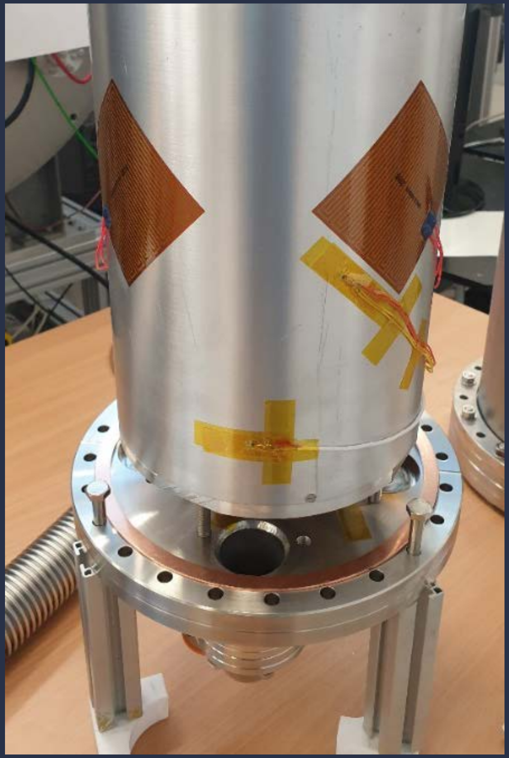
Inspection at CSEM after FOTEC tests determined the source being friction between the flexible grids due to detached spacers (see slide 67).

EM (BBM+) validation – Thermal Vacuum Cycling

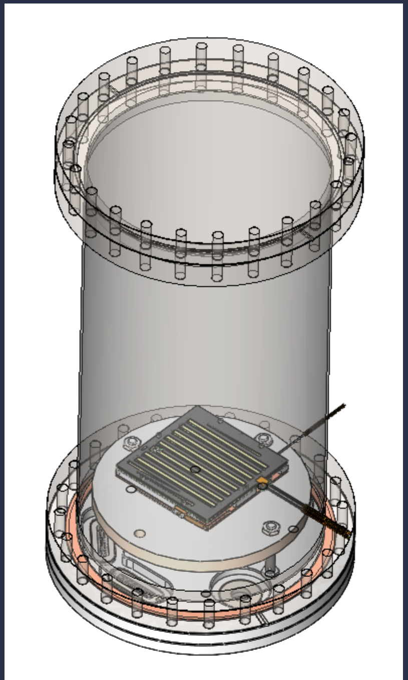
- TVAC tests followed the vibration tests



EM on I/F baseplate and cabling



Heater pads were installed (4 on the mantle of the chamber, 1 at the top and 1 at the bottom)



Complete setup (incl. EM and IF baseplate)

EM (BBM+) validation – Thermal Vacuum Cycling

- The campaign started at the high temperature point +100°C
- One thermal cycle had a duration of approx. 33 h.
- The cool-down to -60°C was quite slow, the decrease in radiative heat transport is quite noticeable.
- TVAC test campaign of 8 cycles successful, no damage after tests

