DEVELOPMENT AND INTEGRATION OF EMBEDDED SENSORS FOR ADVANCED MANUFACTURING PROCESSES (DIESAMP)

Final Presentation – Jan 2025

DISCALAIMER

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AGENDA

- Presentation of the DIESAMP project.
- Results of the trade-off studies and concept selection
- Product and Breadboard design
- Results of Breadboard testing
- Future developments

PROJECT OBJECTIVES

Select and develop a **space products** integrating **embedded sensors** using **Advanced Manufacturing** (AM) techniques and mature the concept to **TRL 4/5** through **breadboarding** and testing .

THE CONSORTIUM

PRIME CONTRACTOR

Expertise: System integration
Product selection
Product design and manufacturing
Project management

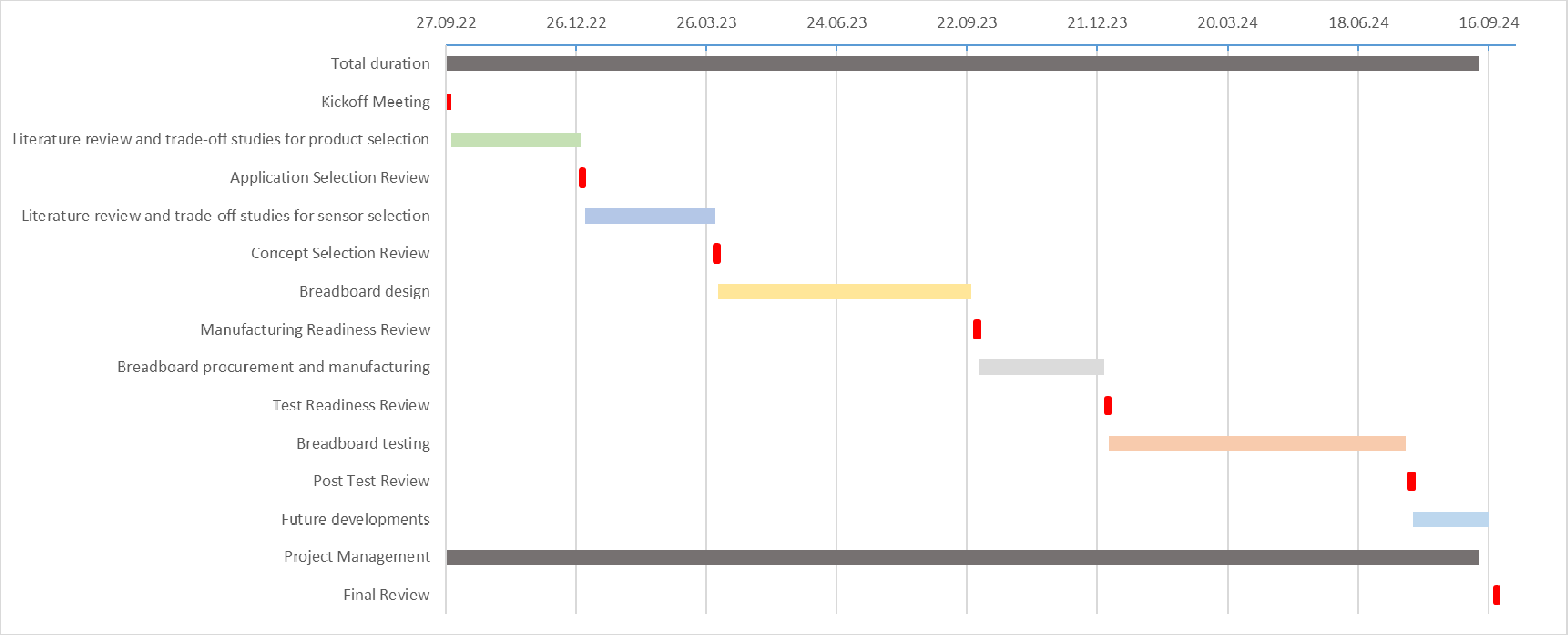
Technical coordination: Luca Celiento

SUBCONTRACTOR

Expertise: Sensor selection
Sensor design and manufacturing
Testing

Technical coordination: Sebastjan Glinsek

PROJECT SCHEDULE

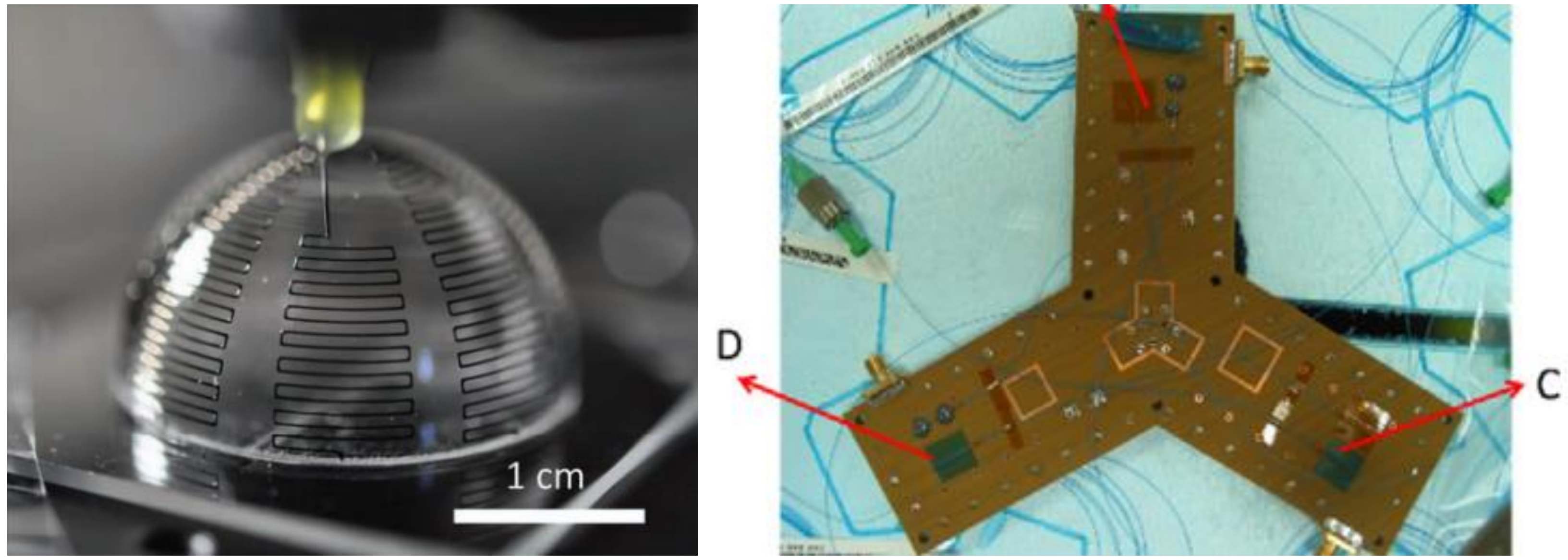


SPACE PRODUCT SELECTION

SPACE PRODUCT SELECTION

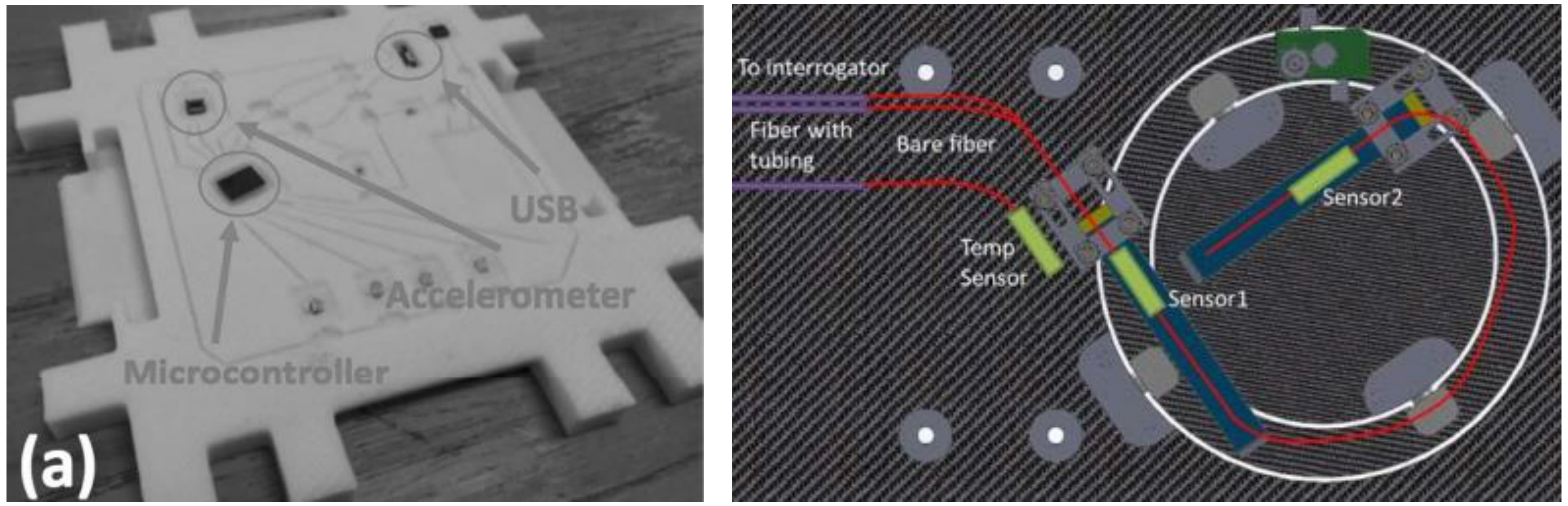
Application survey: traditional space applications

Antennas



Printing process of Antenna over hemispherical surface(left), 9 FBG sensors placed on inner layers and surface on a Mars ROVER divider sample (right).

Structures



Pre-wiring embedding of the fabricated Cubesat demonstrating multiple fabricating points (left), back side of the Smart Panel with embedded sensors (right).

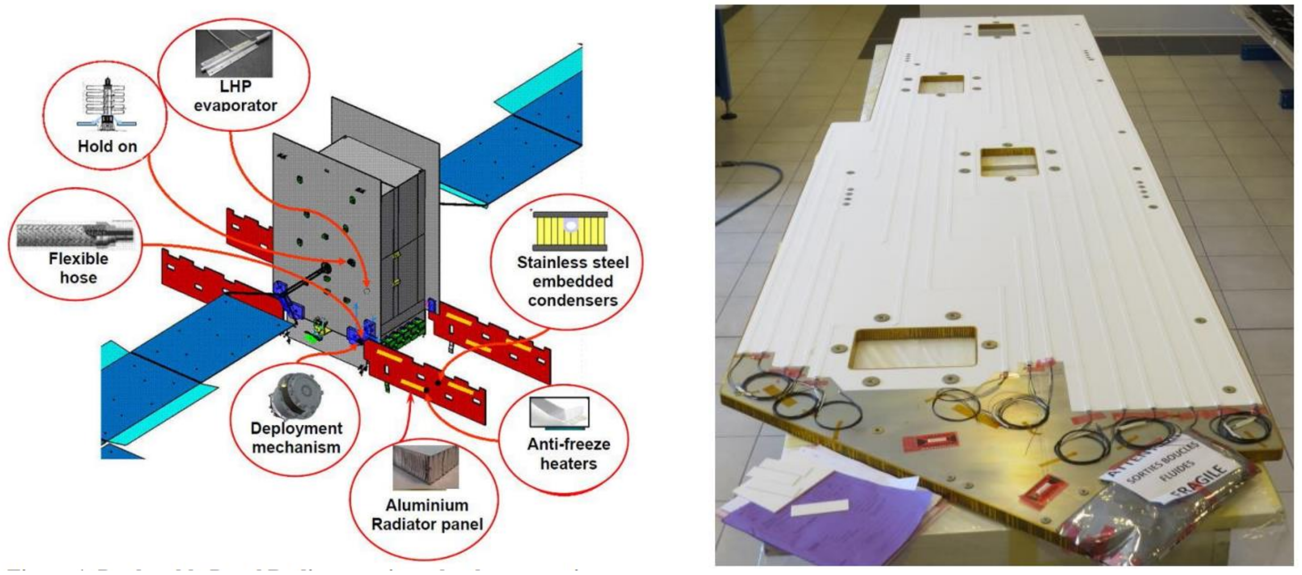
Pressure vessels

Composite tanks with embedded optical-fibers sensors (NASA).

Multi-Layer Insulation

MLI Blankets showcasing internal fibre netting.

Radiators

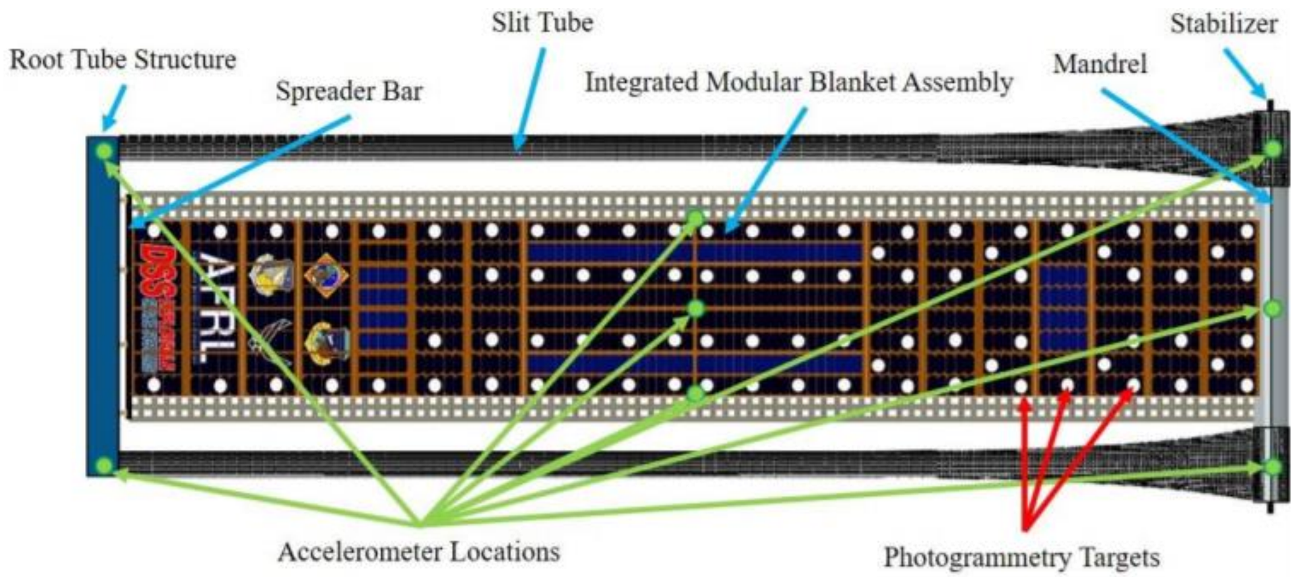


Technological Overview of Deployable Panel Radiator (left), Breadboard of embedded DPR (right).

SPACE PRODUCT SELECTION

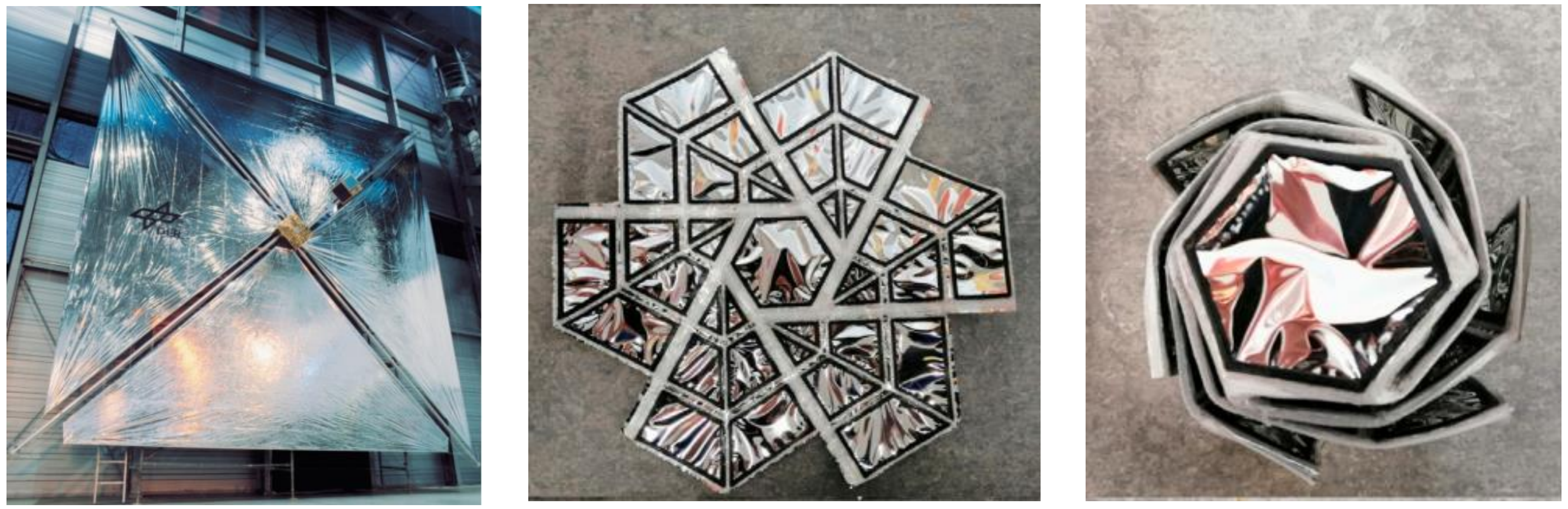
Application survey: deployable structures

Solar Arrays



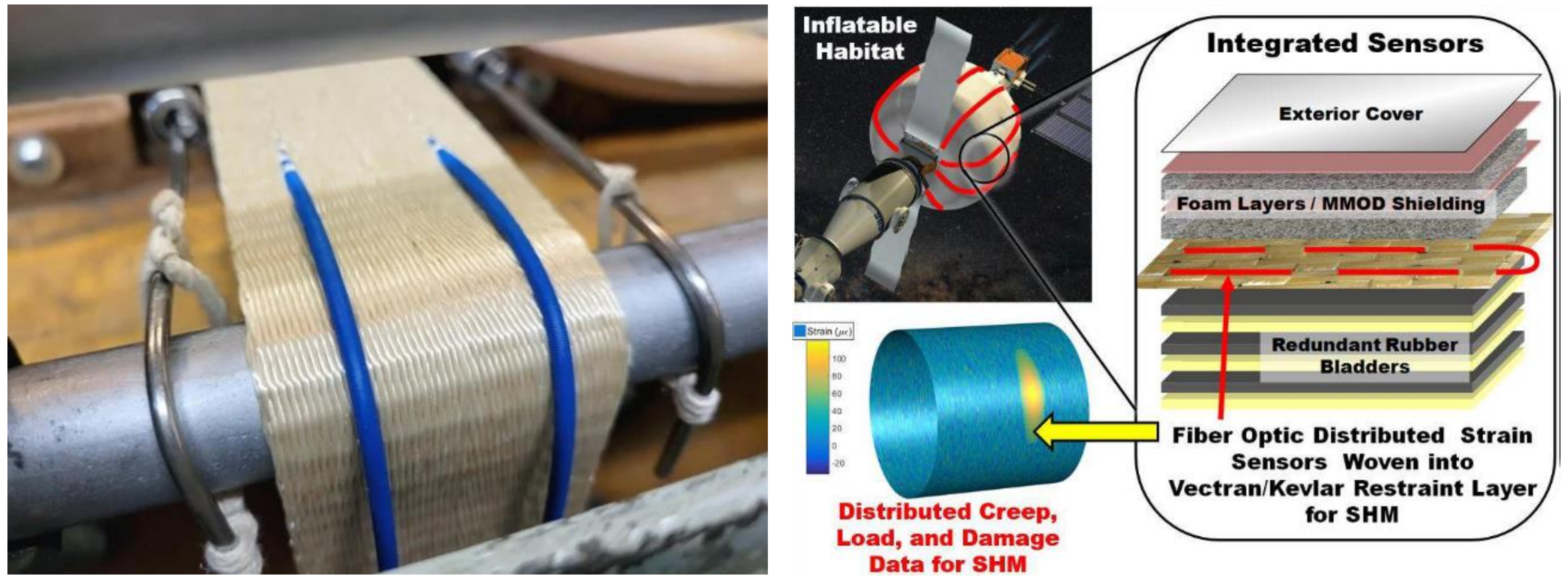
Instrumentation and sensors embedded in the Rollout Panel of the ISS ROSA flight experiment.

Solar Sails



Deployed Solar Sail Mockup at DLR (left) and deployed/folded (center/right) solar sail feasibility model.

Human-rated inflatable structures



Integrating FBG Sensors woven within the VECTRAN webbing (Left), Embedded Sensors for inflatable habitat by LUNA (Right).

Inflatable systems for re-entry

Inflatable Reentry Vehicle Experiment (IRVE, right) and LOFTID Flight Demonstrator post launch (right).