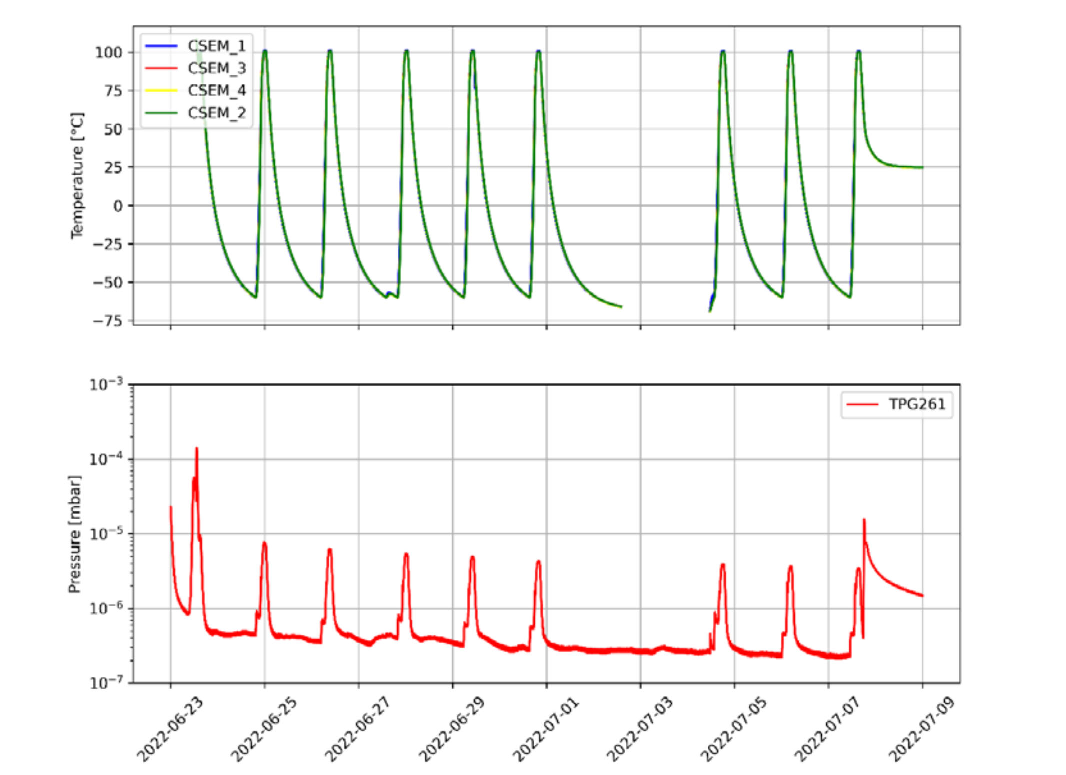
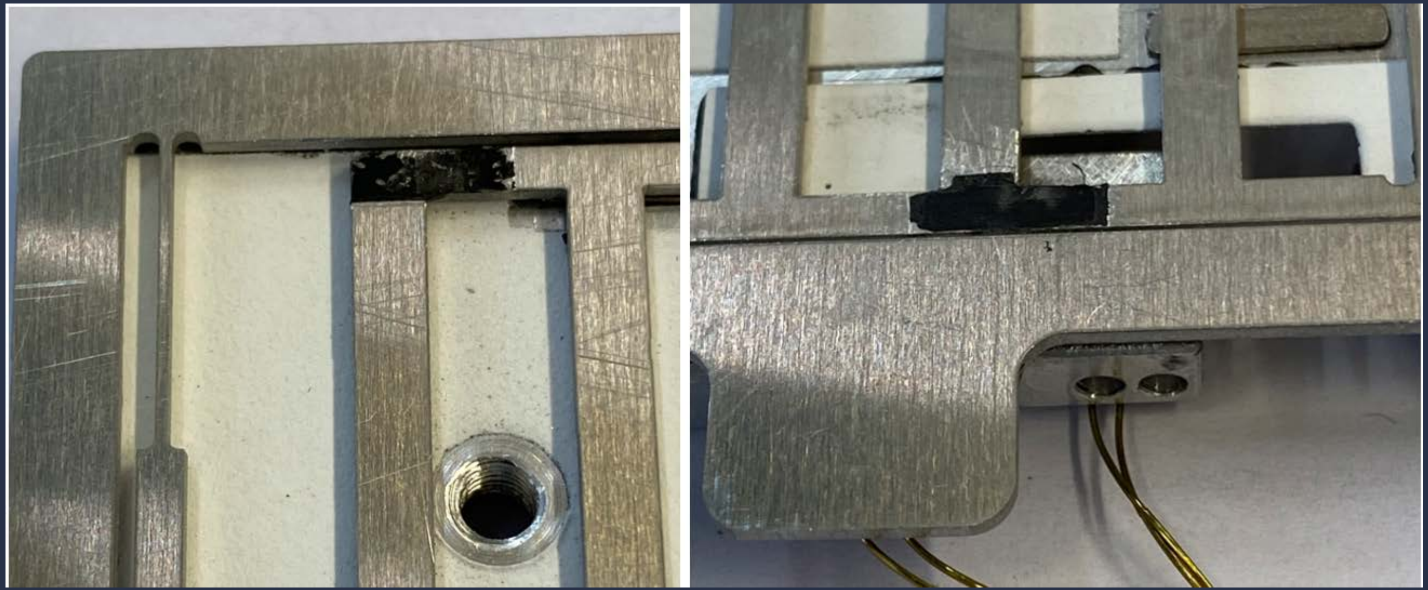


Table 5-13: Thermal cycling test main parameters

quantity	value
cycles	8
T_{min}	-60 °C
T_{max}	+100 °C
t_{hold}	1 h
temperature rate	est. 0.75-1.5 K/min