SPACE PRODUCT SELECTION

Figures of Merit for space product selection

Objective: selection of a shortlist of an application to be developed during the activity

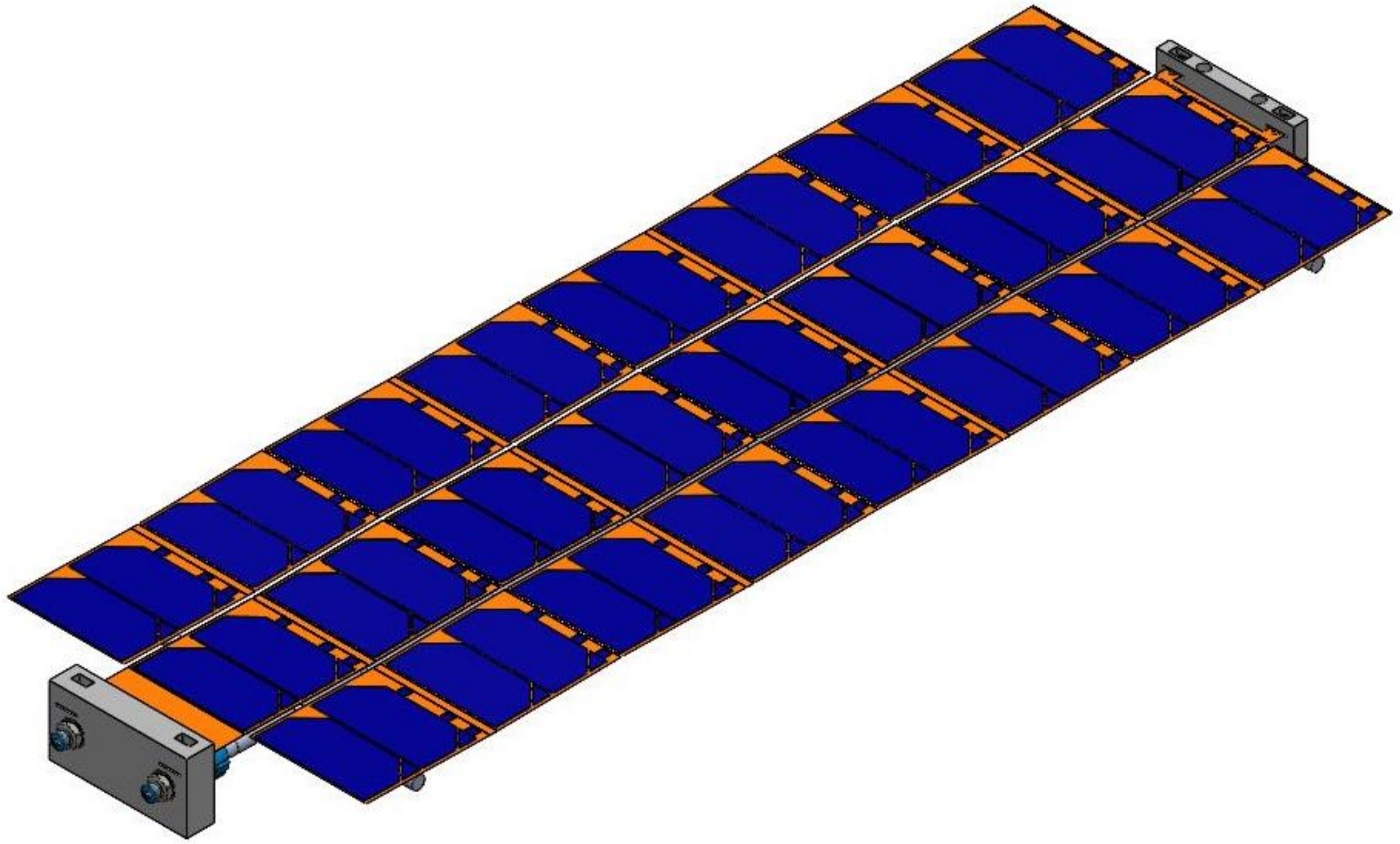
Figures of Merits: weighted through Analytic Hierarchy Process (AHP)

Figure of merit	Definition	Multiplier
Life-cycle	Impact of the embedding the sensors through advanced manufacturing techniques through product life cycle.	[x0.04]
Technological benefit	Benefit of sensor embedding to the performance of the mission of the product.	[x0.29]
Economic benefit	Advantage in terms of revenues resulting from the embedding of sensors.	[x0.29]
Manufacturing adaptability	Qualitative impact of the complexity of the manufacturing process of the product with the embedded sensors.	[x0.12]
Manufacturing complexity	Complexity of the testing campaign, either because of availability of reactants or safety concerns	[x0.08]
Cost	Assessment of the cost increase to embedding of sensors in comparison to the standard configuration in terms of CapEx and OpEx.	[x0.18]

SPACE PRODUCT SELECTION

Trade and product selection

Applications	Score
Antenna	0.51
Composite Structure	0.67
Pressure vessels/tanks	0.52
Multi-layer insulation	0.66
Radiators	0.56
Deployable solar array	0.81
Deployable solar sail	0.47
Human rated inflated structure	0.45
Inflatable systems for re-entry vehicle	0.54
ISRU radiators	0.16
ISRU crucibles	0.38



- The Minimum Viable Product (MVP) is a lightweight **flexible solar array**.
- Mechanism for stowing can be either **rollable or foldable**.
- Interesting for the **small sat market** as a low cost, low mass solution for the power generation, currently not existing on the market.
- Can be **scaled up** for other classes of satellites.

SPACE PRODUCT SELECTION

Product and sensors requirements

ID	Type	Text
DSA-MIS-001	Mission	The DSA shall provide a peak power of **50W BOL** to a **CubeSats** platform in **LEO** orbit.
DSA-MIS-002	Mission	The DSA shall provide a minimum of TBD% of the BOL power peak after 1 year of mission in LEO orbit.
DSA-MIS-003	Mission	It shall be possible to integrate **2 DSA modules in 1U CubeSat**.
DSA-MIS-004	Mission	It shall be possible to launch the DSA on board of Ariane 5 (TBC), **Falcon 9** and the Vega (TBC).

Manufacturing depends if either flexible or rigid cells are implemented:

- **Rigid cells** cannot be bended and must be integrated on a foldable blanket. The use of **flexible-PCBs** is recommended. Sensors can be integrated on a sockets and encapsulated.
- **Flexible cells** can be integrated with flexible or bendable blanket. It is recommended to **laminate** the cells within bottom and covers together with connections and sensors.

Due to constraints with supply chain, rigid cells were implemented. To be compatible with such technique, **sensors shall be thin** (i.e. <50% of thickness of flexible PCB), it shall be possible to connect them to **electrodes embedded** in the PCB and **encapsulate** them on Kapton.

Selected sensors shall monitor **strain** and **temperature**.

SPACE PRODUCT SELECTION

Relevant environment definition

Sensors shall be able to monitor the DSA during:

- **Launch**: monitoring of DSA status.
- **Orbital life**: monitoring of deployment operations, operational conditions and real-time predictions of performance degradation.

Vibrations and thermal-vacuum are identified as **relevant environment** for the sensors. Other environmental conditions (e.g. plasma and radiation) are not relevant for manufacturing process and sensors operability at TRL5.

Property	Value	Unit
Pressure	10^{-5}	mbar
Temperature (hot)	+120	°C
Temperature (cold)	-60	°C

Relevant thermal vacuum environment

Sine Load	Band [Hz]	Amplitude [g]
Longitudinal	2÷50	1.0
	50÷100	0.9
Lateral	2÷25	0.8
	25÷100	0.6

Relevant launcher environment for sine loads

Frequency [Hz]	PSD [g^2/Hz]
20	0.0044
100	0.0044
300	0.01
700	0.01
800	0.03
925	0.03
2000	0.00644
GRM	5.13

Relevant launcher environment for random vibrations

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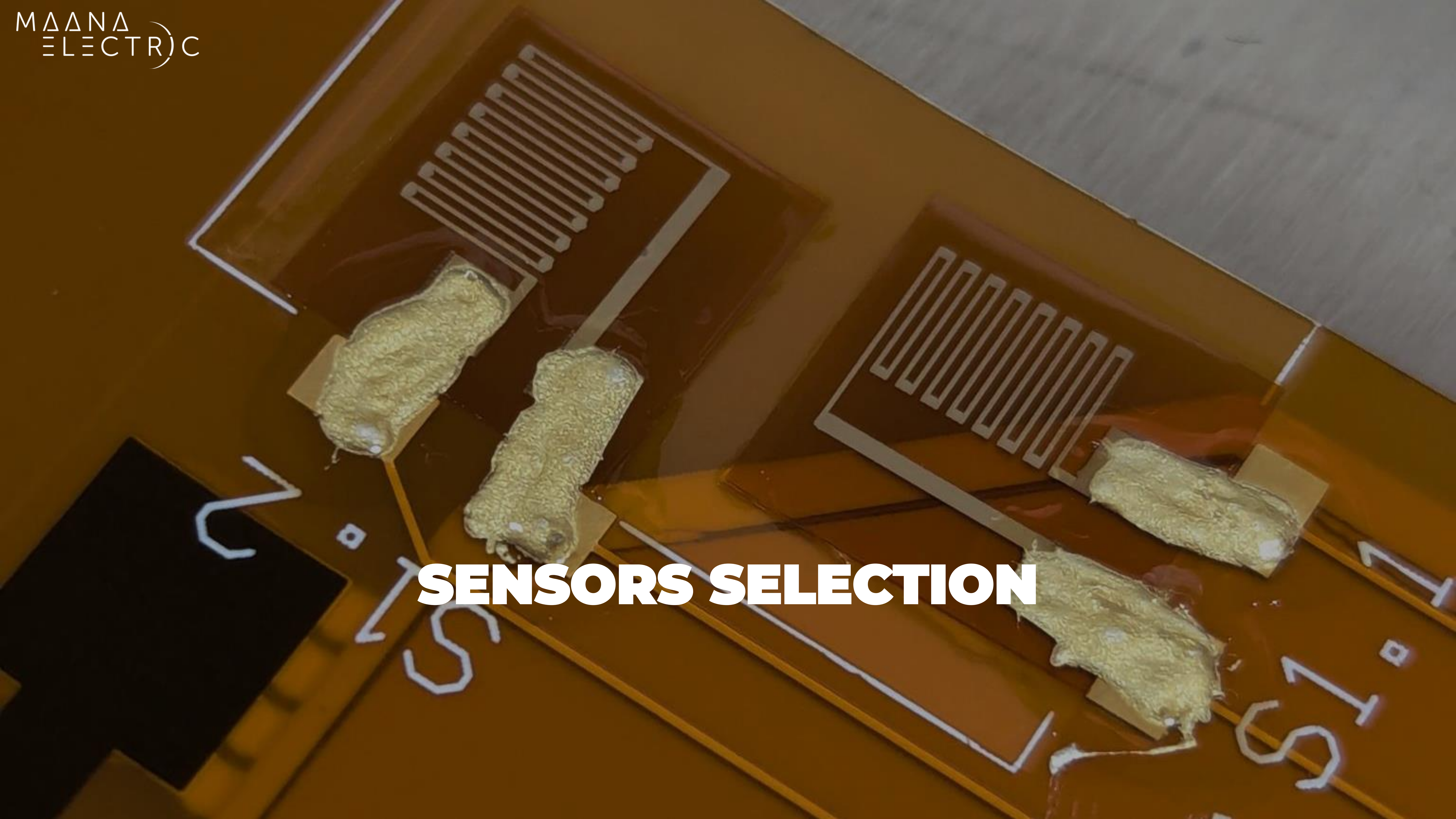
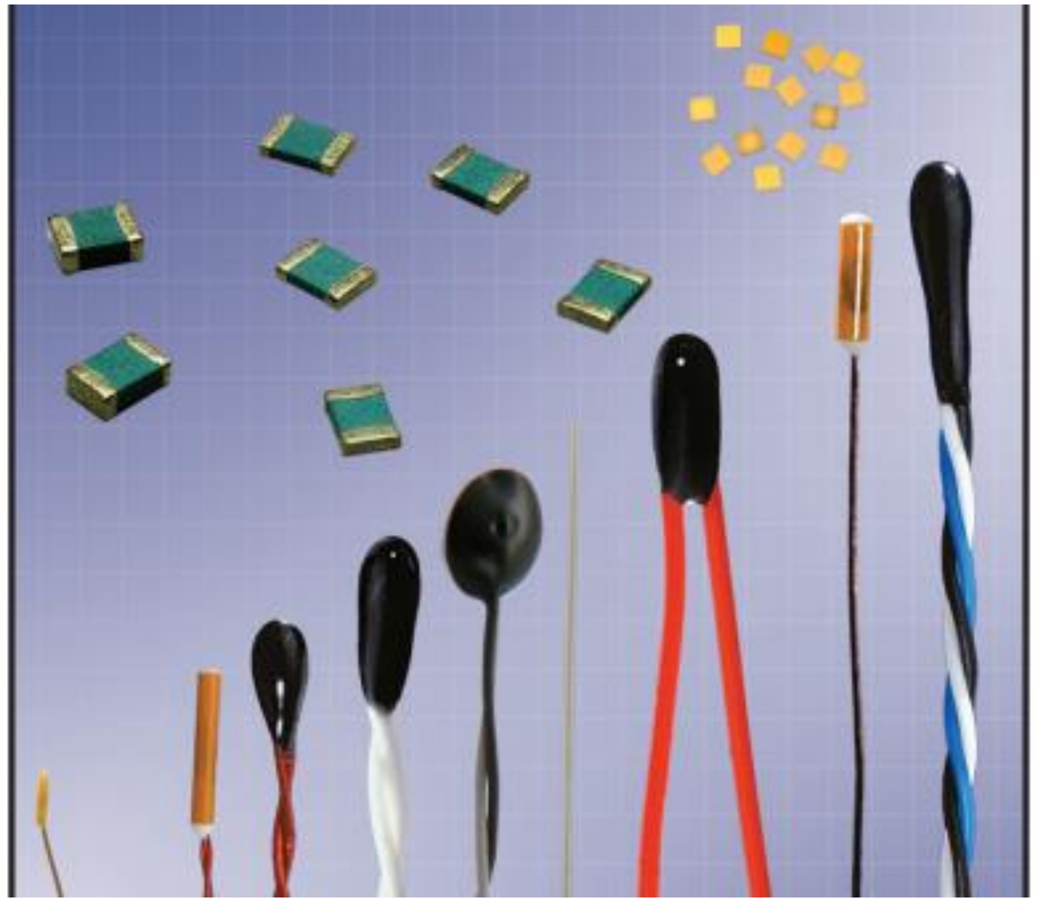


SENSORS SELECTION

SENSORS SELECTION

Commercial temperature sensors

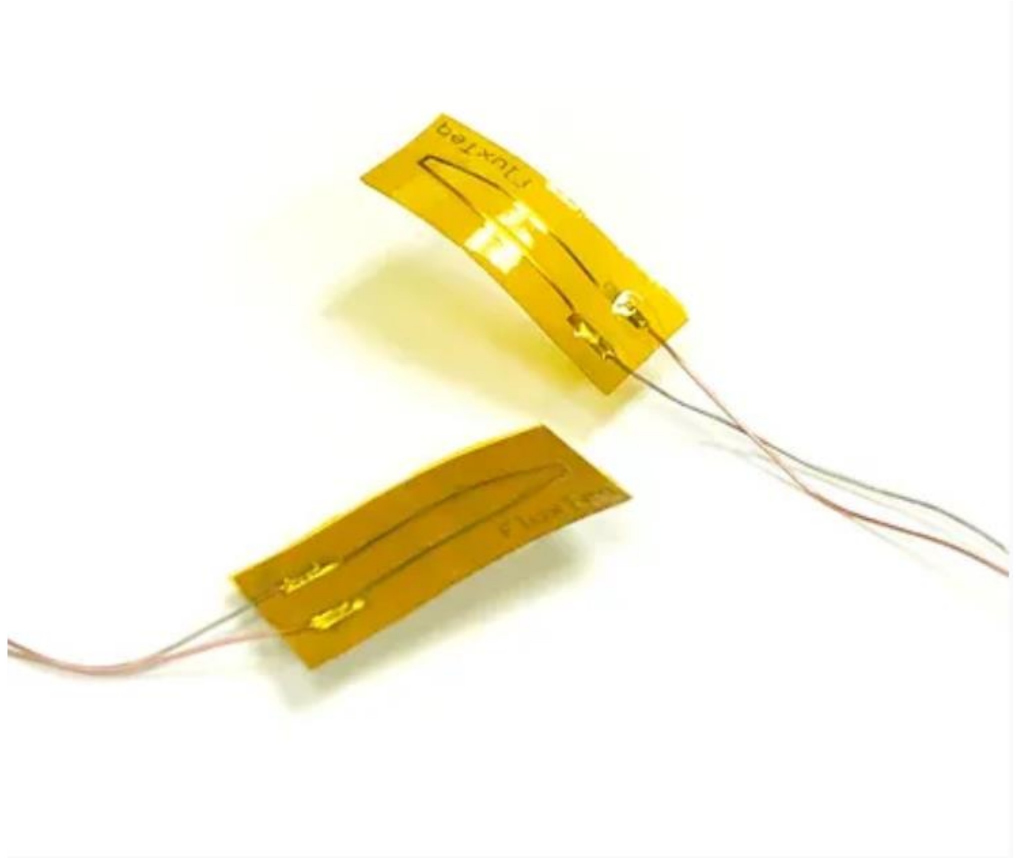
Thermistors



Lavenuta, QTI Sensing Solutions, White Paper

- Change of resistance in semiconductor with temperature.
- NTC (decrease with temperature) and PTC (increase with temperature) types.
- Common in space applications (ESCC No. 4006/014).

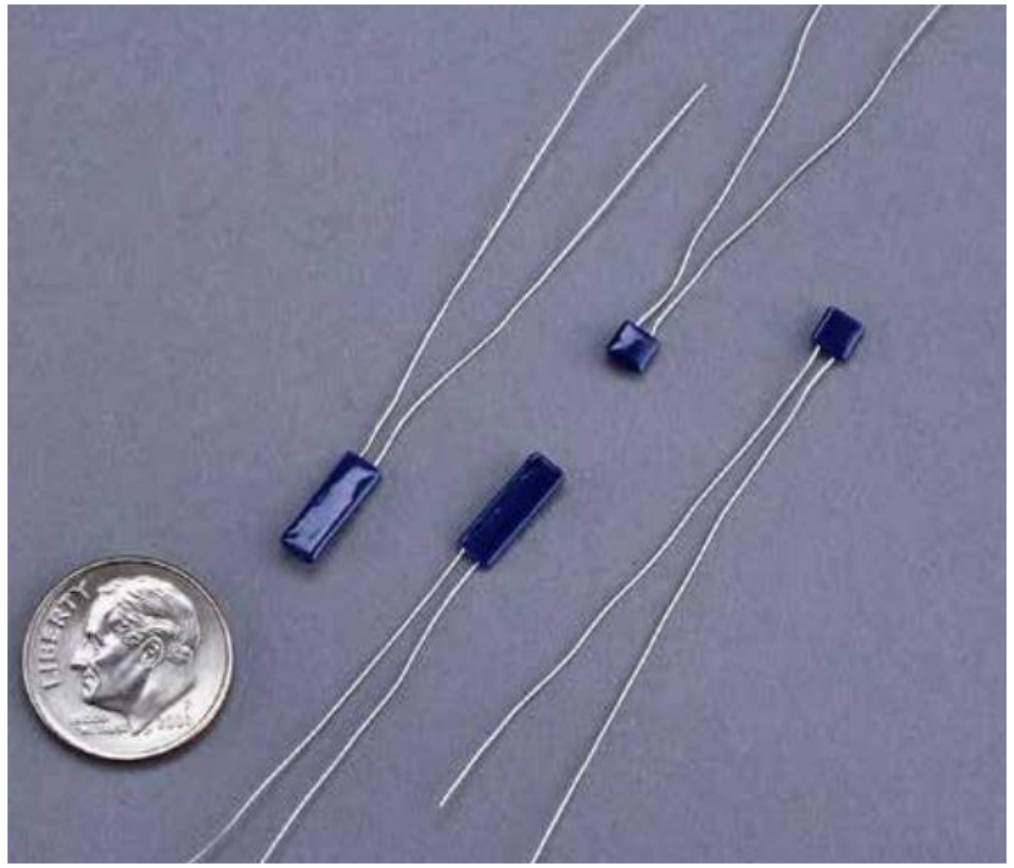
Thermocouples



fluxteq.com

- Junction of two metals producing temperature-dependent voltage.
- Different types available (K-, J-, etc.) – wide usable temperature range.
- Flexible geometry possible.
- Common in space applications.

RTDs



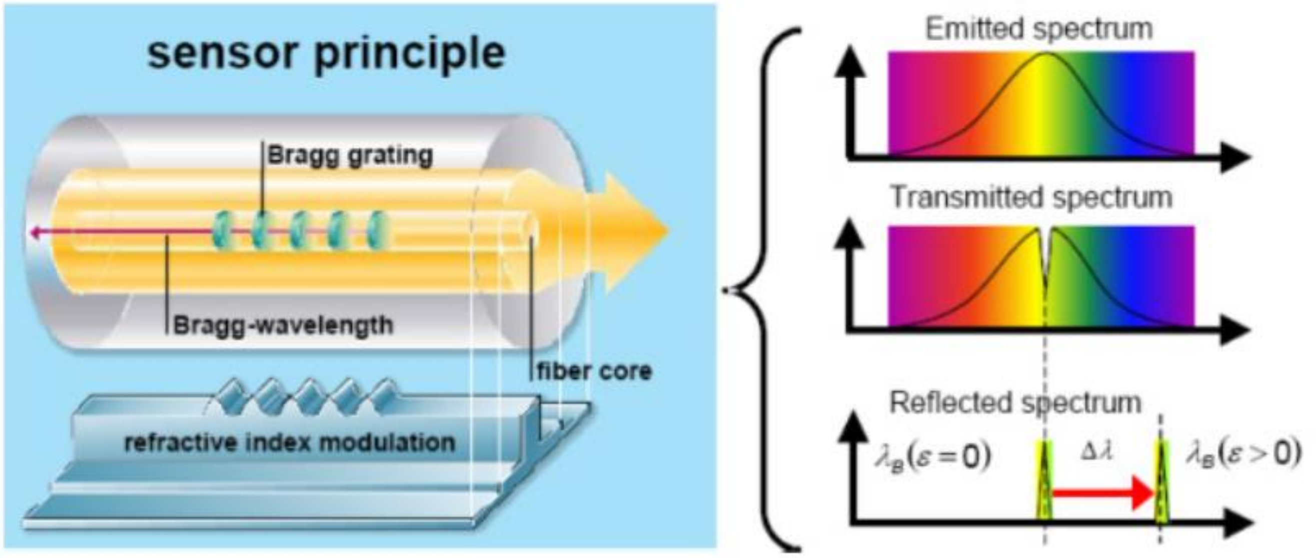
collinsaerospace.com

- Change of resistance of metal with temperature
- Different metals: Pt, Ni, Cu,...
- Thin-film configuration interesting due to geometry.
- Common in space applications (ESSC 4006/015).

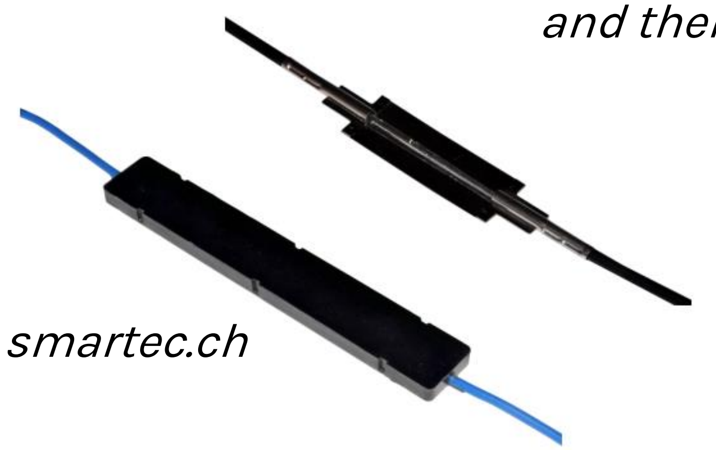
SENSORS SELECTION

Commercial strain sensors

Optical Fiber Bragg Gratings



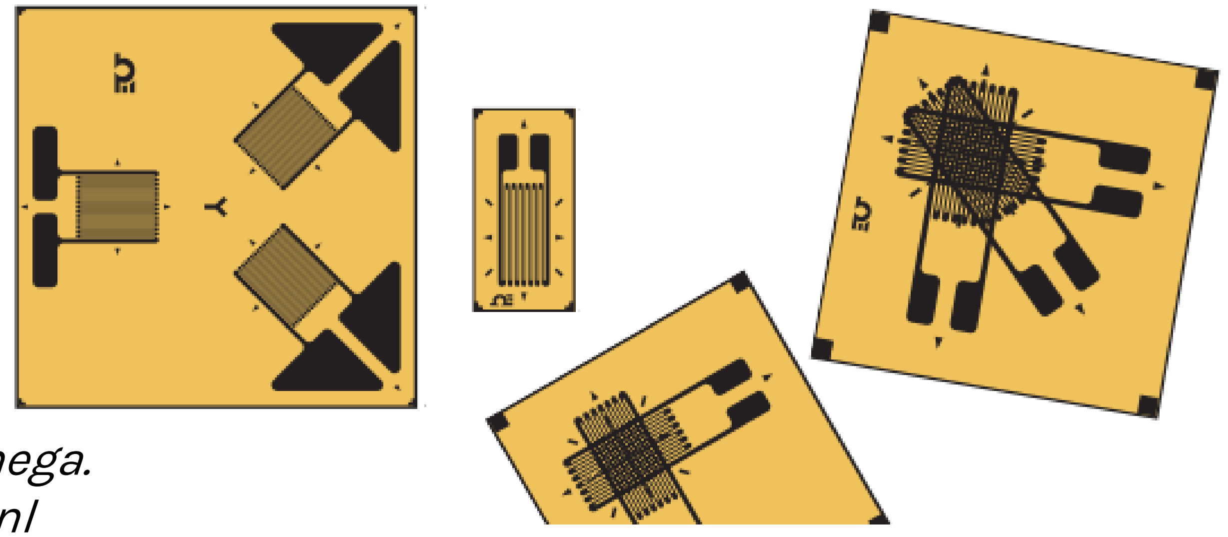
Cai et al., in Composites and their applications, 2012



smartec.ch

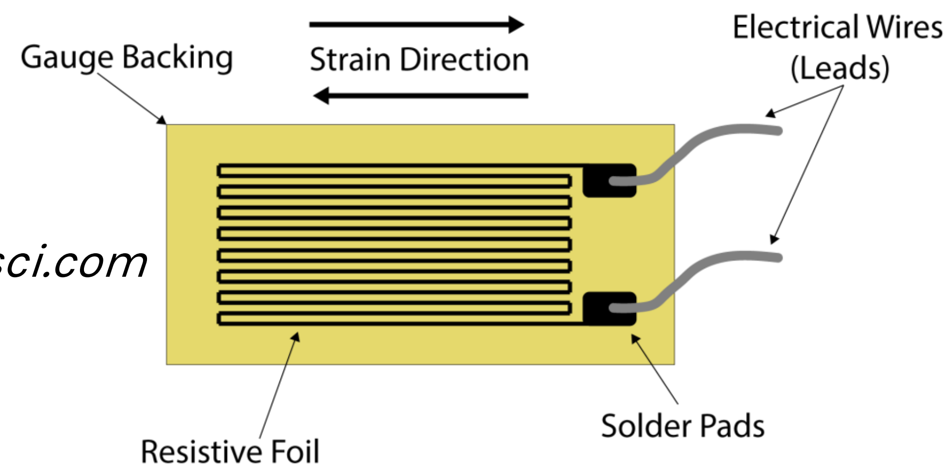
- Change of reflected optical frequency with strain.
- Vacuum compatible, small heat-load.
- Less common.
- Embedment inside the composites.