Full inspection at CSEM after environmental tests

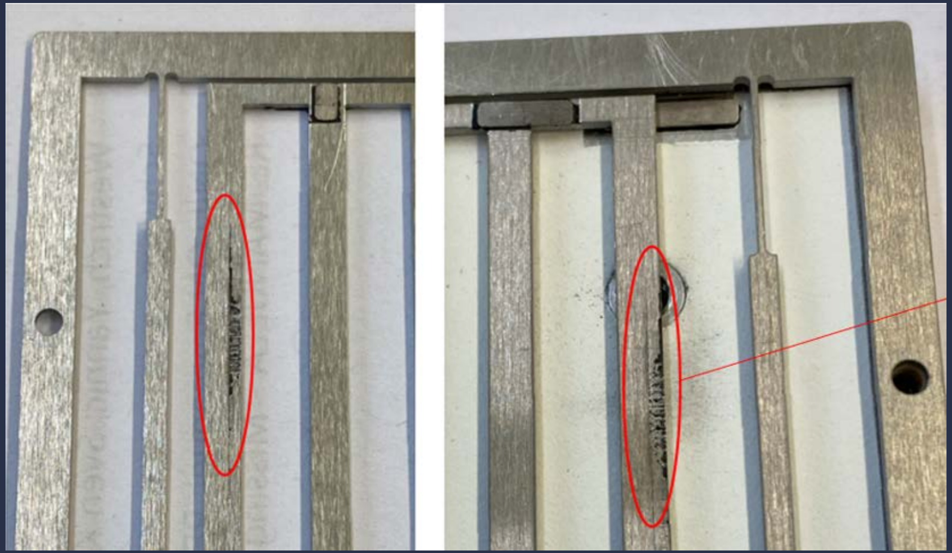
- Visual inspection & disassembly
  - All flexures remained intact, and no damage observed visually or during operation
  - 1 low friction spacer fallen off from top surface of top flex grid during vibration tests
  - 2 low friction spacers fallen off from top surface of bottom flex grid during vibration tests

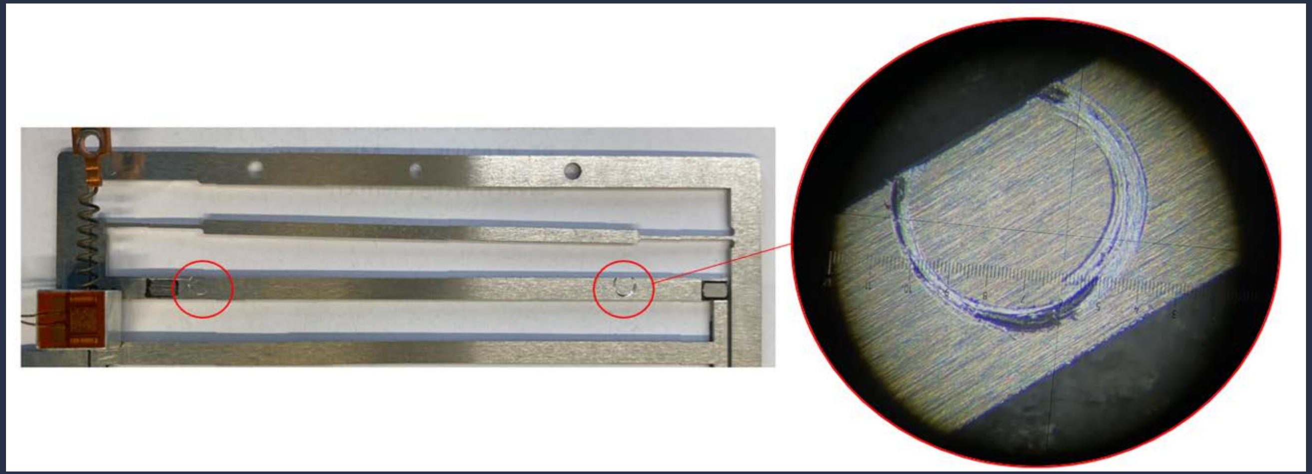


Missing spacer that fell off during vibration tests (top surface-bottom grid)

Full inspection at CSEM after environmental tests

- Visual inspection & disassembly
  - Wear marks between top and bottom grids during X-direction vibration tests (left): LLD blocks flex lower grid against end-stop but upper grid had additional movement due to pin/groove interface which allowed an additional 1-2mm displacement creating scratches
  - Cylindrical marks on bottom surface of bottom flex grid (right): FOTEC used screws that were slightly too long (~1mm). By screwing them, the screws pushed on the blades of the flex grid

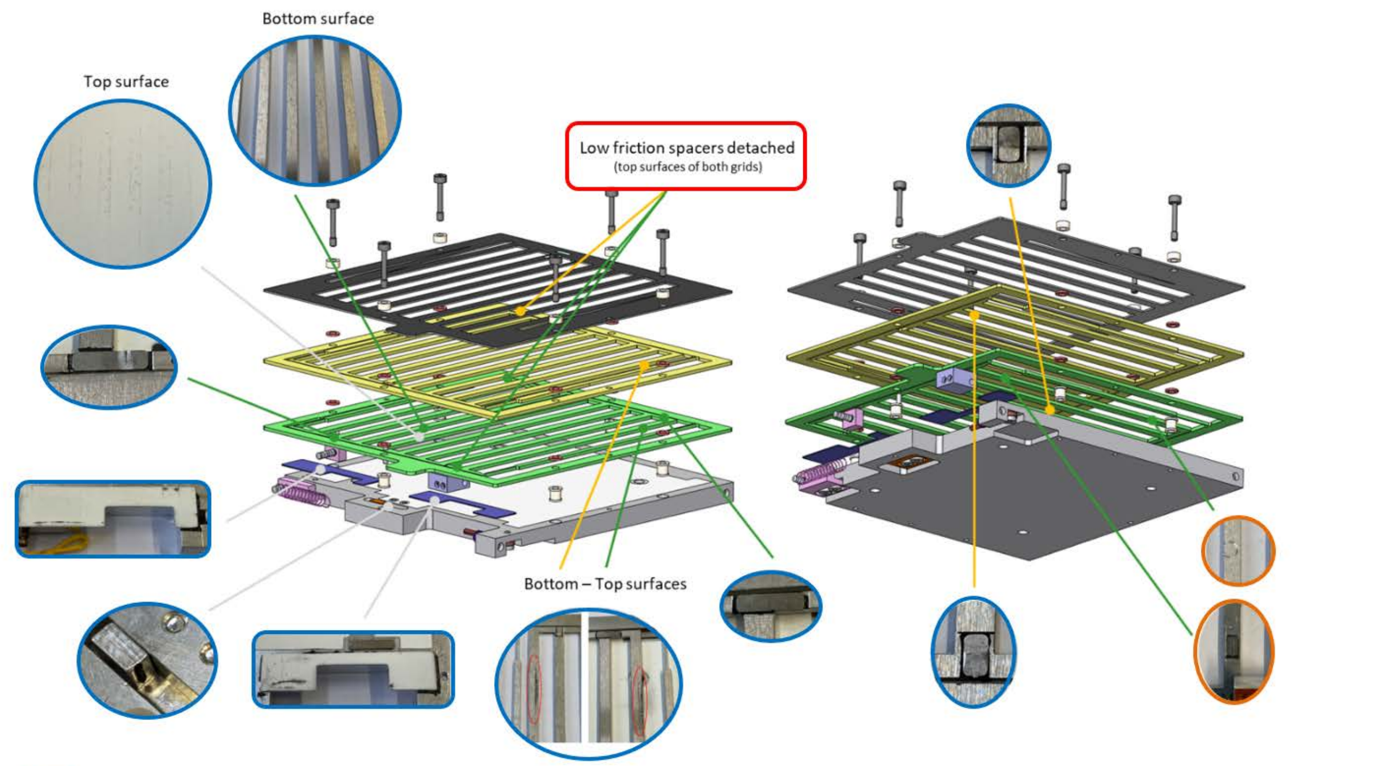




Full inspection at CSEM after environmental tests

- Visual inspection & disassembly resume

In the image below is a list of the observations made during inspection and source.