Strain Gauges



omega.nl

michsci.com

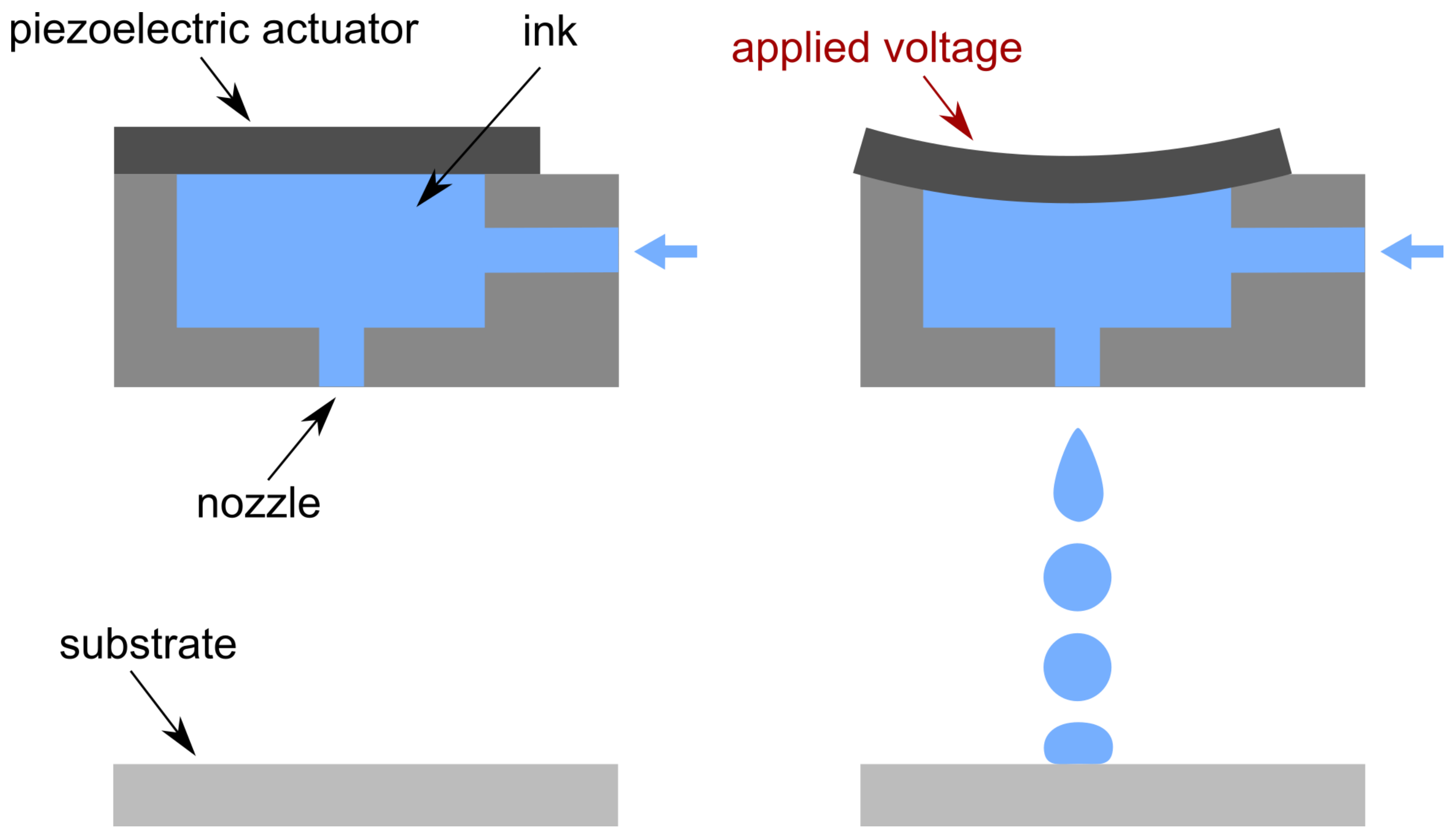


- Change of resistance of a metal layer with strain.
- Constantan or modified Karma alloys.
- Mature technology, common in space applications.

SENSORS SELECTION

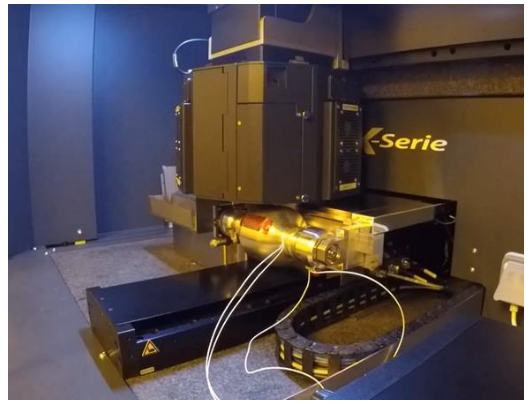
Inkjet-Printing process

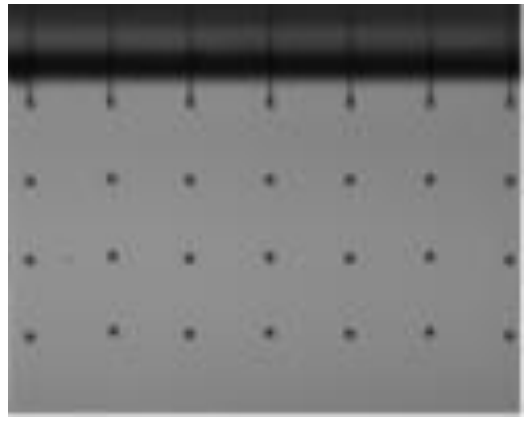
Characteristics



- Mask-less digital deposition.
- High manufacturing throughput.
- Large-scale patterning.
- Freedom of design.
- Accurate deposition

The Tool: Ceradrop X-Series



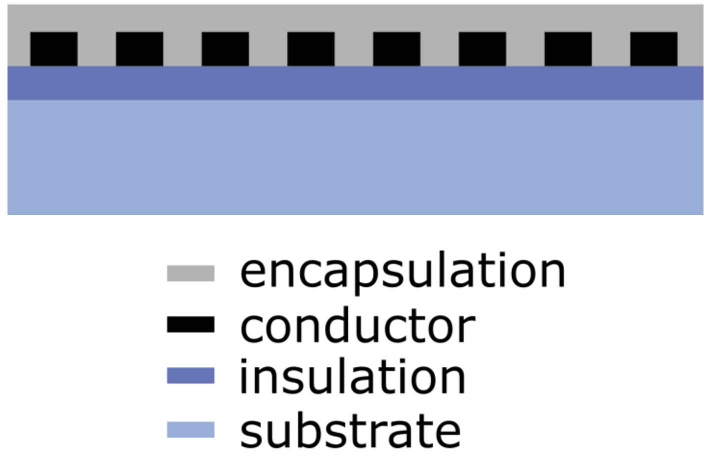


- 3 printheads (3 different materials).
- Printing on flat and curved substrates.

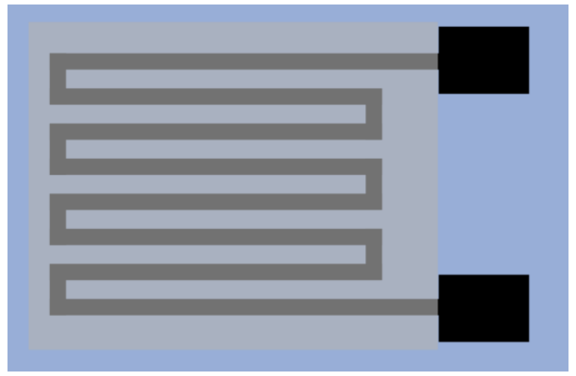
SENSORS SELECTION

Inkjet-Printing of sensors

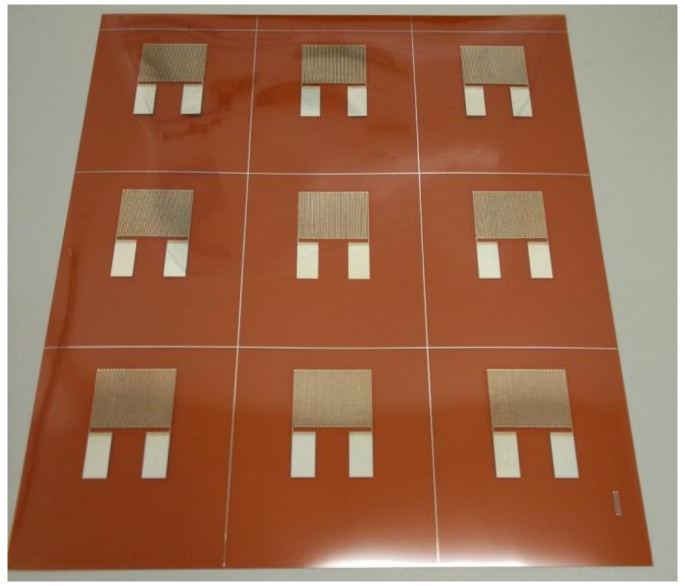
Cross-section

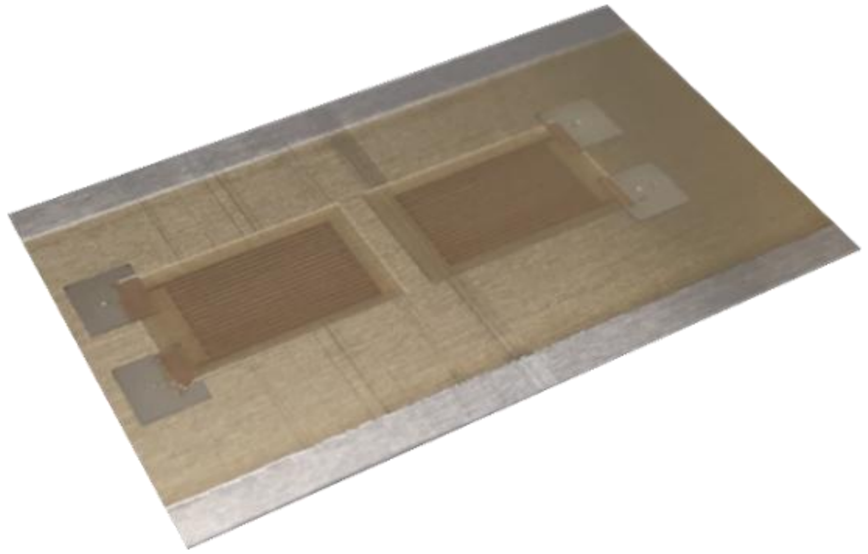


Top-view



- Substrate: aluminium, Kapton®
- Insulation: **polyimide (inkjet), SU-8 (inkjet)**
- Conductor: **Ag (inkjet)**
- Encapsulation: **polyimide (inkjet), SU-8 (inkjet)**





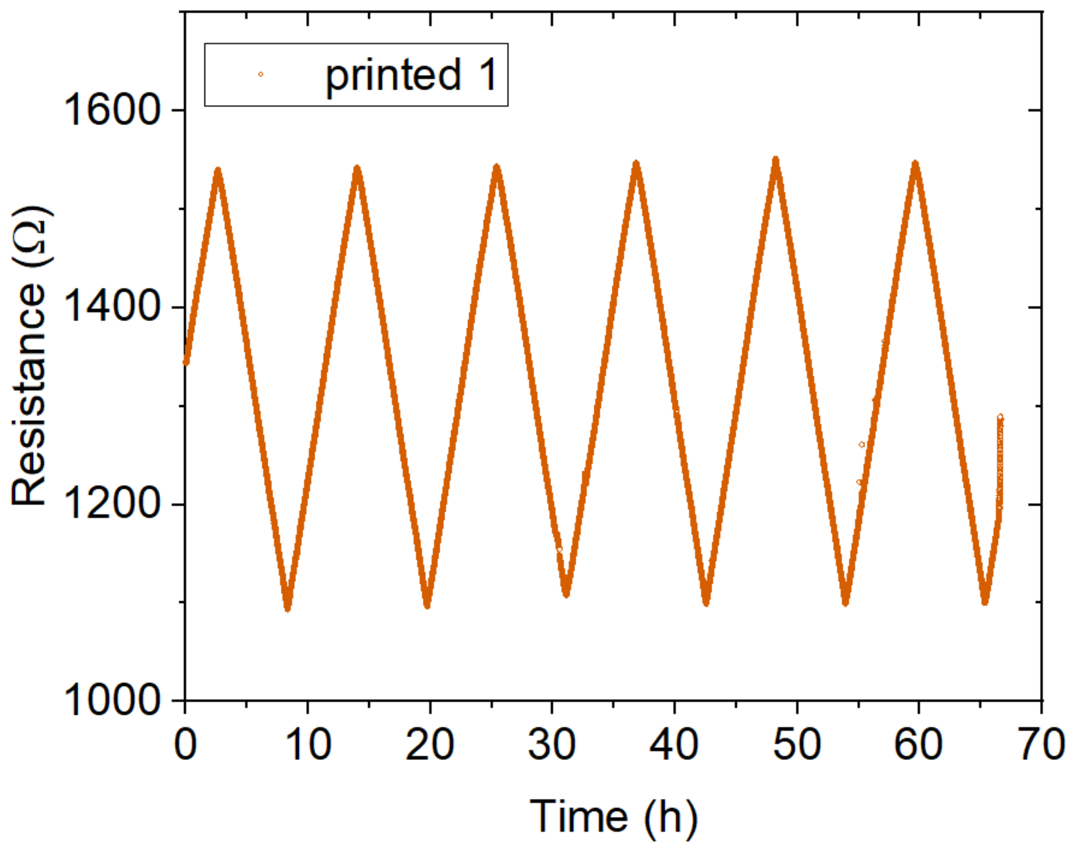
Temperature sensor: **RTD-type**

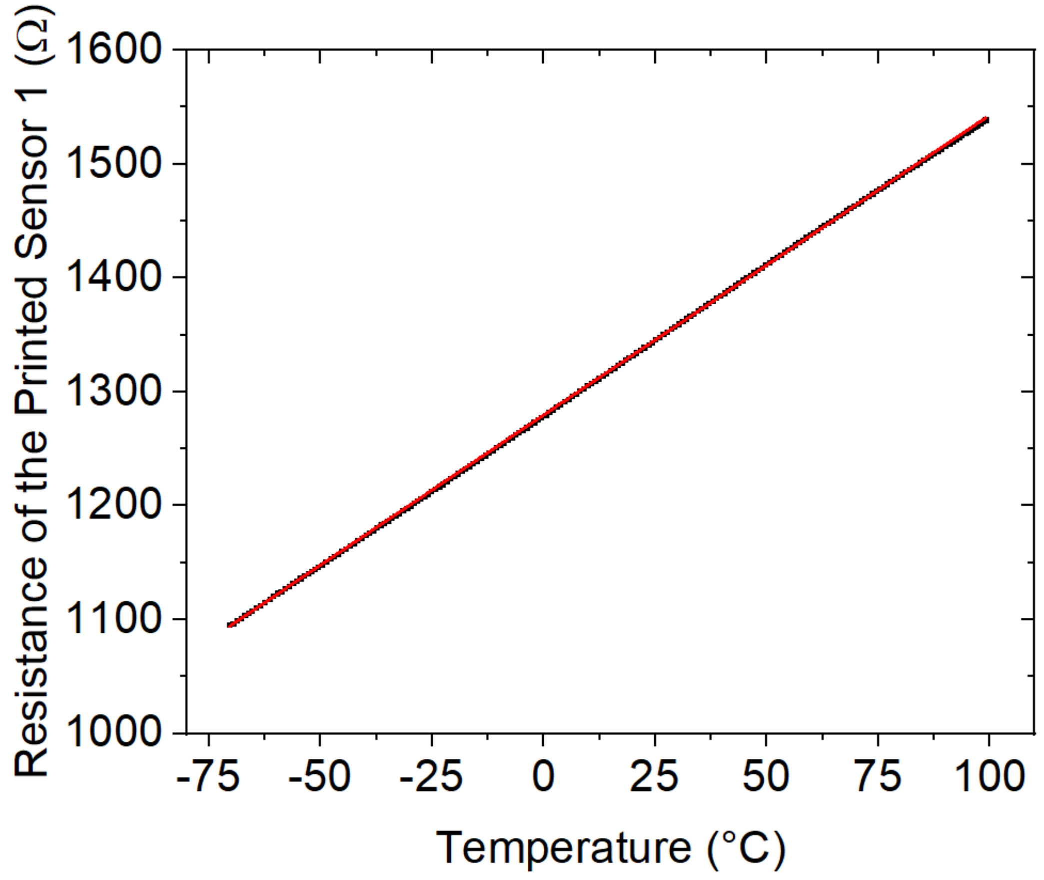
Strain sensor: **strain-gauge-type**

SENSORS SELECTION

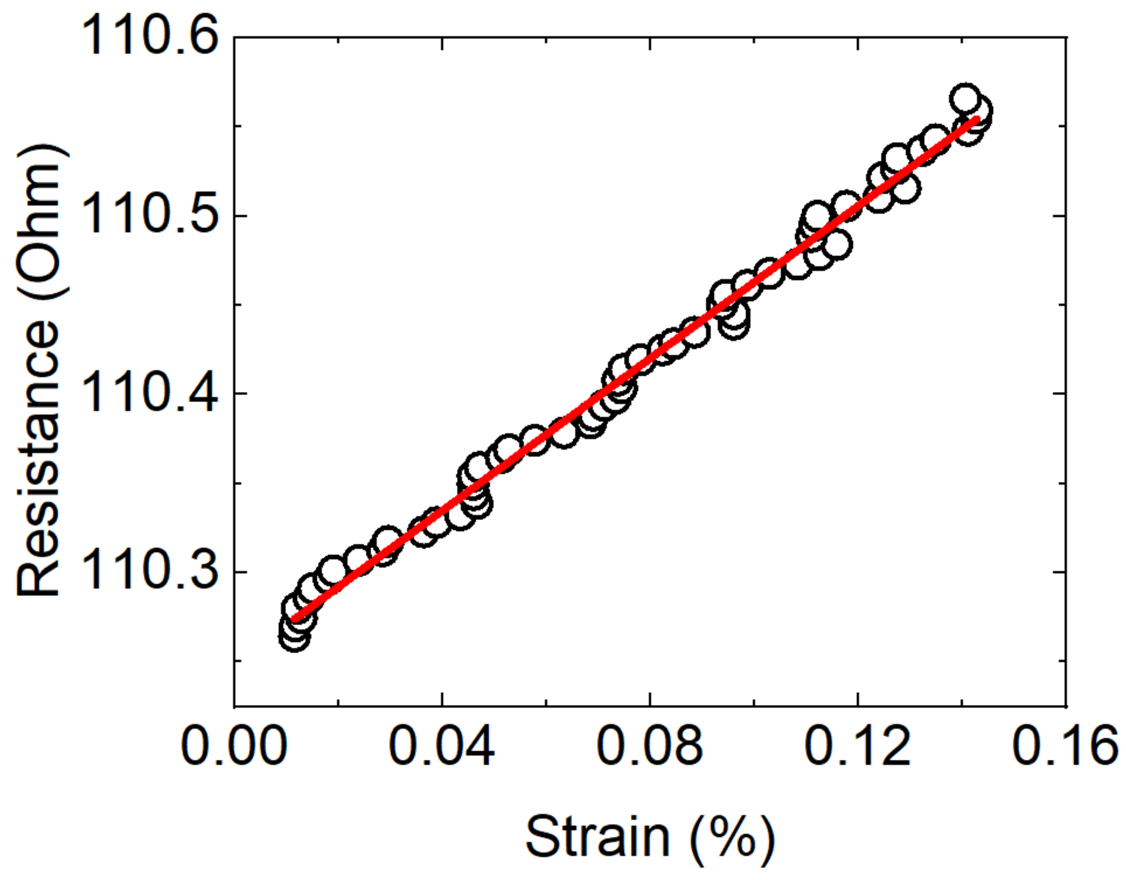
Inkjet-Printing of sensors

Temperature Sensors





Strain Sensors



TCR – temperature coefficient of resistance

TCR ($°C^{-1}$)	Accuracy (°C)
0.00206	0.7

GF – gauge factor

1.6-2.0

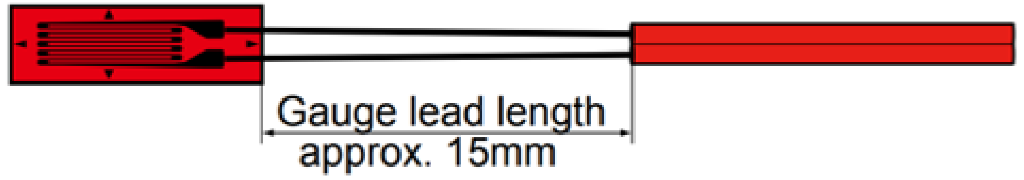
SENSORS SELECTION

Wire Connections

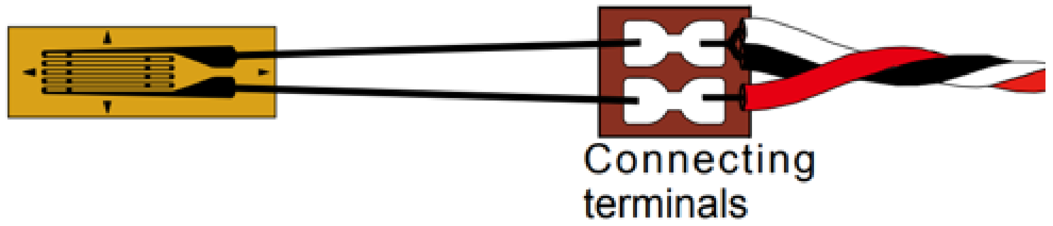
Commercial sensors

- Pre-connected sensors: commercial thermocouples, thermistors and FBGs
- RTDs and strain gauges: soldering