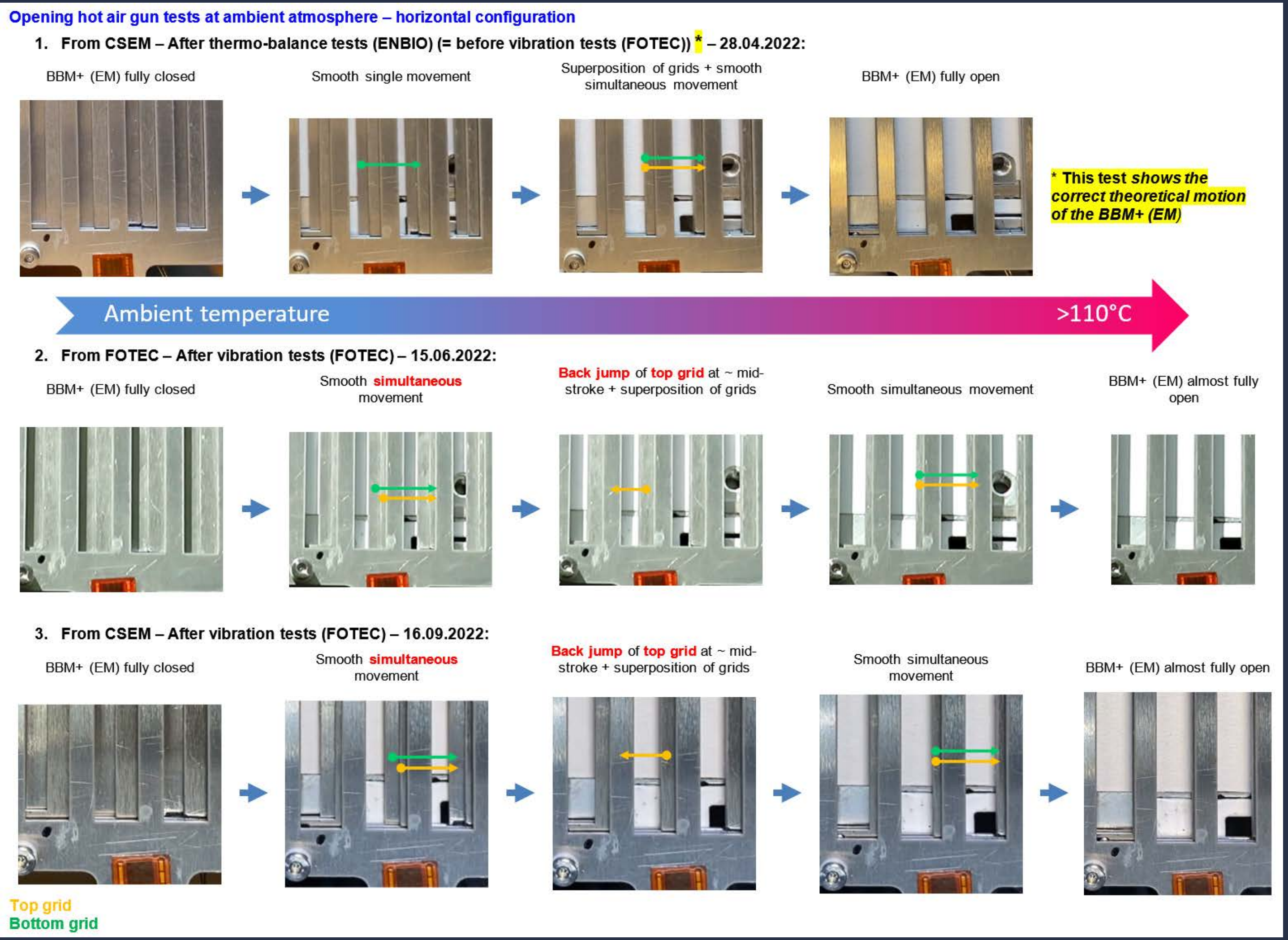
Impact marks related to vibration testing contact and abrasion. Does not affect movement.

Areas related to friction sources and jerky movement during operation (horizontal config.)