Direct type

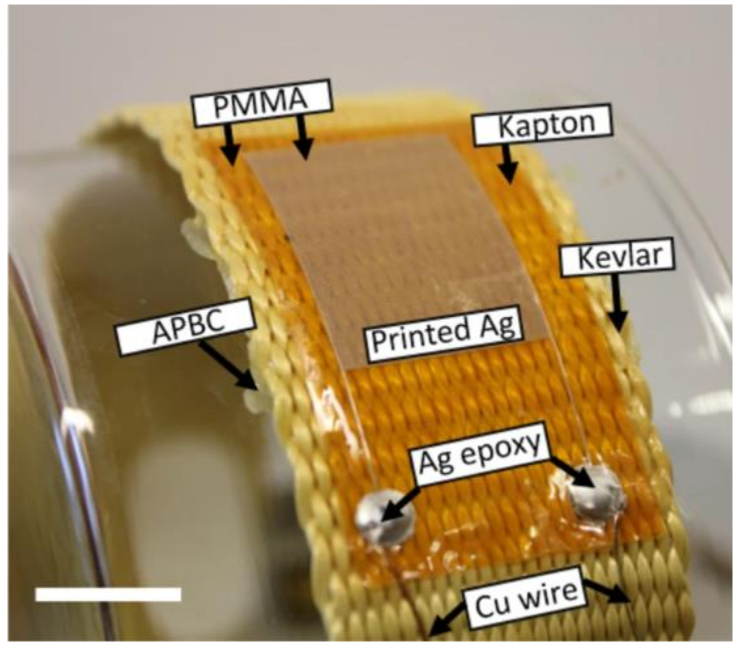


Integral type

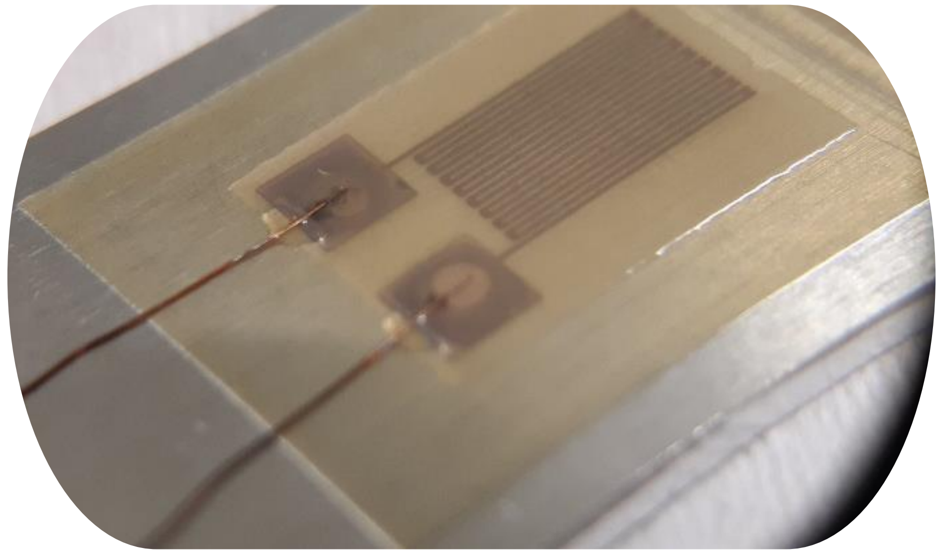


Connected terminals joint type

Ink-jet Printed sensors



Ag epoxy



Printed connections

SENSORS SELECTION

Advantages and Disadvantages

Type of Sensor	Sensor Technology	Advantages	Disadvantages
Temperature	Commercial Thermocouples	Self-powered, simple, **inexpensive,** wide variety available, wide temperature range (at least from -184 °C to 1260 °C), fast thermal response, (0.1-10 s typically), mature technology. Measuring points can be very small.	Non-linear, **low-voltage response** (~tens of μV per °C), reference required, **less stable and sensitive (above 1 °C)** compared to RTDs and thermistors. **Require manual handling, gluing, and fixing during the application.**
	Commercial RTDs	**Stable and accurate (0.01 °C),** more linear than thermocouple, fair temperature range (-269 °C and +400 °C), mature technology.	Expensive, current source required, small change of resistance, self-heating. **Require manual handling and gluing during application.**
	Commercial Thermistors	Fast response (0.05 – 2.5 s), accuracy (better than 0.01 °C). Fair temperature range (-100 - +300 °C).	Non-linear, limited T-range (-60 °C to +160 °C), self-heating, required external supply. **Require manual handling and gluing during application.**
	Inkjet-Printed RTDs	Linear, **sensitivity comparable to commercial RTDs**, fair accuracy (<1 °C). **Adaptable fabrication,** additively manufactured, tunable resistance, **inherent contact with the object of interest, low profile**.	Less sensitive than commercial RTDs, operational range tested so far (-70 °C - +100 °C). **Technology in development.**
Strain	Optical Fiber Bragg Gratings	Sensitivity (few με) and range (up to 10^4 με), fast response (100 Hz). **Vacuum compatible, small size, radiation resistant.**	Need for pre-load, temperature-sensitive, **extremely difficult integration into existing hardware.**
	Commercial Strain Gauges	Sensitivity (few με) and range (up to 10^4 με), fast response (100 Hz), **low profile and flexible.**	**Require manual handling and gluing during application**, which requires personnel skilled in the art.
	Inkjet-Printed Strain Gauges	Sensitivity and response comparable to commercial gauges. **Flexible fabrication, additively manufactured**, tunable resistance, inherent contact with the object of interest, **low profile.**	**Less mature technology,** require temperature compensation. Operational range tested so far (-70 °C - +100 °C)

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SENSORS SELECTION

Figures of Merit and sensors technology trade-off

FoM	Definition	Multiplier
Requirements compliance	Benchmarking towards the product, manufacturing and sensor requirements	40%
Adaptability of integration	Placement on different areas and at different levels, which must be accessible with the process. Precision of positioning can play an important role	15%
Cost	Cost of the sensor and integration process	11%
Innovation potential	Potential to innovate the market with new features	14%
Integrability with product	Flatness and thickness to be adaptable with intended thin-sensors requirement	20%

Sensor	Score
Commercial thermistor	0.28
Commercial thermocouple	0.35
Commercial RTDs	0.38
Inkjet-printed RTDs	0.75
Optical Fibre Bragg Gratings	0.24
Commercial strain gauges	0.53
Inkjet-printed strain gauges	0.75

SENSORS SELECTION

Data transfer technologies: Strain Sensor

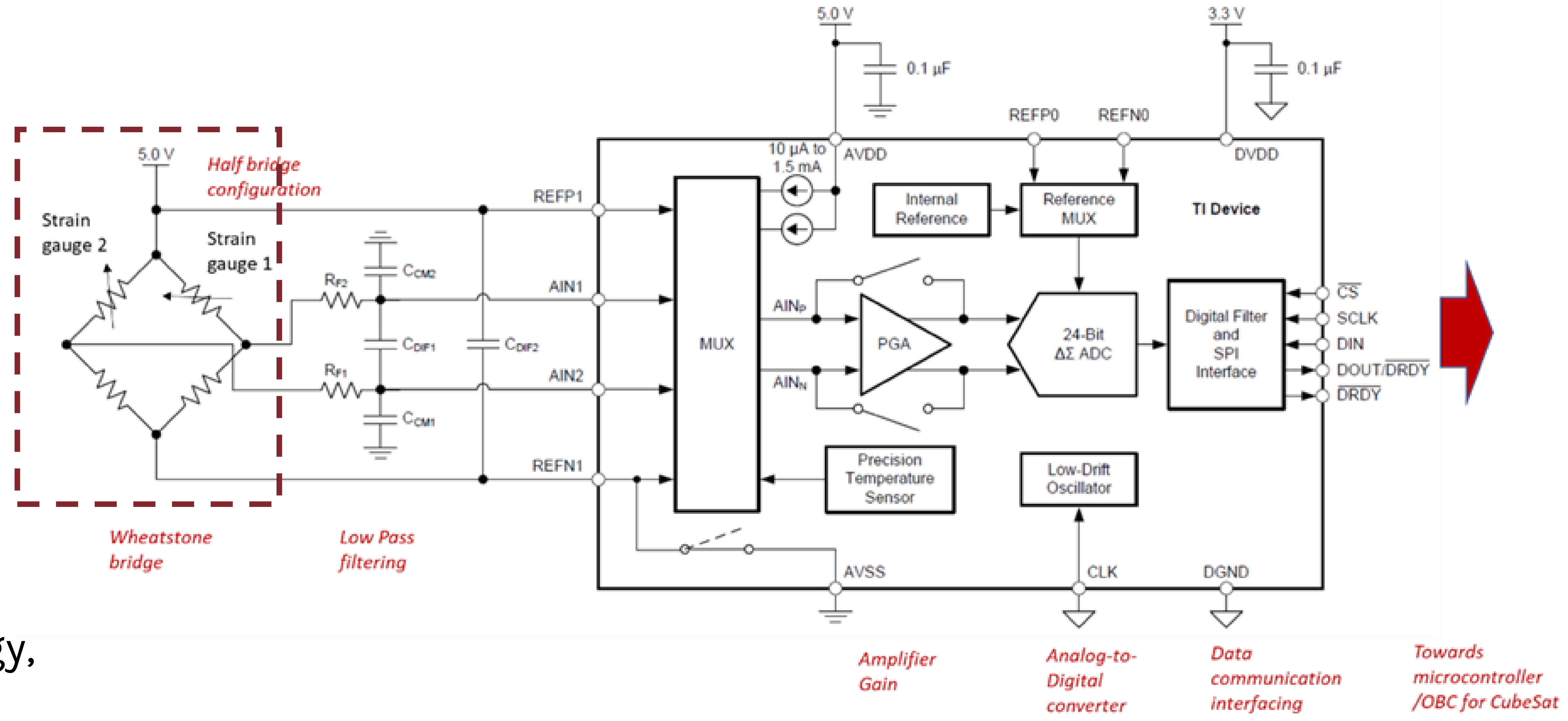
Same chipset re-configured for RTD

Included high-resolution ADC of 24 bits

Low power consumption (3.3 V and 5 V supplied voltage buses, <20 mA in full dynamic operation).

Miniaturization and standardized communication protocols. Data transfer done by SPI communication protocol.

Chipset already considered in the Ten-Koh LEO satellite (Kyushu Institute of Technology, Japan, 2019)



ADS1220 chipset (Texas Instrument)

SENSORS SELECTION

Data transfer technologies: Temperature Sensor

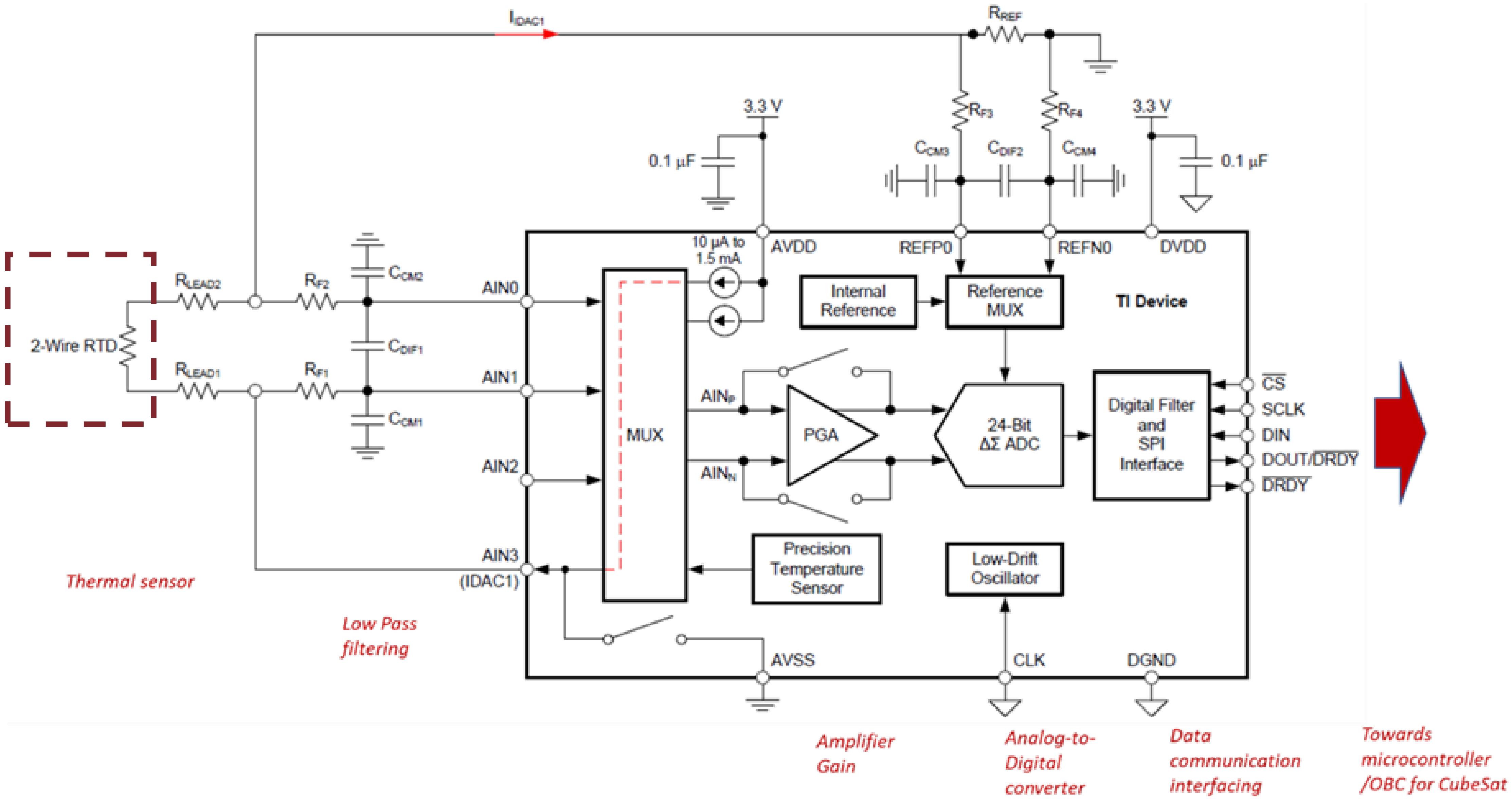
Removal of thermal drift – half-bridge integration with two similar strain gauges arranged perpendicularly on the same surface location

Included high-resolution ADC of 24 bits

Low power consumption (3.3 V and 5 V supplied voltage buses, <20 mA in full dynamic operation).

Miniaturization and standardized communication protocols. Data transfer done by SPI communication protocol.

Chipset already considered in the Ten-Koh LEO satellite (Kyushu Institute of Technology, Japan, 2019)



ADS1220 chipset (Texas Instrument)

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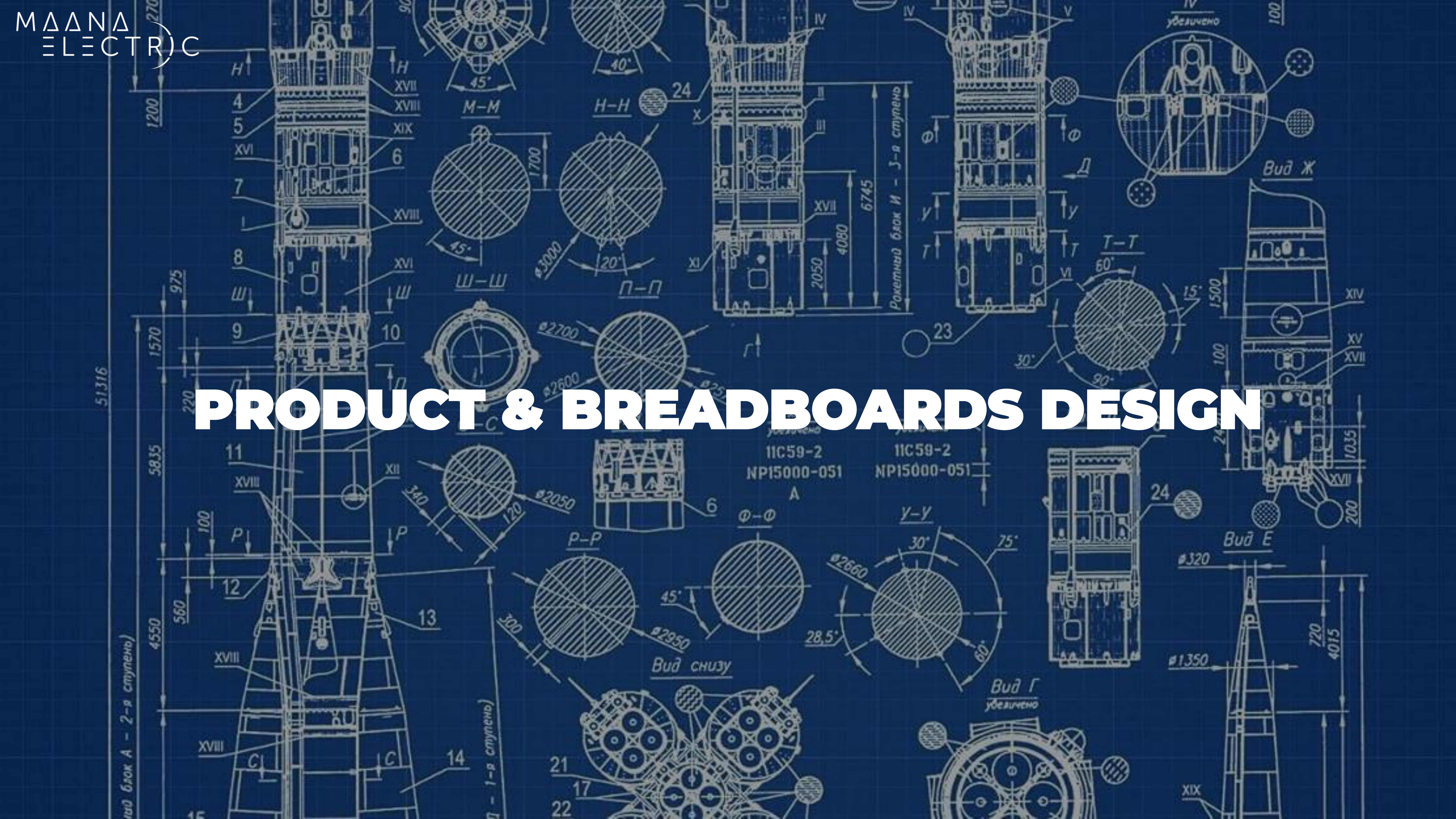
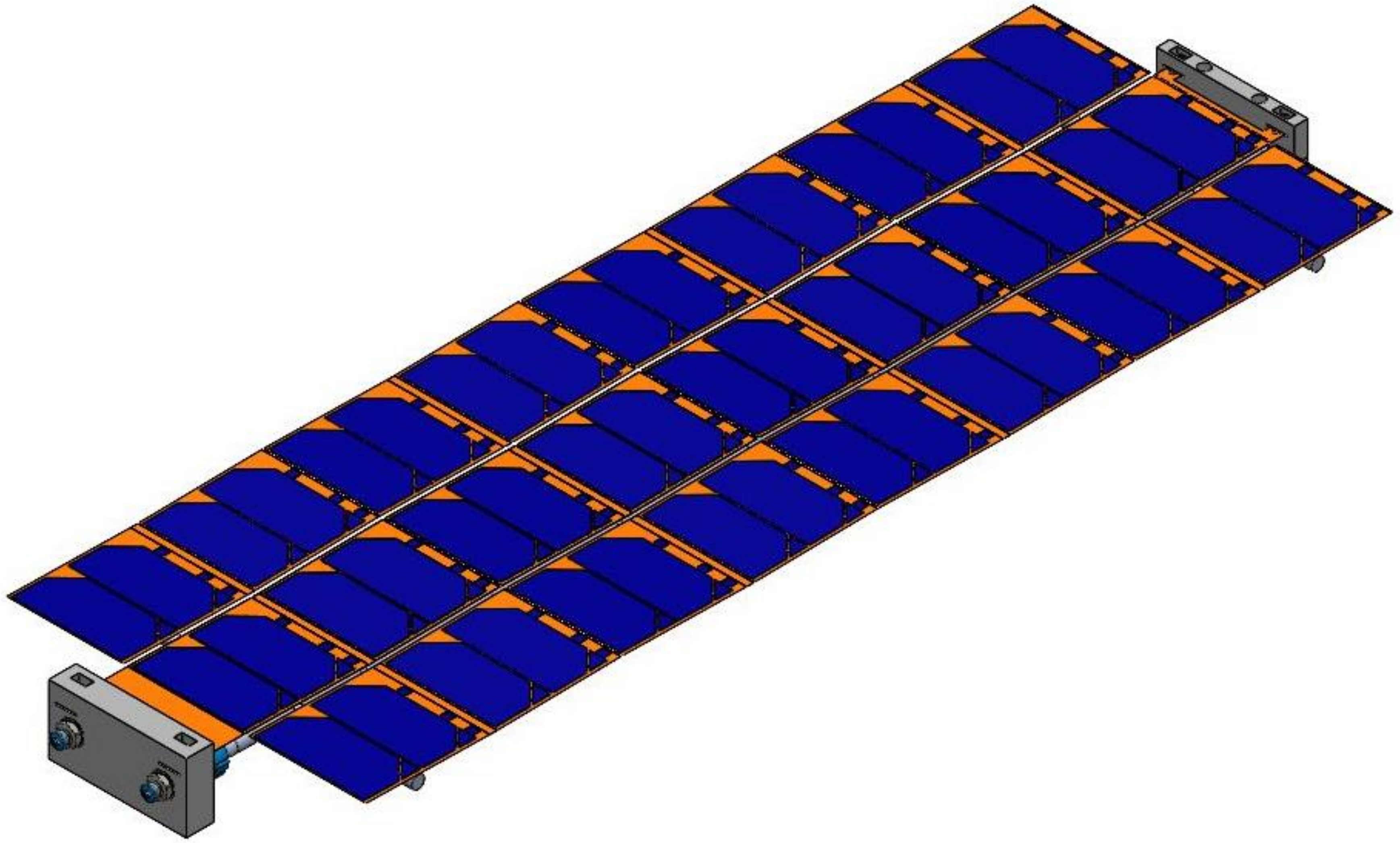