Handling error during assembly

Full inspection at CSEM after environmental tests

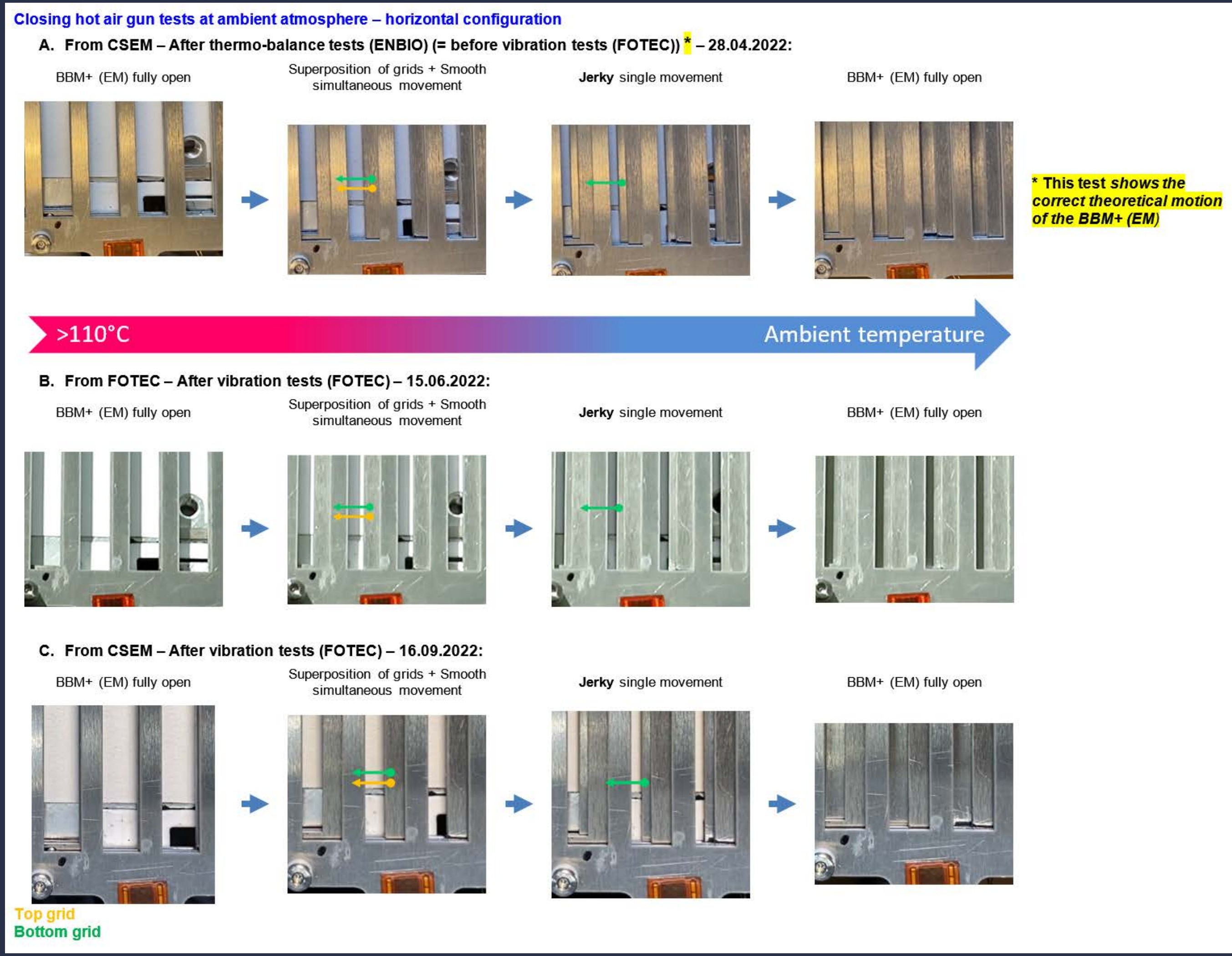
- Assembly & functional tests to compare with FOTEC tests



Full inspection at CSEM after environmental tests

- Assembly & functional tests to compare with FOTEC tests

  - Full displacement in open and closed positions is achieved.
  - A jerky movement is visible when opening the mechanism due to the two mobile flex grids being in contact with one another
  - The cause of this friction is primarily due to the low friction spacers that were detached during the vibration tests



Test Matrix compliance as per EM Test Plan (TN-08) (1/3)

Req ref.	Requirement	Status	Verif.	Comment
VTR1	The Cooler mechanism shall be subject to 8 thermal cycles over the temperature range specified in IR4 with a hold-time of 1hour at each temperature extreme.	C	R, A T	§7.5 Thermal cycling facility at FOTEC
VTR2	The Cooler mechanism shall be subject to sinusoidal tests for all axes with 1 sweep-up at 2 octaves per minute.	C	A, T	§7.4 FOTEC vibration tests
VTR3	The Cooler mechanism shall be subject to random vibration for the duration of 2.5 minutes per axis.	C	A, T	§7.4 FOTEC vibration tests
VTR4	Thermal performances of the Cooler mechanism shall be measured. In particular effects of aging of thermo-optical properties shall be quantified.	C	T	§10.1 Verified at sample level by ENBIO before & after Humidity ageing cycling
VTR5	Simulation of heat load variations shall be performed (by increasing and decreasing the applied heat load).	C	A	§7.3 ENBIO Thermal Balance tests done
VTR6	The actuator shall be life-time tested with 40’000 operational cycles according to AD3	C	T	§10.2 Nimesis tests achieved 300’000 cycles with 1 N load without failure
VTR7	The insulation of the electrical wires shell be not less than 100 MΩ measured with a DC voltage of 500 V applied.	NA	T	§6.2.1 NA since no electrical components in mechanism
VTR8	The Cooler mechanism shall be electrically bonded, and this point shall be test it as per AD3.	PC	T	§6.2.2

Test Matrix compliance as per EM Test Plan (TN-08) (2/3)