PRODUCT & BREADBOARDS DESIGN

PRODUCT PRELIMINARY DESIGN

The Deployable Solar Array (DSA) specifications

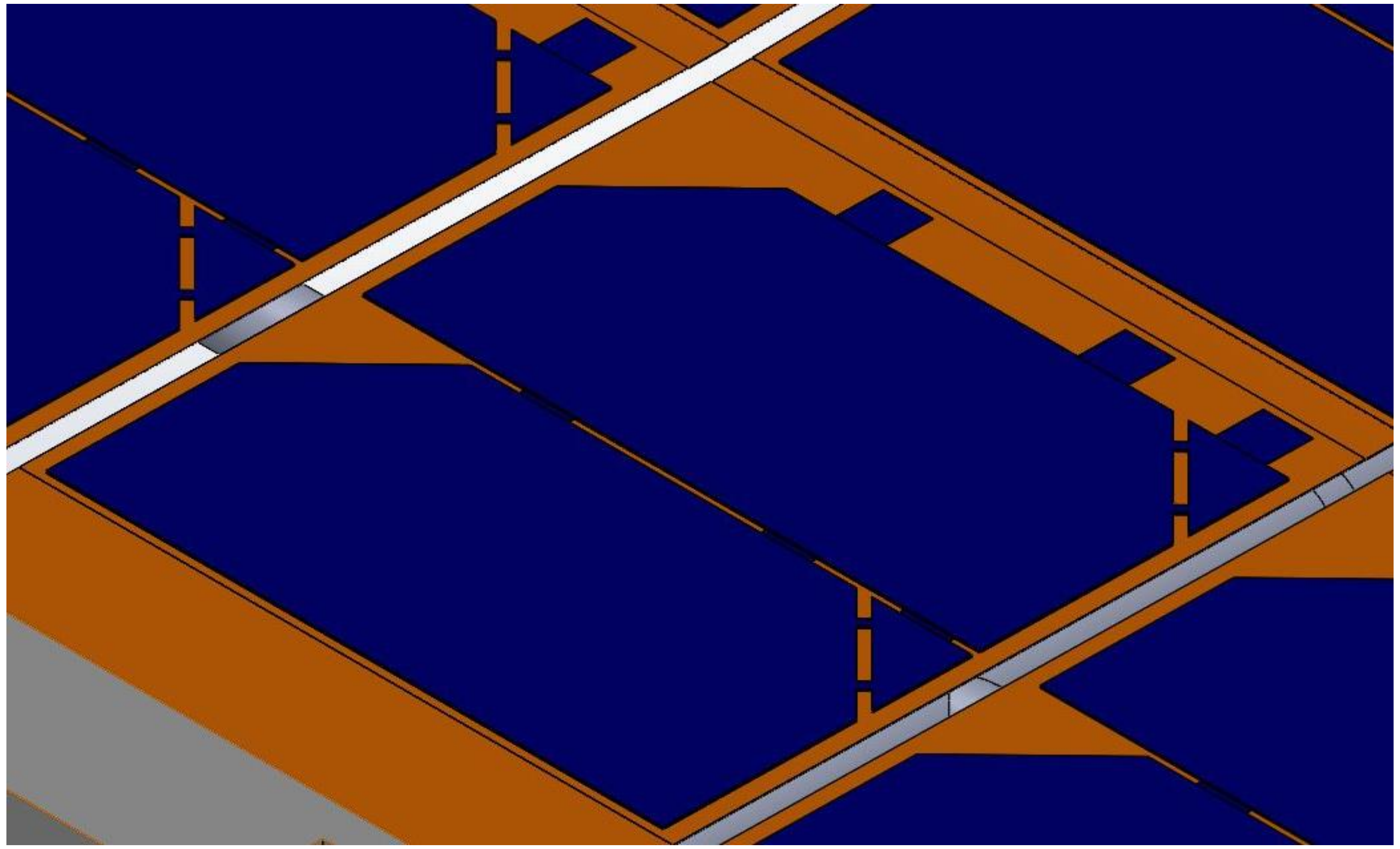
Specification	Value	Unit
Length	870	mm
Width	270	mm
Power EOL	54	W
Voltage EOL	18.5	V
Current EOL	2.9	A
Number strings	6	-
Number cells/string	8	-
Thickness substrate	230	µm
Thickness CIC	280	µm
Deployable mech.	Inflation	-



One DSA in deployed configuration

PRODUCT PRELIMINARY DESIGN

Segment and Sensors



Highlight of the segmented structure of the DSA, where each pair of PV cells forms a rigid segment connected to other segments by FPC

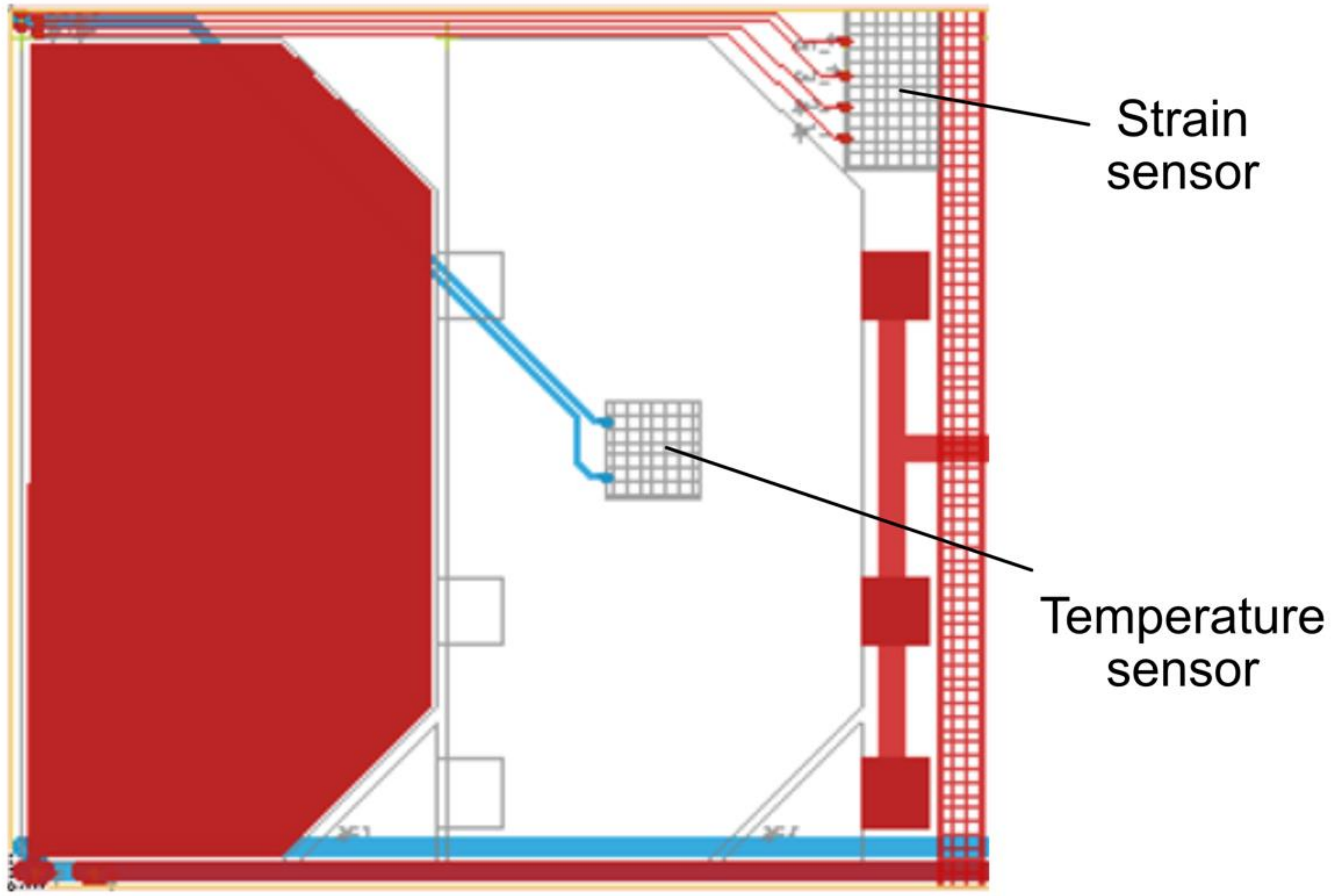


Diagram showing the position of the strain and temperature sensors on one segment of the DSA

PRODUCT PRELIMINARY DESIGN

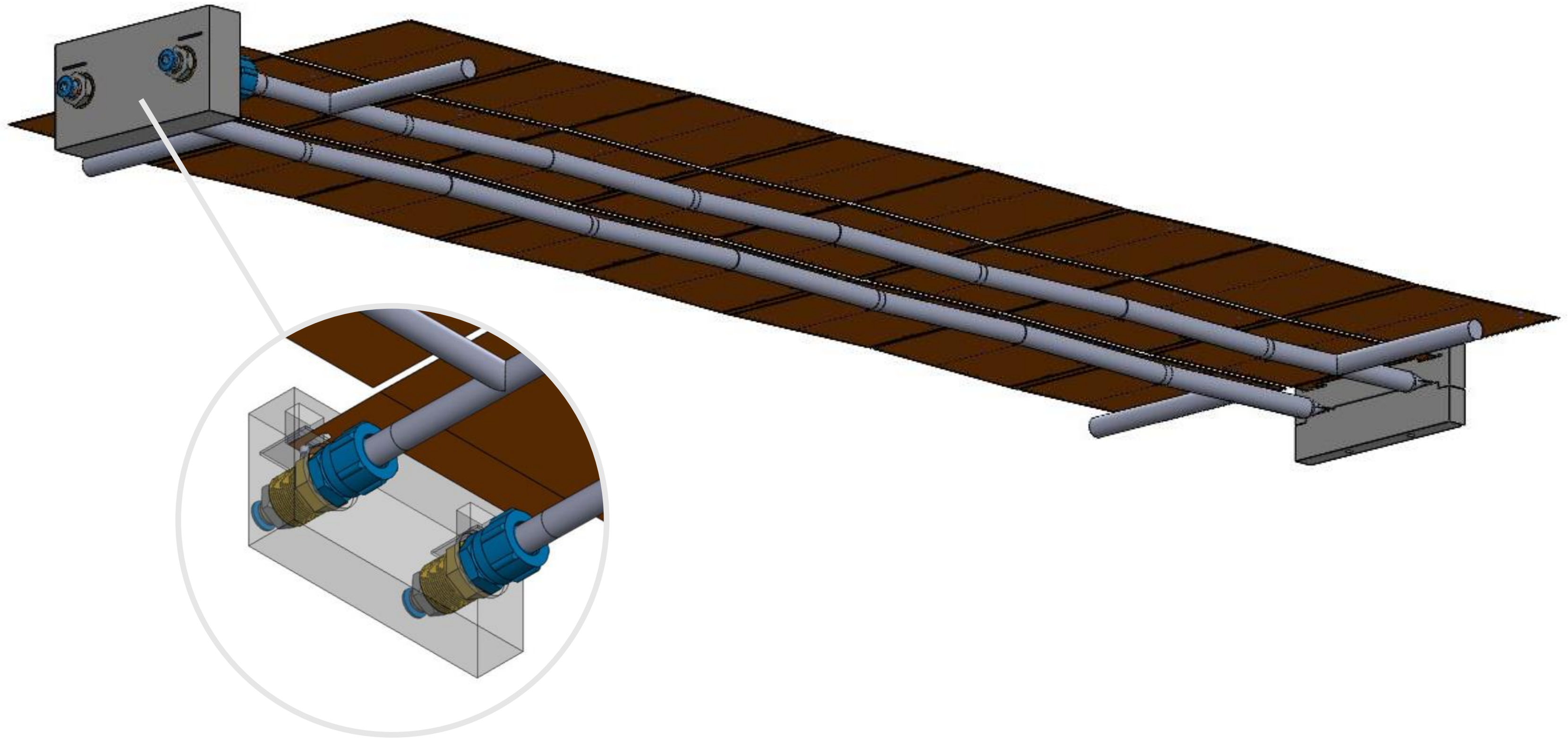
The Flexible-PCB (FPCB) structure

Coverlay(white) (1mi AD: 30µm)	Coverlay(1MIL)		25.00	µm		
	Adhesive	Ni/Au	30.00	µm	5.00	µm
FCCL (1 Mil 1 Oz ED) S/S Side	Copper		35.00	µm	35.00	µm
	Adhesive		12.00	µm	12.00	µm
	Polyimide		25.00	µm	25.00	µm
	Adhesive		12.00	µm	12.00	µm
	Copper		35.00	µm	35.00	µm
Coverlay(white) (1mi AD: 30µm)	Adhesive	Ni/Au	30.00	µm	30.00	µm
	Coverlay(1MIL)		25.00	µm	25.00	µm

Stack of the FPCB along its thickness

PRODUCT PRELIMINARY DESIGN

Deployable mechanism and inflation system



The rear-side view of the deployed DSA, showing the deployable mechanism with proposed inflatable branching of the inflatable tubes. Highlight of the interface with the gas-management system and the physical holder of the Kapton substrate.

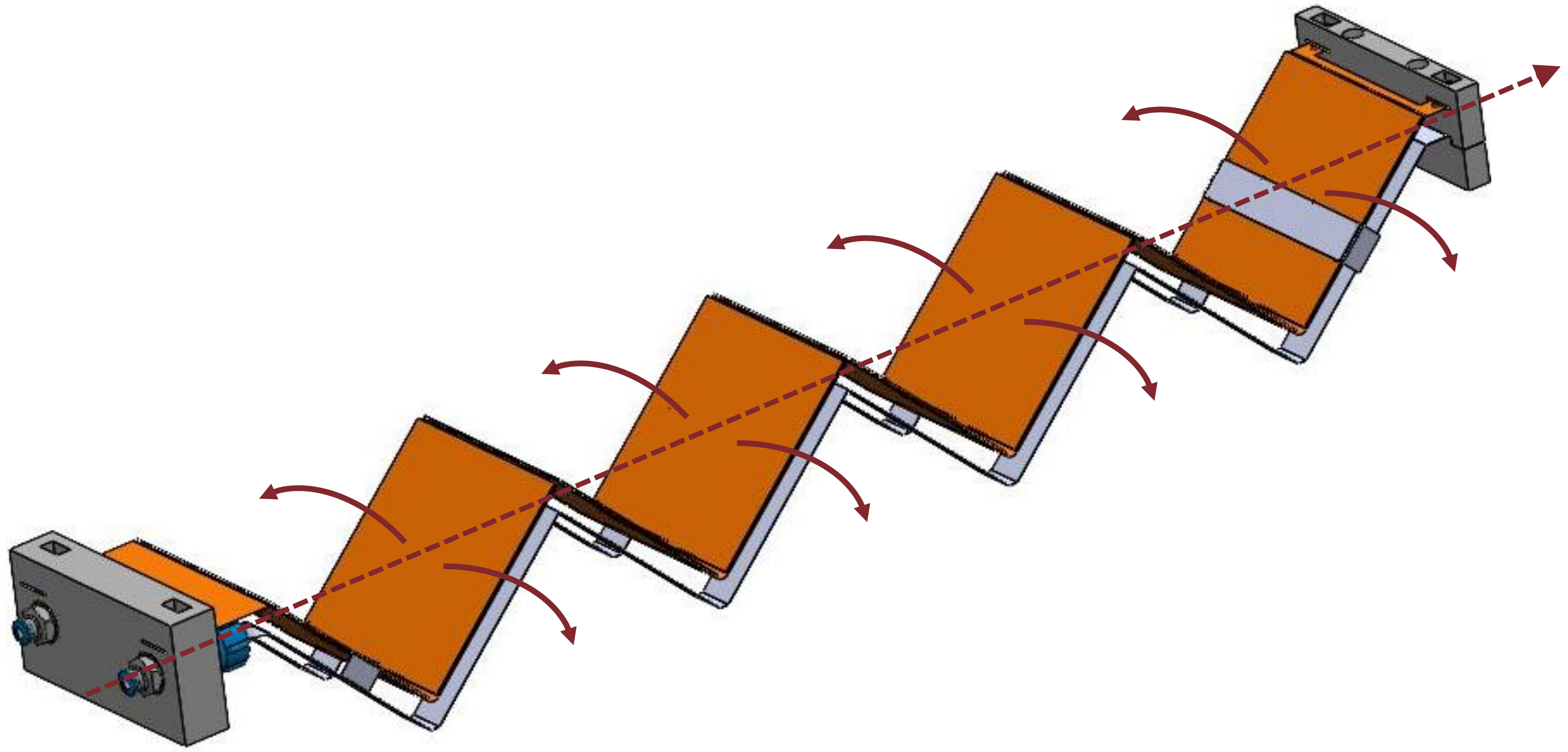


Diagram of the deployment operations of the DSA: first the folded segments are inflated along the main axis, later the lateral rows unfold transversally.

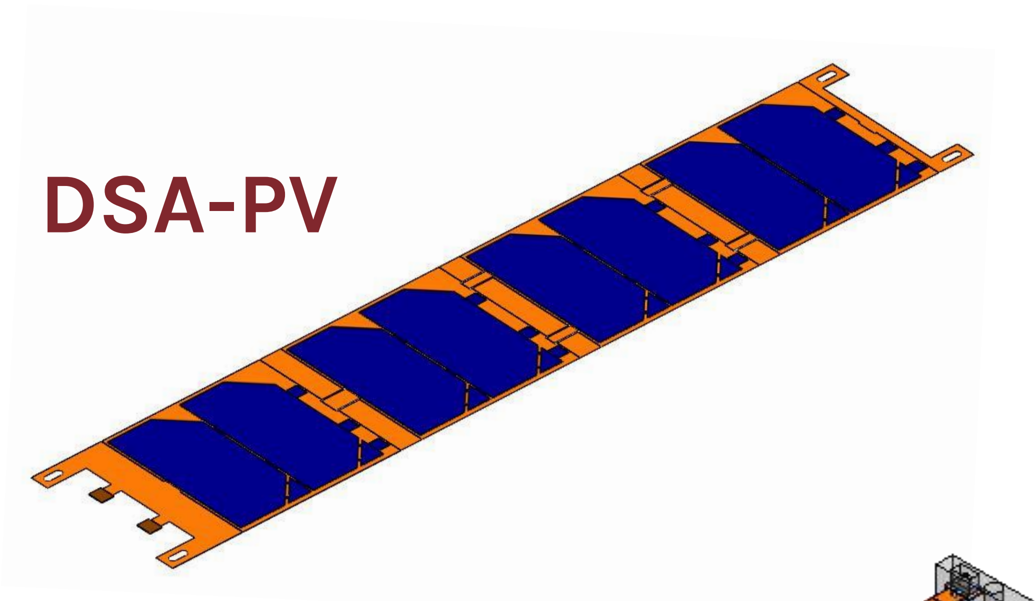
BREADBOARDS DESIGN

The DSA-PV and the DSA-M

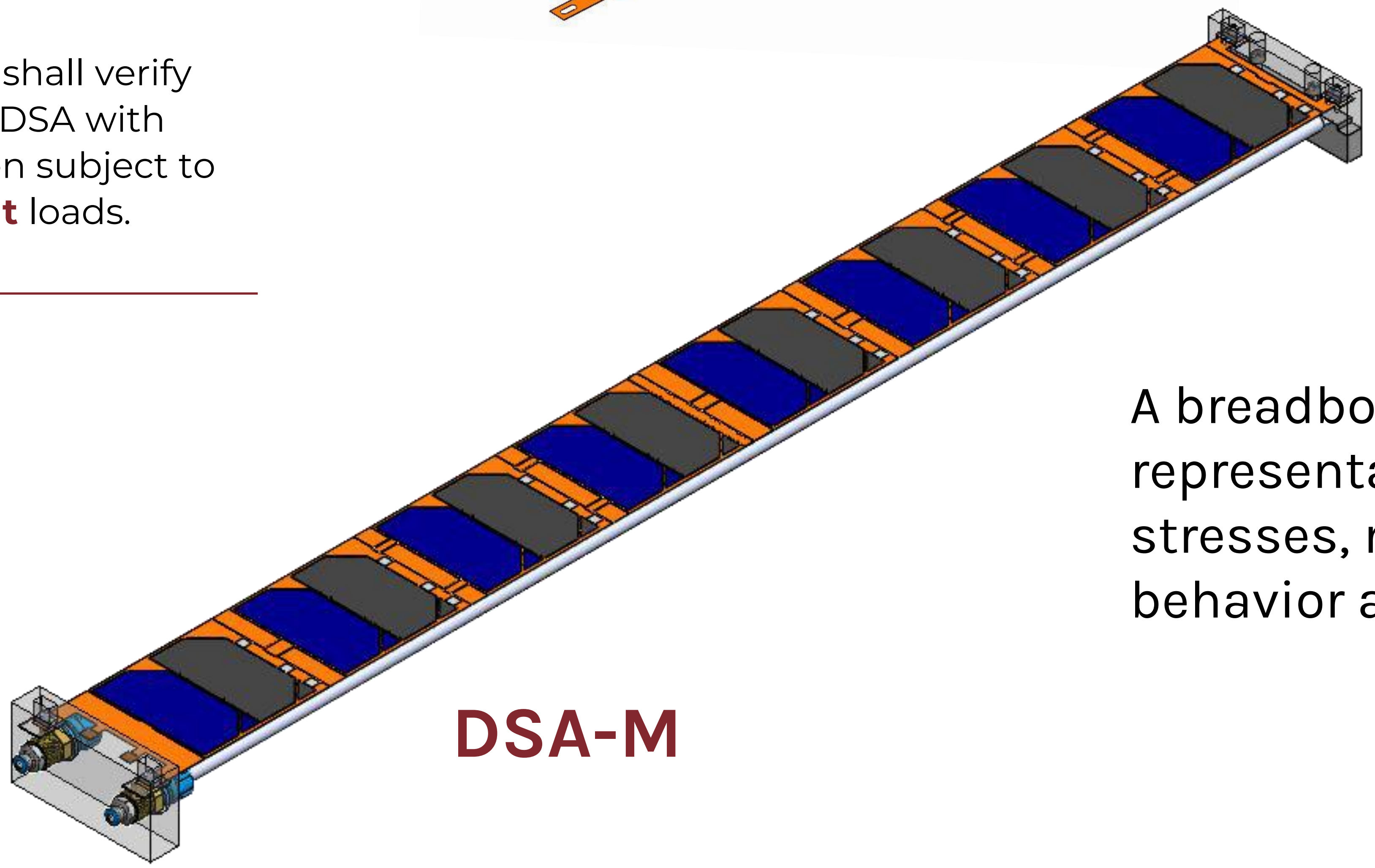
Requirement	Description
DSA-PV-MIS-001	The DSA-PV breadboard shall verify the performance of the DSA with embedded sensors in relevant environment subject to scaling effects.
DSA-M-MIS-001	The DSA-M breadboard shall verify the performance of the DSA with embedded sensors when subject to **launch and deployment** loads.

The different environmental conditions are tested on **two** separate breadboards

DSA-PV



A small and compact breadboard designed for testing materials and geometries in **thermal-vacuum** environmental conditions.



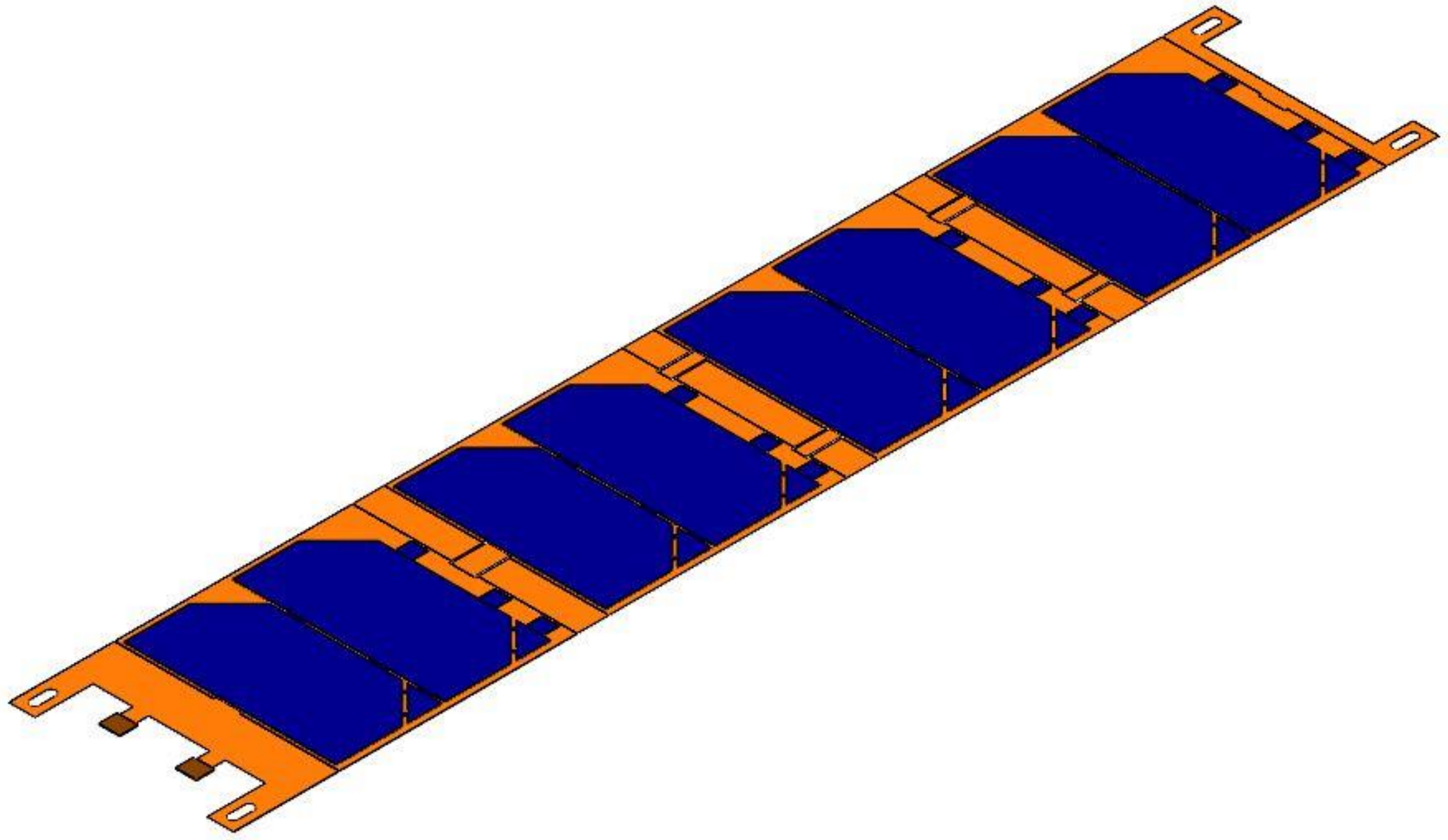
DSA-M

A breadboard designed for testing representative **mechanical loads** and stresses, replicating the mechanical behavior and structural integrity of the DSA.

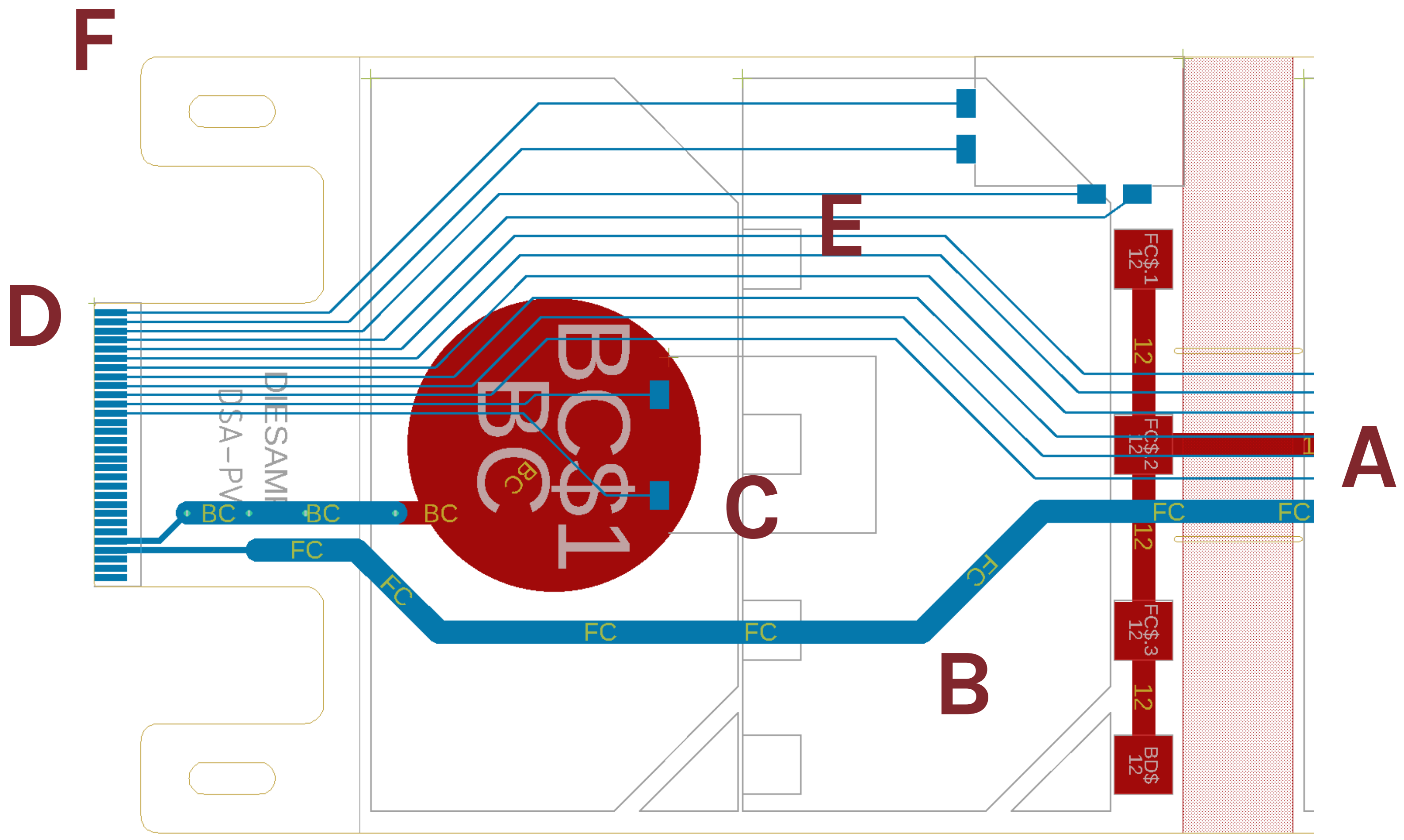
MAANA ELECTRIC

BREADBOARDS DESIGN

DSA-PV: architecture and FPC design



CAD representation of the DSA-PV

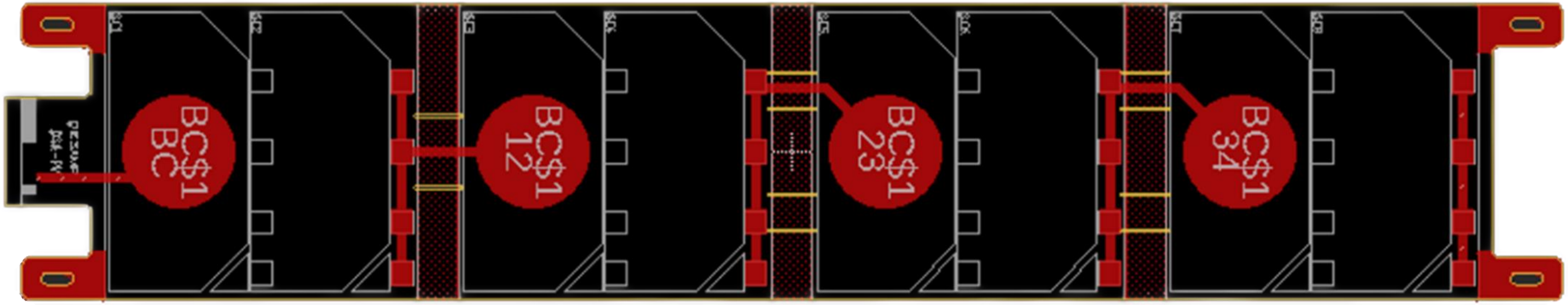


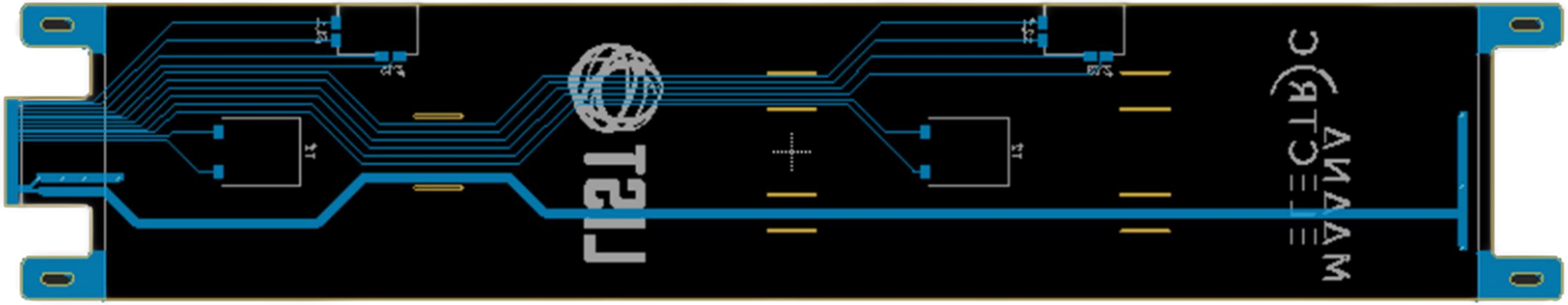
FPC design of the DSA-PV

A. Electrical and data lines through bridges
B. Electrical back line on bottom level
C. Circular pad for rear-cell connection
D. Electrical and data output on bottom level
E. Data line on bottom level
F. Rounded corners to reduce stress when folding

BREADBOARDS DESIGN

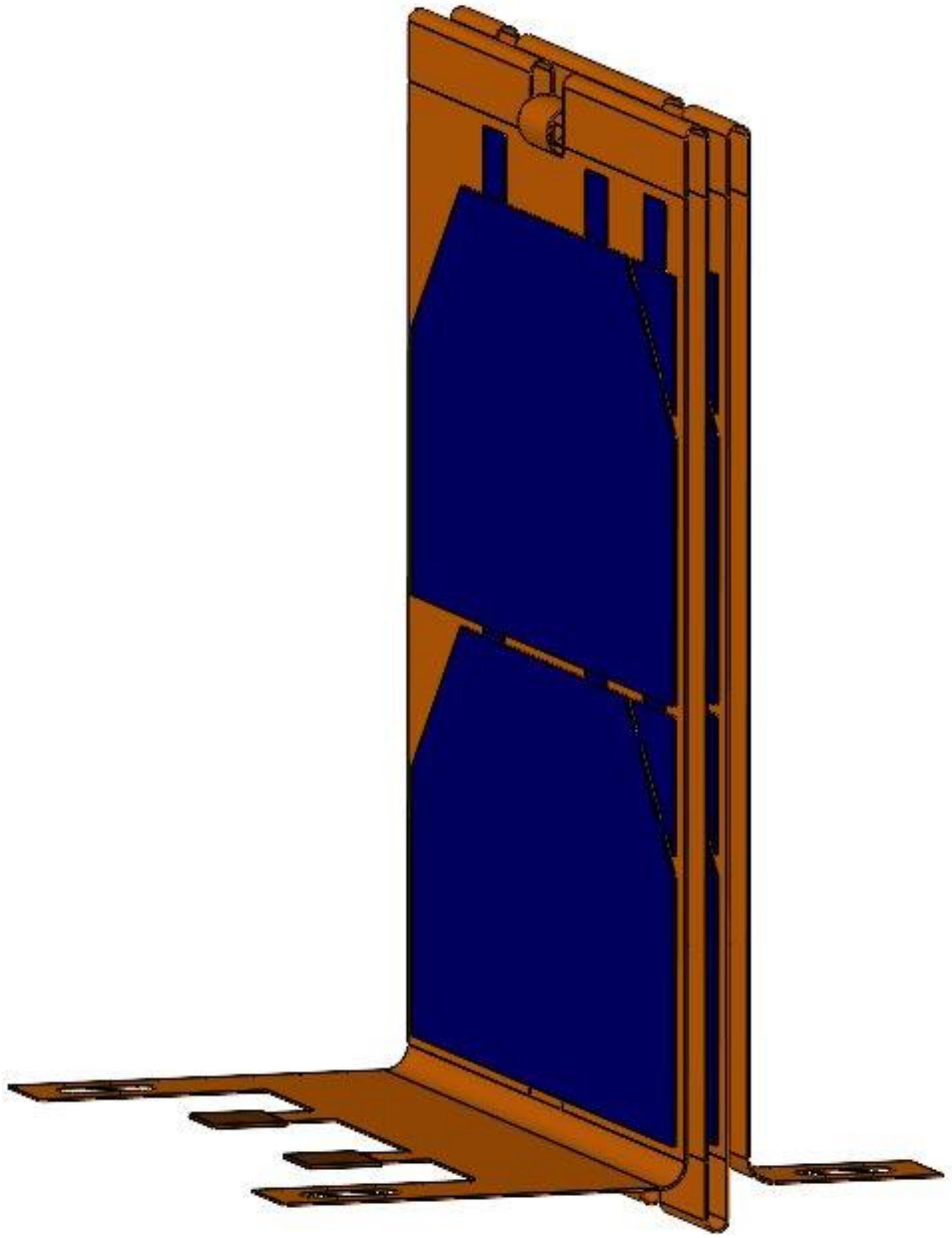
DSA-PV: electrical and data architecture

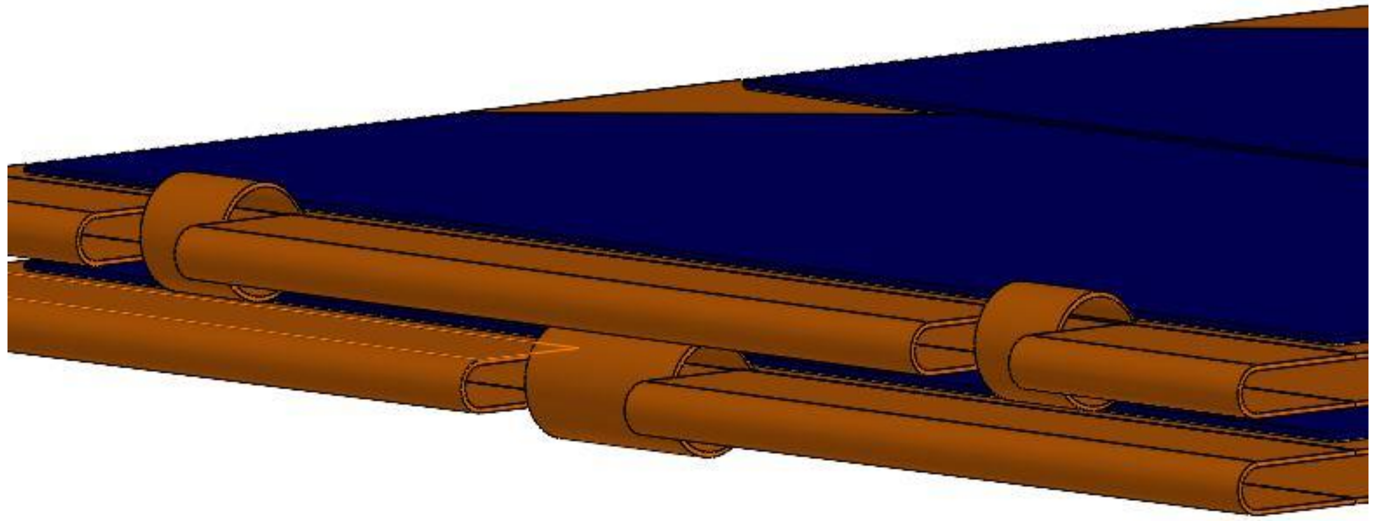


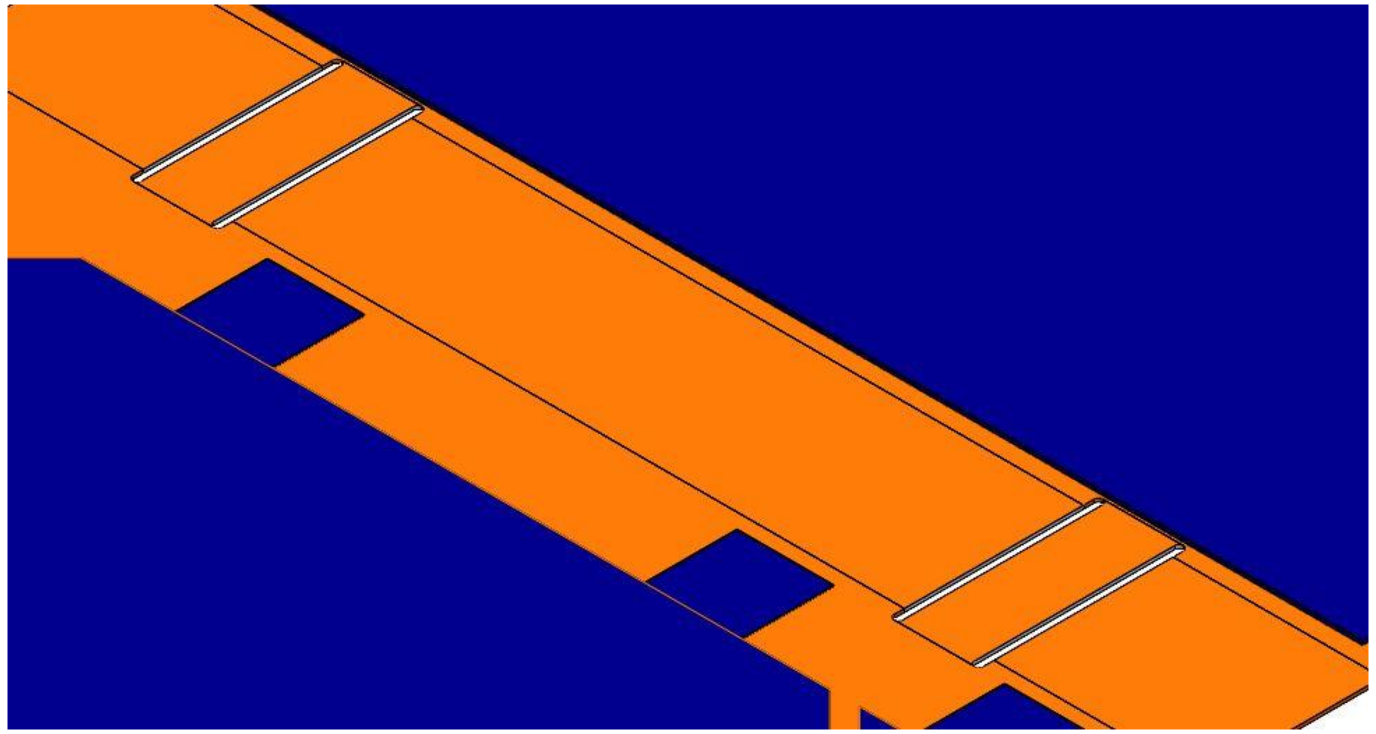


BREADBOARDS DESIGN

DSA-PV: folding



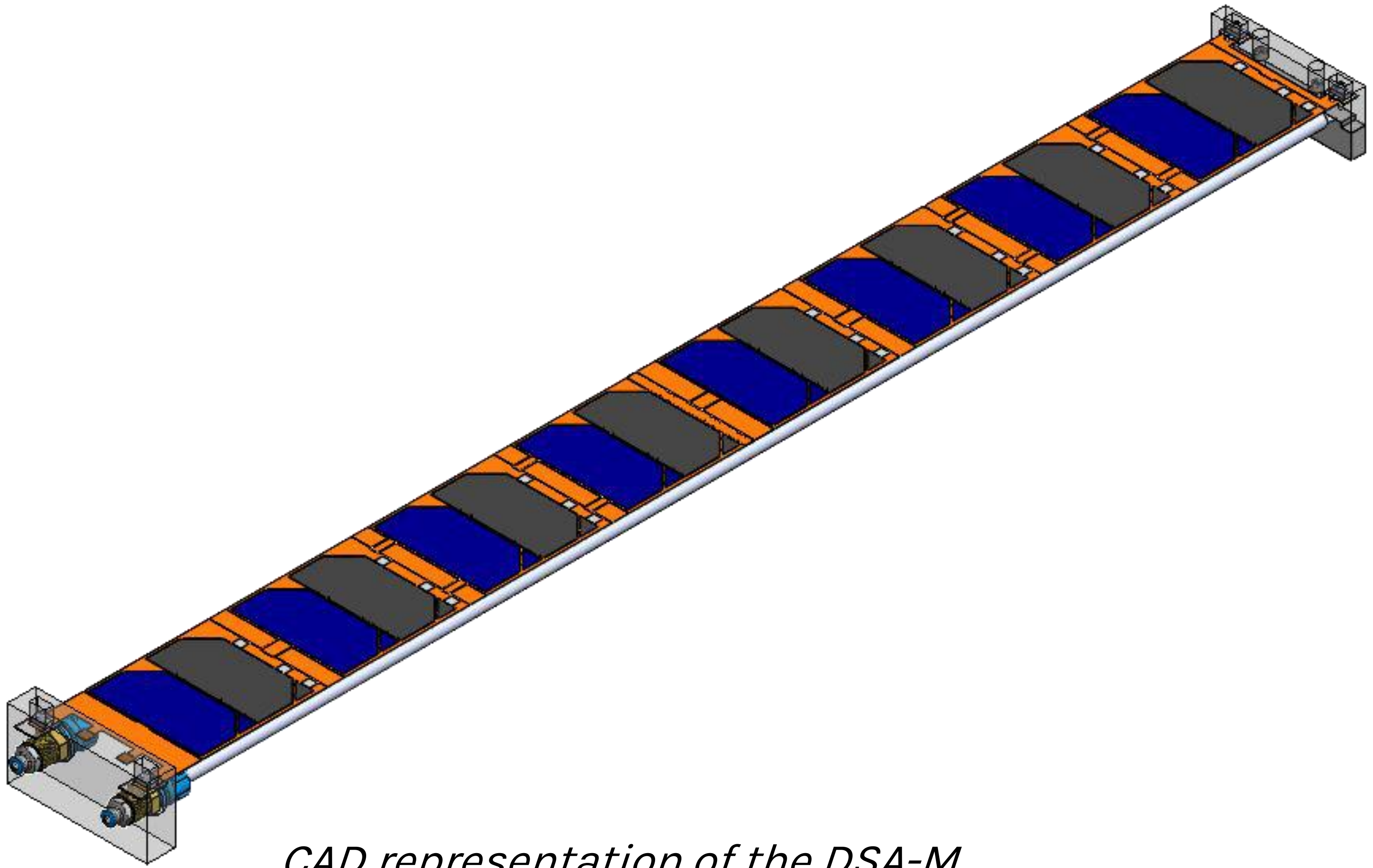




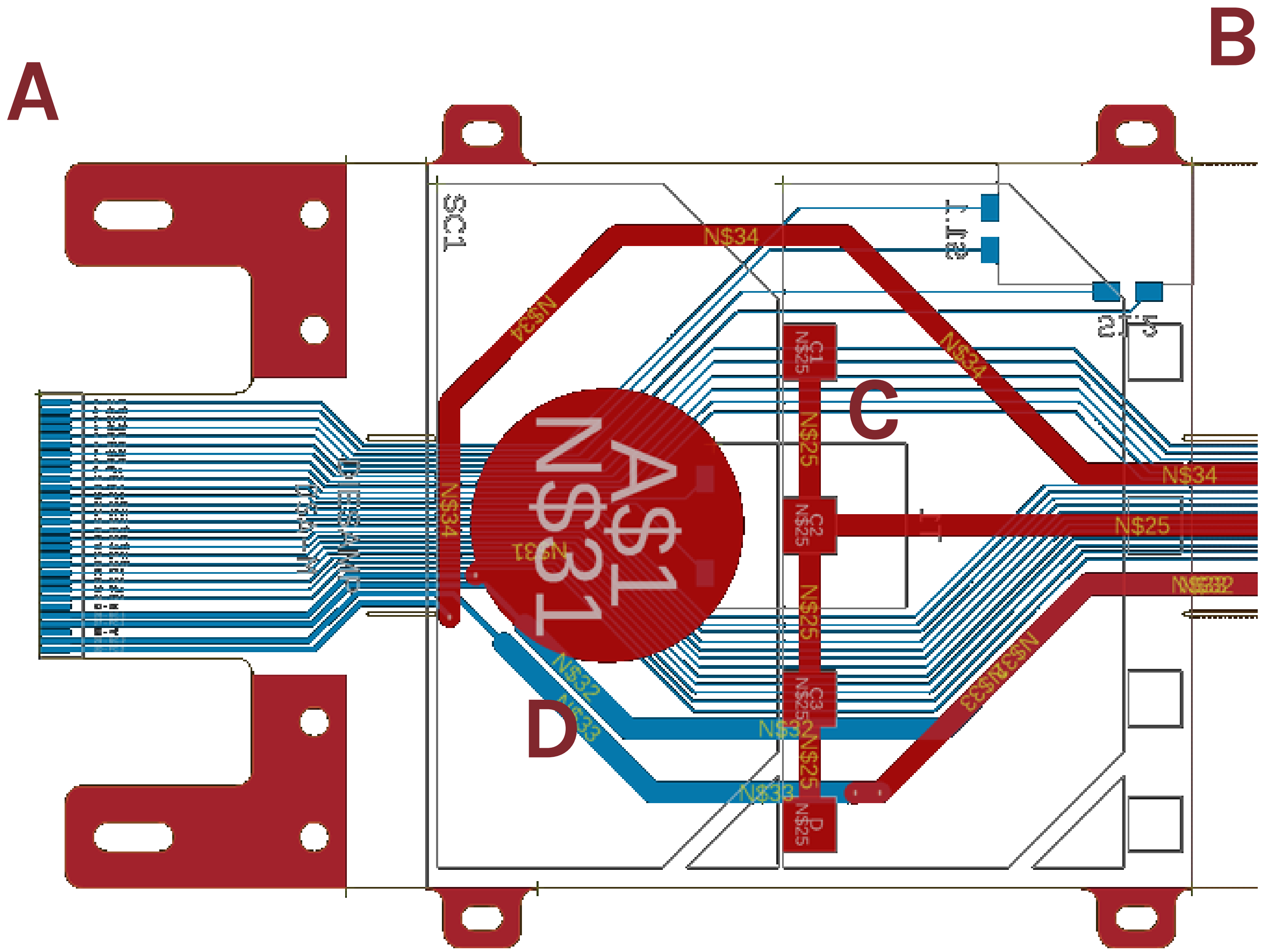
On the right, the CAD of the folded DSA-PV. On the left, a highlight of the connection bridges once the segments are folded (right top) and when the breadboard is in deployed configuration (right bottom).