Req ref.	Requirement	Status	Verif.	Comment
FPR1	The Cooler mechanism shall be able operate in vacuum and 10 mbar of CO_2.	C	T	§7.2.3 Tested on BBM & EM
FPR3	The COOLER mechanism shall be designed to reject heat in the range 0.1 W to 10 W.	NC	A	§7.3.4 ENBIO Thermal Balance tests & HERON TN-09 For closed configuration, ~2.34 W to reach 90°C For open configuration, ~3.40 W to reach 90°C
FPR5	The actuator shall guarantee the opening/closing of the within a minute from the moment the opening/closing temperature is reached.	C	T	§7.2.4 Tested on BBM and BBM+ Reactivity of the SMA is dependent on the rate of change of the heat source. (0.076mm / min)
FPR6	Stability of the opening and closing set points shall be ± 1°C.	C	T	§7.2.5 Tested on BBM and BBM+
FPR8	Temperature sensors shall be used to command the active actuator or as monitoring sensors for passive actuator.	C	R, T	§7.2.6 Passive actuation
FPR11	Parasitic heat entering the system in closed configuration shall be less than 15 W/m2.	C	A	Will require additional MLI, ENBIO Thermal Balance tests performed
IR4	The Cooler mechanism shall have a full closed to full open temperature range of 15°C to 20°C (heating) Selected/adjusted within the range -50°C to 90°C.	NC C	A, T	§7.2.7 Heating range (closed→open) 54°C CSEM data §7.2.7 Cooling range (open→close) 60°C CSEM data Nimesis alloy CuAlNi 39 - 69°C

Test Matrix compliance as per EM Test Plan (TN-08) (3/3)

Req ref.	Requirement	Status	Verif.	Comment
ER1	The qualification temperatures for the Cooler mechanism are the temperatures derived from IR4 and extended on both extremes by 10K.	C	A, T	§7.5 Thermal cycling facility at FOTEC
ER2	The Cooler mechanism shall sustain the following mechanical environment in each of the 3 orthogonal axes : - Sinus (from AD4): *see thumbnail ER2 Tables* - *Random (from AD4): see thumbnail ER2 Tables*	C	A, T	§7.4 FOTEC vibration tests
ER4	The Cooler mechanism shall be able to work in every position with respect to gravity acceleration (Earth, Moon, Mars) and in 0g.	C	A, T	§7.1.1 – 7.1.3 Tested on BBM & EM
DR3	Fatigue life demonstration shall be performed in conformance with AD2.	C	S+A T	For any Flexures & structure §10.2 For actuator, see VTR6 (Nimesis tests)

Outline

- Overview of critical specifications
- Concept trade-off & Breadboard selection
- BBM Test results and EM (BBM+) selection for Test campaign
- FEM analysis (Mechanical & Thermal)
- EM Assembly
- EM Test campaign
- **EM Correlation**

EM Correlation

Outline

- The goal is a thermal correlation between measurement and FEM & network results
- Central is ε_{eff} of the louver in open and closed configuration
- Tells how much heat Q is expelled from T_h to T_e
- Unavoidably, measurements include heat losses : radiation, conduction
- Need to separate $Q \rightarrow \varepsilon_{eff}$ from losses in Q_R and Q_C
- As reference use aluminium sheet with known ε_{eff}
- Parameters extracted from measurements are R_R and R_C

EM Correlation

- Model for $T(t) = T(R_R, R_C, t, \ldots)$, based on a single temperature
- Energy balance, conservation
- Differential equation, $\mathrm{d}T/dt = T_t(R_R, R_C, C_P, t)$
- Measurements deliver $T(t)$
- Options to fit
  - 1. Integrate the differential equation $\rightarrow T(t)$
  - 2. Differentiate $T(t)$ from the measurements
- Option 1 with numerical integration, Runge Kutta 4 step
- Option 2 with e.g. running average, local regression, …

EM Correlation

- Three equations for R_R, R_C, C_P
- The slope fitting results have discrepancy with steady-state results
- Use the steady results, P to keep T_h, and reduce equations to two
- Slope fitting results depend on which t_1 and t_2 you measure dT/dt
- Variation in fitted parameters, uncertainty errors
- Use regression analysis on $T(t)$ with initial guess from slope results
- Use aluminium sheet to find radiation heat losses
- Correct louver open and closed, and also Solar Black, and find ε_{eff}