BREADBOARDS DESIGN

DSA-M: architecture and FPC design



CAD representation of the DSA-M

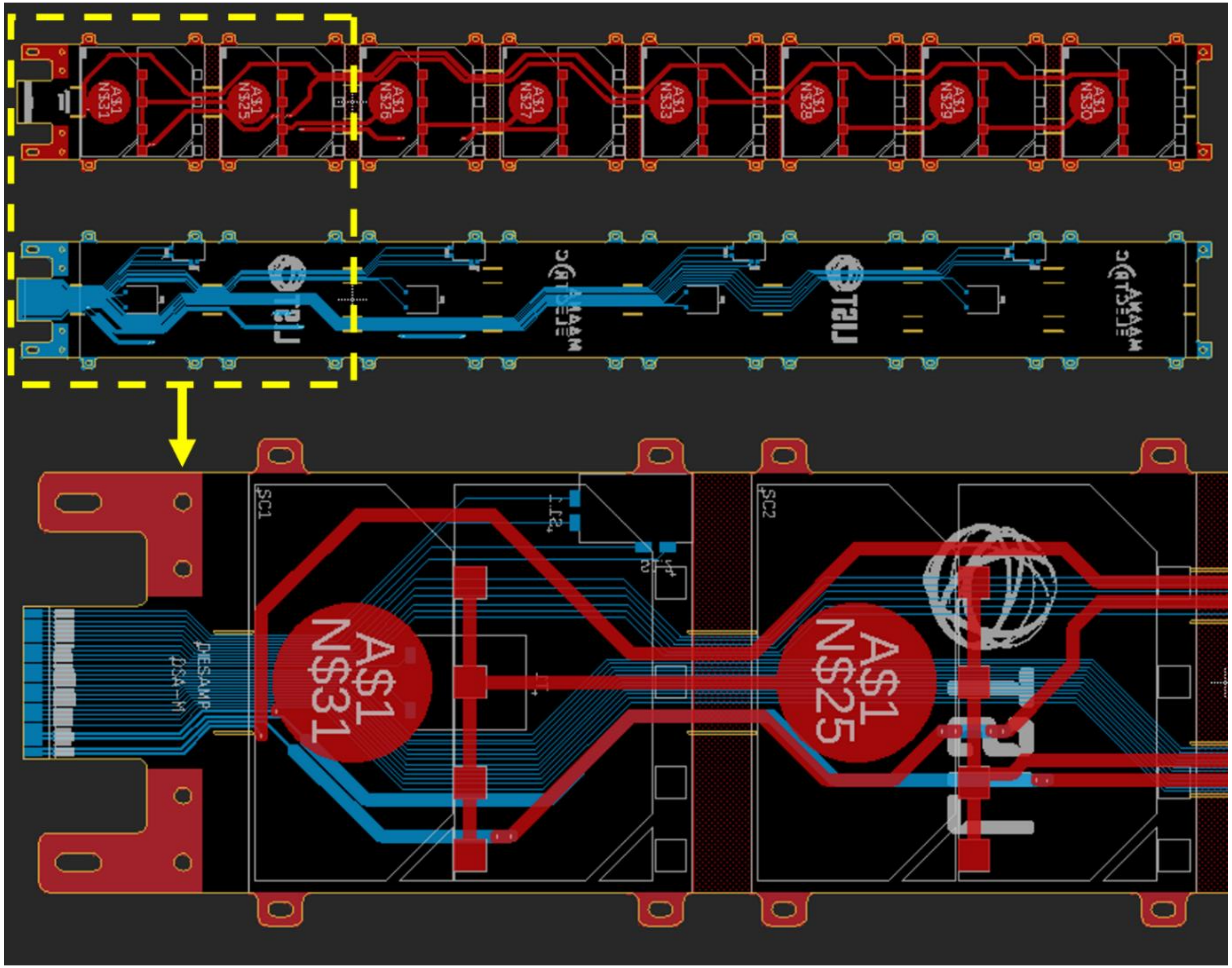


FPC design of the DSA-M

A. Copper-reinforced interface with mounting holes.
B. Loop for fixture to CubeSat and deployment testing.
C. Direct ribbon to FPCB connection.
D. Parallel electrical lines for two strings.

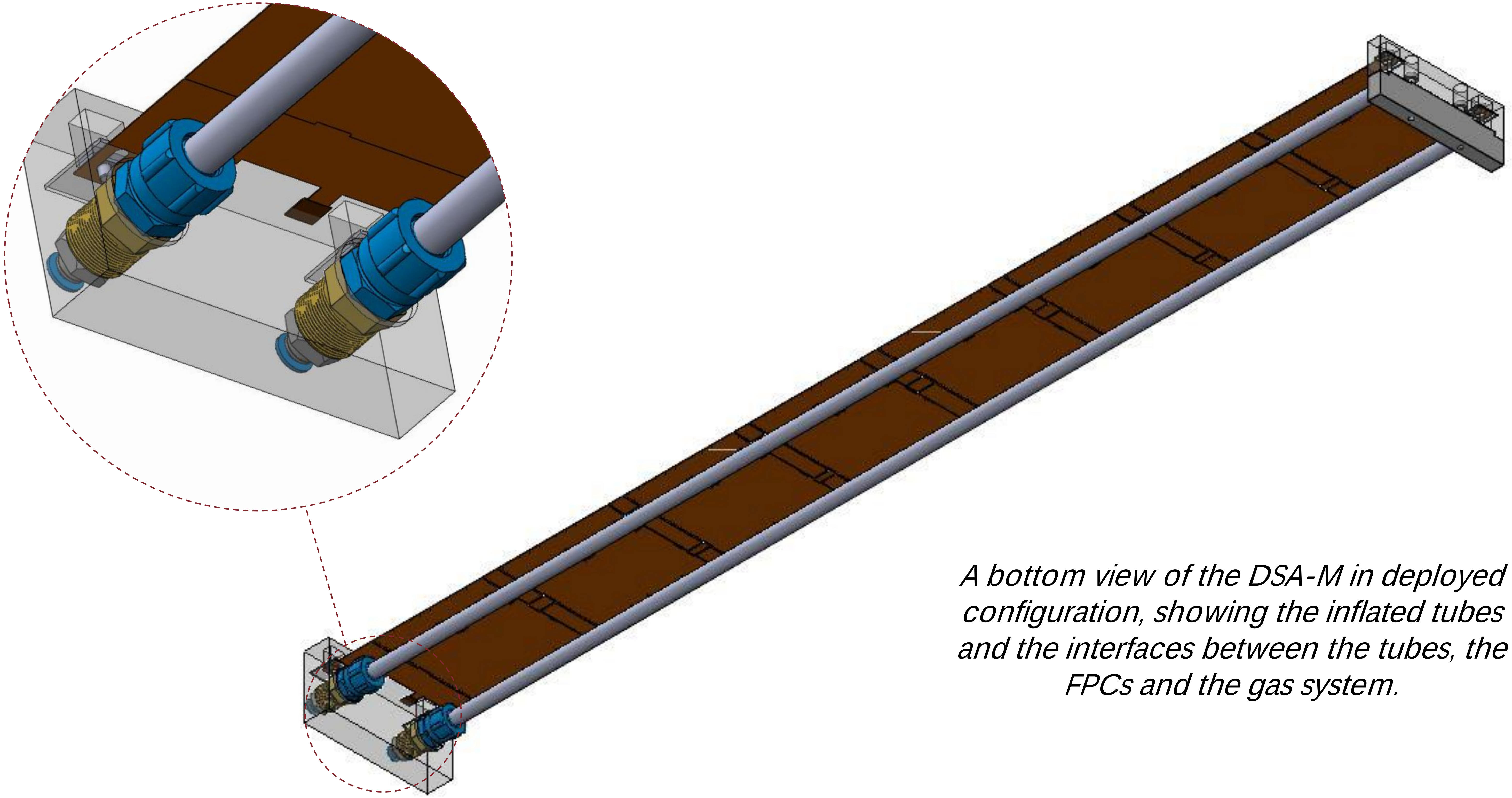
BREADBOARDS DESIGN

DSA-M: electrical and data architecture



BREADBOARDS DESIGN

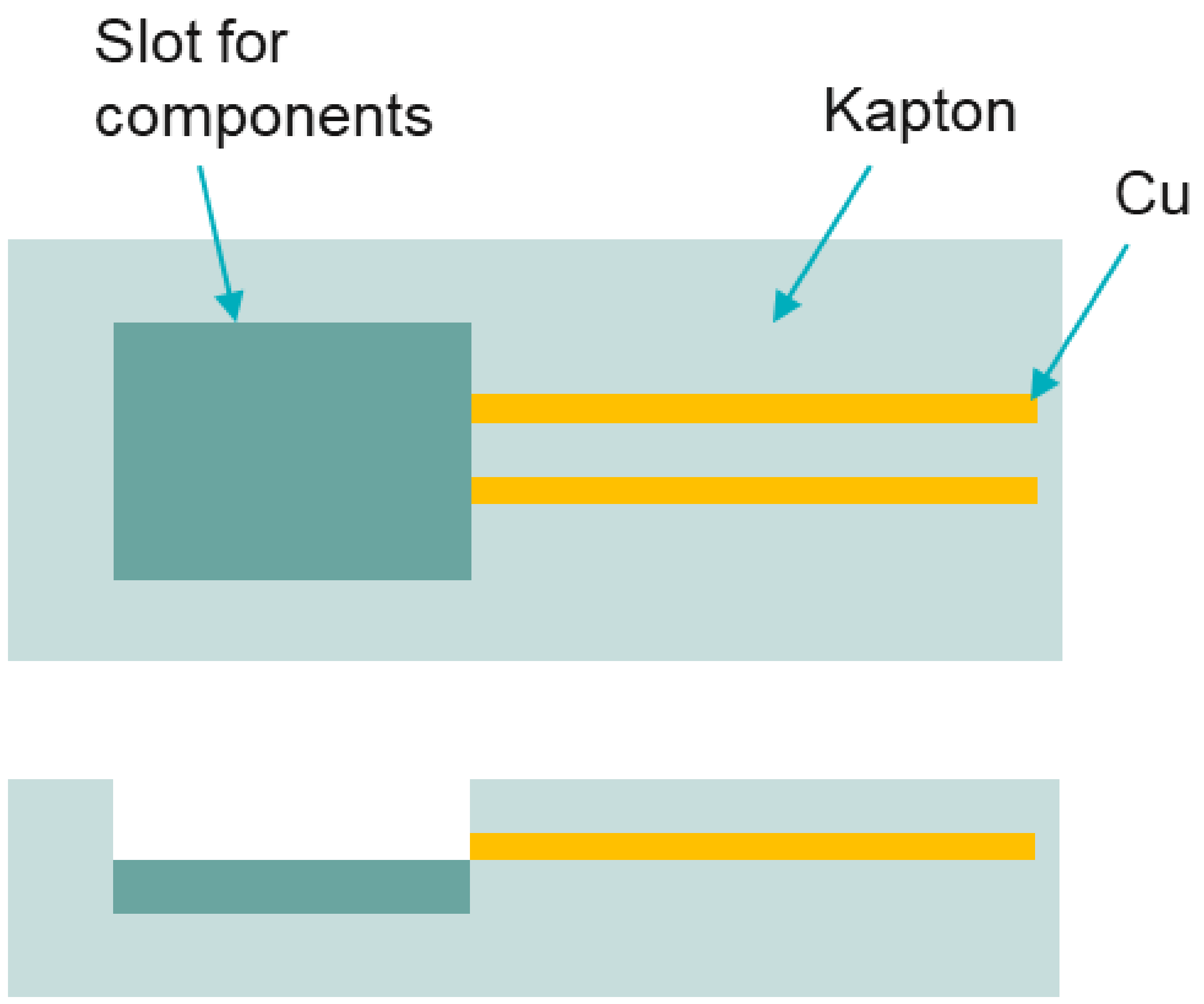
DSA-M: Inflation and deployment system



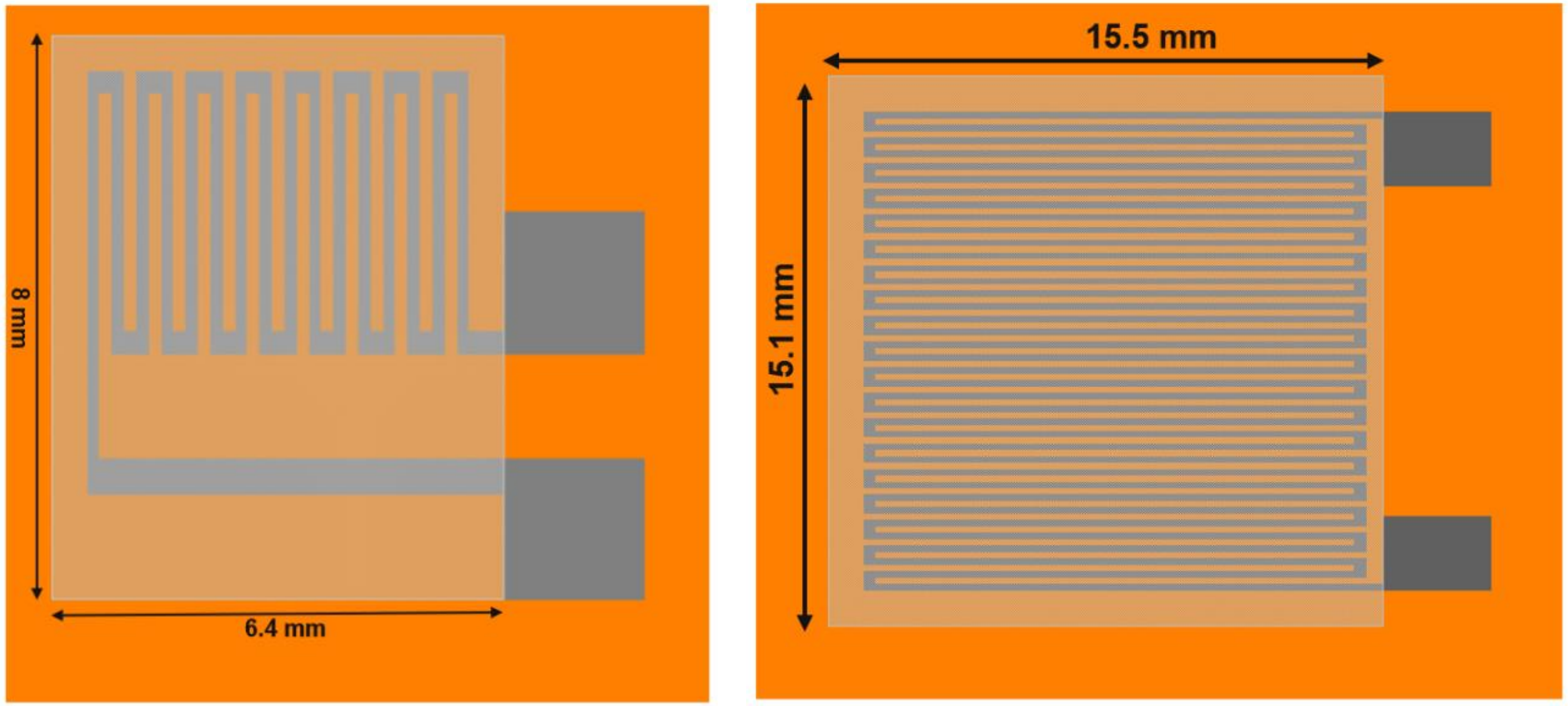
A bottom view of the DSA-M in deployed configuration, showing the inflated tubes and the interfaces between the tubes, the FPCs and the gas system.

BREADBOARDS DESIGN

Sensors design



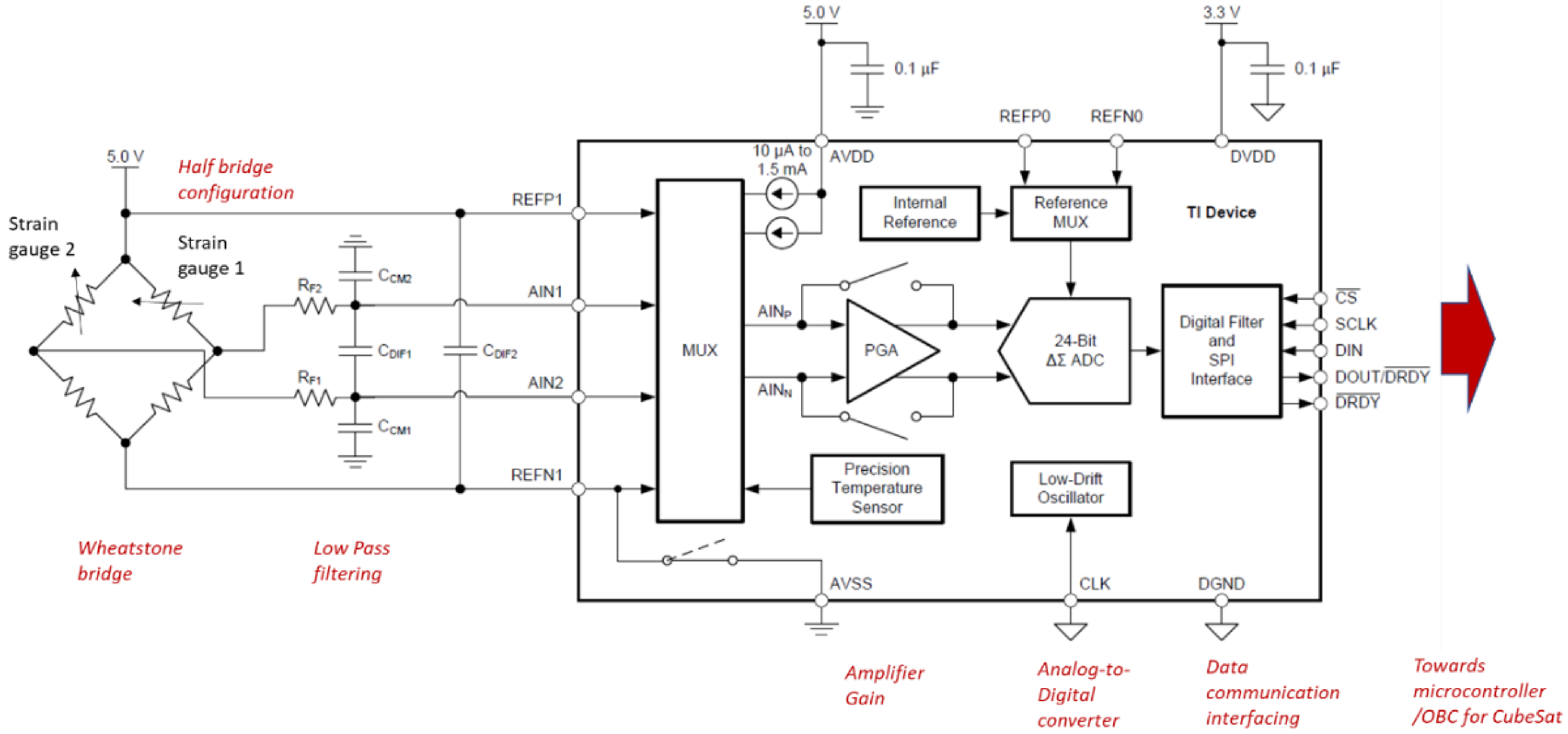
Top and side-view of the flexible PCB design for integration of printed sensors.



Design of the strain (left) and temperature (right) sensors .SU-8 encapsulation footprint is highlighted with the light area.