EM Correlation

- Some anomalies in measurements of Solar Black
- Fitted ε_{eff} of is 0.6 instead of 0.8
- Correction for ε_{eff} of shroud is minimal
- Results for louver open and closed within 6% of numerical predictions
- This includes estimate of radiation heat loss of louver through sides
- Conclusion : good agreement between measurement and predictions
- Observations from TN-06 unchanged

EM Correlation - recommendations

- Original requirements were to reject heat in the range 0.1 W to 10 W.
- Assume operating temperatures from -20 C to + 40 C
- Then, in practice the requirement should be from 0.15 to 4.4 W
- The louver rejects from 0.3 closed to 1.8 W open
- Number of blades was reduced from 5 to 2 for mechanical reasons
- With obtained experience check if this number can be increased to 3
- That would lift the open heat rejection, but with limited improvement
- Re-visit previous concepts

Requirements / performance comparison

ESA requirements and COOLER performance			Color code :	yellow	input	
				red	required	
				green	outcome heatflow	
Parameters				Demand :		
Highest oper. temp	313	K	Closed	0.1	W	
Lowest oper. Temp	253	K	Open	10	W	
space temp	5	K		100	required heat rejection ratio	
sigma	5.67E-08	W/(m2K4)		9.9	W difference	
Area	0.01	M^2				
What Is possible ?						
Some values			Then :			
min eps : alu	0.064		Q out fixed surf H	0.035	@ high oper. Temp	
max eps : solar white	0.90		Q out fixed surf L	0.015	@ low oper. Temp	
opening fraction	0.90		Q var open H	4.407	@ high oper. Temp	
			Q var closed L	0.134	@ low oper. Temp	
			Qmax	4.442	W	
			Qmin	0.149	W	
				29.9	heat rejection ratio	
				4.3	W heat difference	
		COOLER	eps_max	0.330	Take from simulations	
			eps_min	0.130	or from measurement	
			Qopen	1.796	W	
			Qclosed	0.302	W	
				5.9	COOLER heat rejection ratio	
				1.7	W heat difference	

Requirement feedback / performance comparison

Req ref.	Requirement	Status	Verif.	Comment
FPR1	The Cooler mechanism shall be able operate in vacuum and 10 mbar of CO_2.	C	T	§7.2.3 Tested on BBM & EM
FPR3	The COOLER mechanism shall be designed to reject heat in the range 0.1 W to 10 W.	NC	A	§7.3.4 ENBIO Thermal Balance tests & HERON TN-09 For closed configuration, ~2.34 W to reach 90°C For open configuration, ~3.40 W to reach 90°C
FPR5	The actuator shall guarantee the opening/closing of the within a minute from the moment the opening/closing temperature is reached.	C	T	§7.2.4 Tested on BBM and BBM+ Reactivity of the SMA is dependent on the rate of change of the heat source. (0.076mm / min)
FPR6	Stability of the opening and closing set points shall be ± 1°C.	C	T	§7.2.5 Tested on BBM and BBM+
FPR8	Temperature sensors shall be used to command the active actuator or as monitoring sensors for passive actuator.	C	R, T	§7.2.6 Passive actuation
FPR11	Parasitic heat entering the system in closed configuration shall be less than 15 W/m2.	C	A	Will require additional MLI, ENBIO Thermal Balance tests performed
IR4	The Cooler mechanism shall have a full closed to full open temperature range of 15°C to 20°C (heating) Selected/adjusted within the range -50°C to 90°C.	NC C	A, T	§7.2.7 Heating range (closed→open) 54°C CSEM data §7.2.7 Cooling range (open→close) 60°C CSEM data Nimesis alloy CuAlNi 39 - 69°C

- **In practice (operating temp -20 to +40°C) the requirement should be from 0.15 to 4.4 W**
- **Louver rejects from 0.3 W closed to 1.8 W open**

Conclusion

- Simple and robust flexure mechanism developed and tested
- Performance tests under vacuum conditions successful
- Environmental tests (sine & random vibration, thermal vacuum cycling) completed successfully with minor wear on mechanism
- Thermal balance tests and thermal simulation model correlation in good agreement
- Requirements and performance:
  - Initial requirements to reject heat in the range 0.1 W to 10 W very ambitious without a specific applicable temperature range. Based on the tests and simulation data the maximum heat rejection would be 4.9W
  - Tests show that mechanism rejects 2.3 W (Closed) and 3.4 W (Open) with a baseplate temperature of 90°C.
  - With assumed oper. Temp. -20°C to +40°C, requirements would be 0.15 to 4.4 W.
  - Simulations show louver mechanism would reject from 0.3 W closed to 1.8 W open (at +40°C)

Thank you for your attention

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