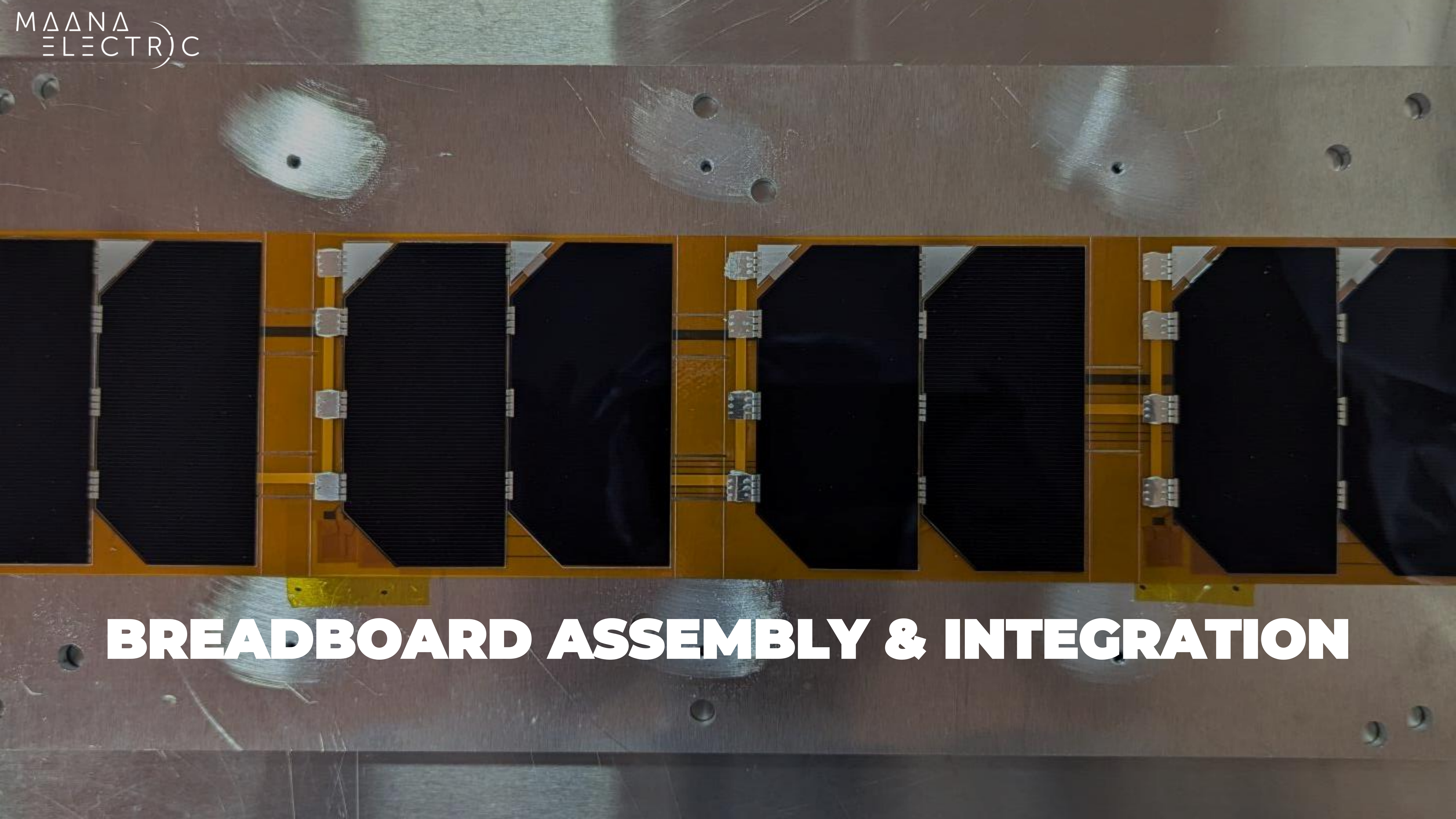
BREADBOARDS DESIGN

DSA breadboards' Data Management System



General view of the measurement chain and with analogue-to-digital data conversion for strain gauge monitoring. Similar diagram for RTD sensors.

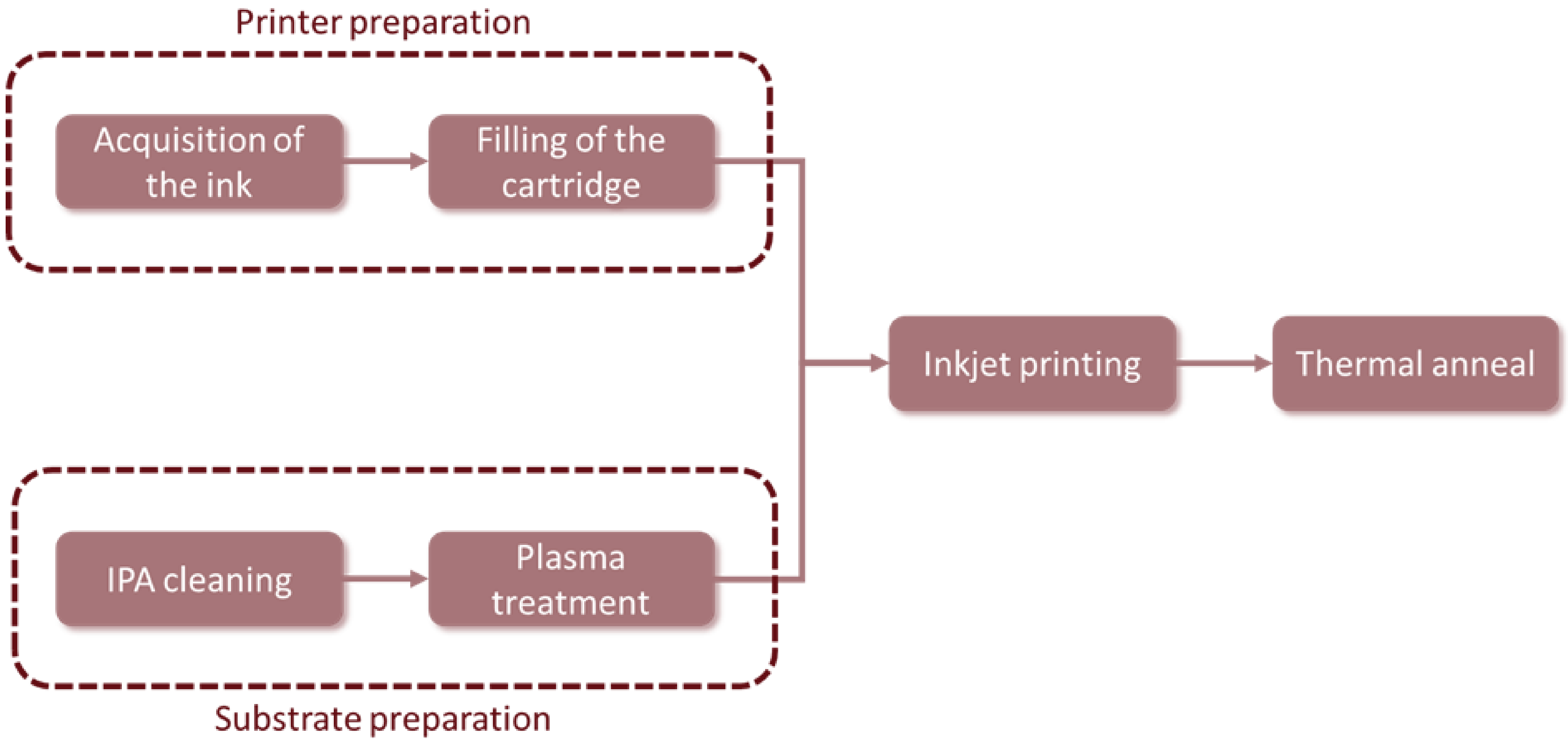
Power supply	Voltage range: from 2.7V to 5.5V Power consumption: Standby mode: <100uW; acquisition/ transmission mode: <50mW
ADC with integrated PGA	Programmable gain from 1V/Vto128V/V Effective resolution of 20 bits SPI interface Data rate up to 1kSps
Microcontroller	SPI interface Integration of RTC for sleep mode
Can controller	SPI interface CAN V2.0B implementation Data rate up to 1Mbps
Data transferred	Temperature: minimum 16bits Deformation: minimum 16bits Status: 16bits Setting parameter data: 32bits
Software	ECSS-E-ST-50-15C CANbus extension protocol



BREADBOARD ASSEMBLY & INTEGRATION

ASSEMBLY & INTEGRATION

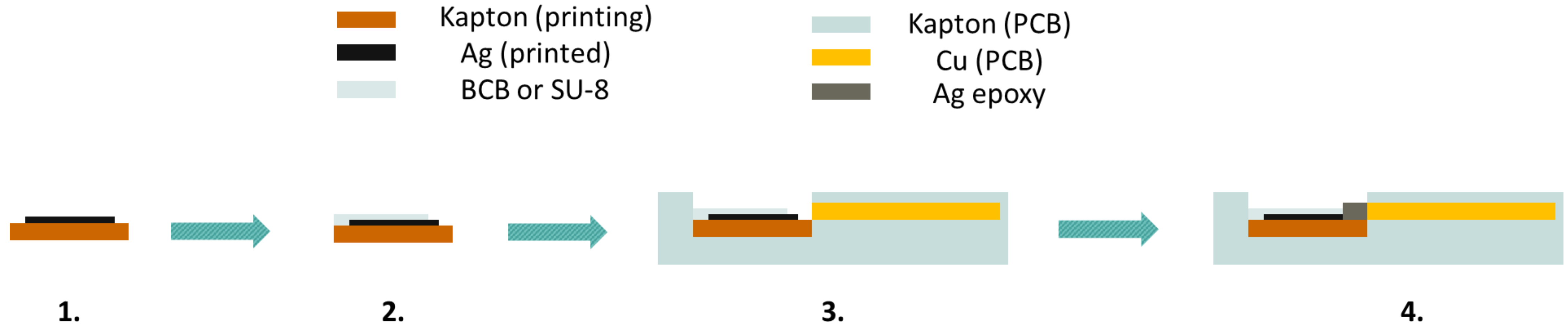
Sensors: manufacturing and integration



Two strategies were evaluated:

- **In-situ printing**, which integrates sensors directly into the array for better contact and efficiency but requires material compatibility.
- **Ex-situ printing**, which simplifies compatibility by printing sensors separately but requires an additional attachment step.

The second was preferred to match surface finishing of FCB.

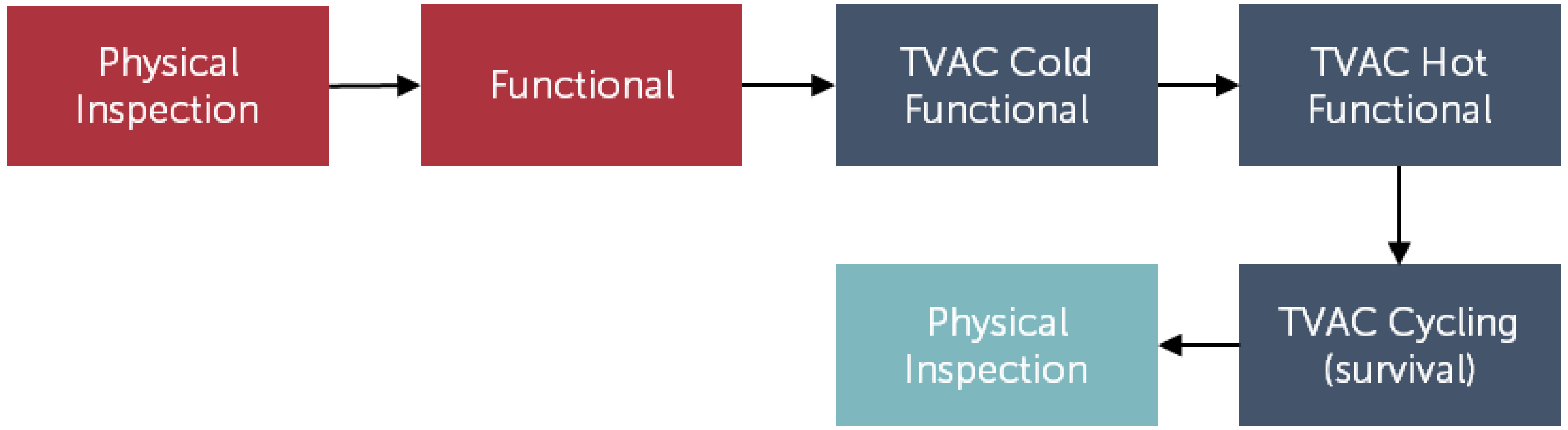


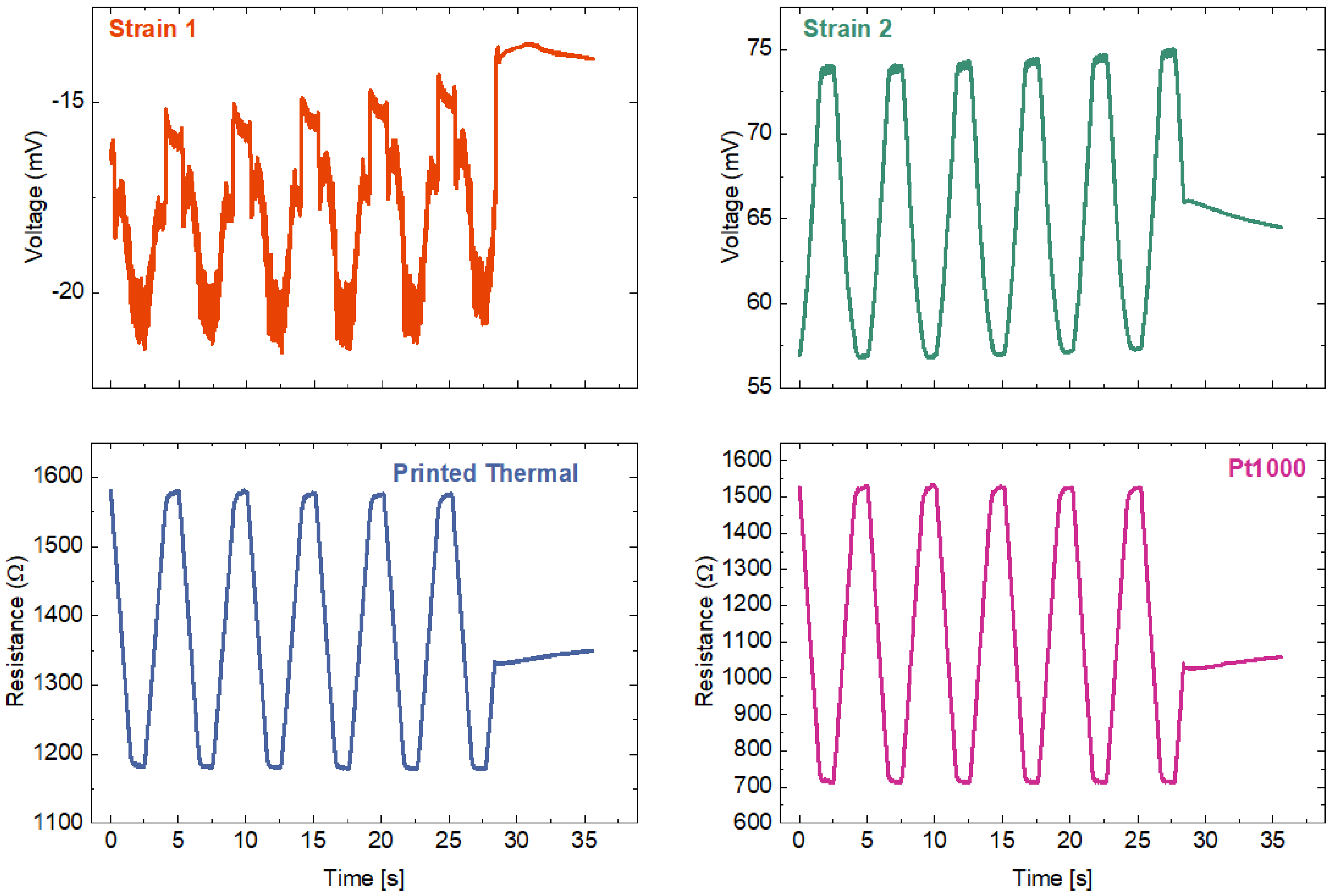
Flow of integration of printed sensors into the DSA breadboards:

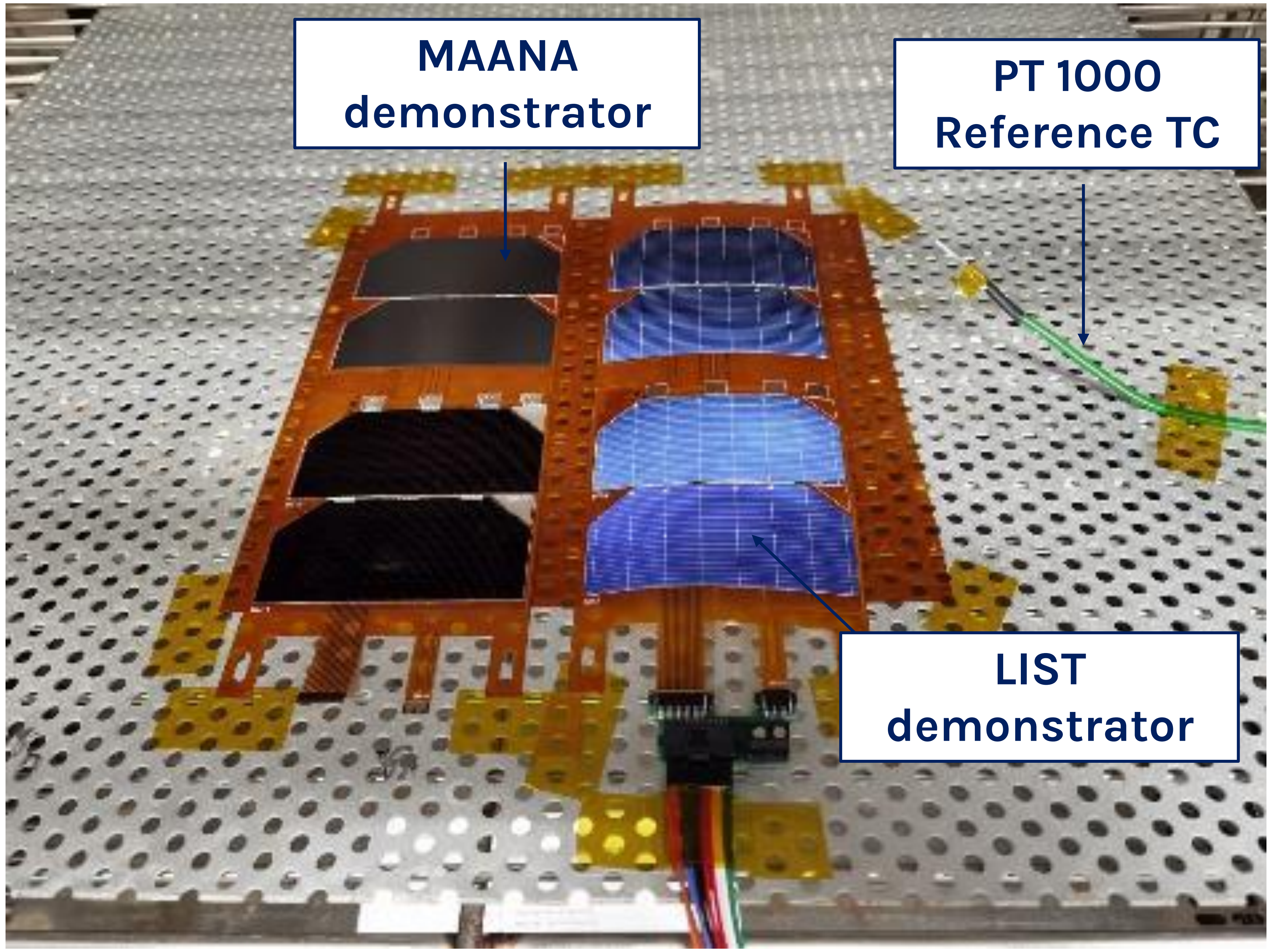
1. Printing of the gauge and the pads.
2. Spray-coating of an encapsulant.
3. Gluing sensors onto the flexible PCB.
4. Application of Ag epoxy.

ASSEMBLY & INTEGRATION

Sensors-level testing and verification



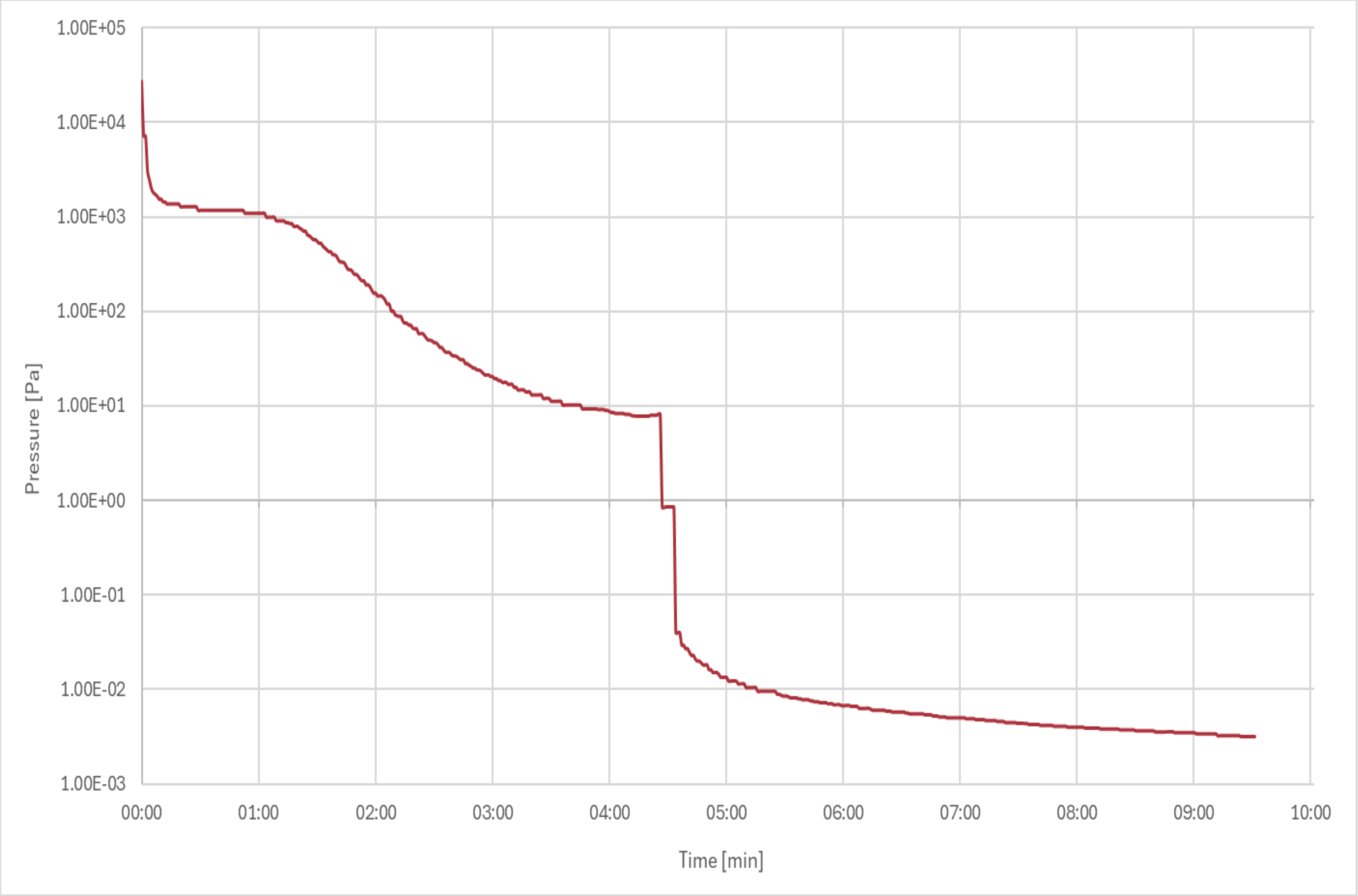


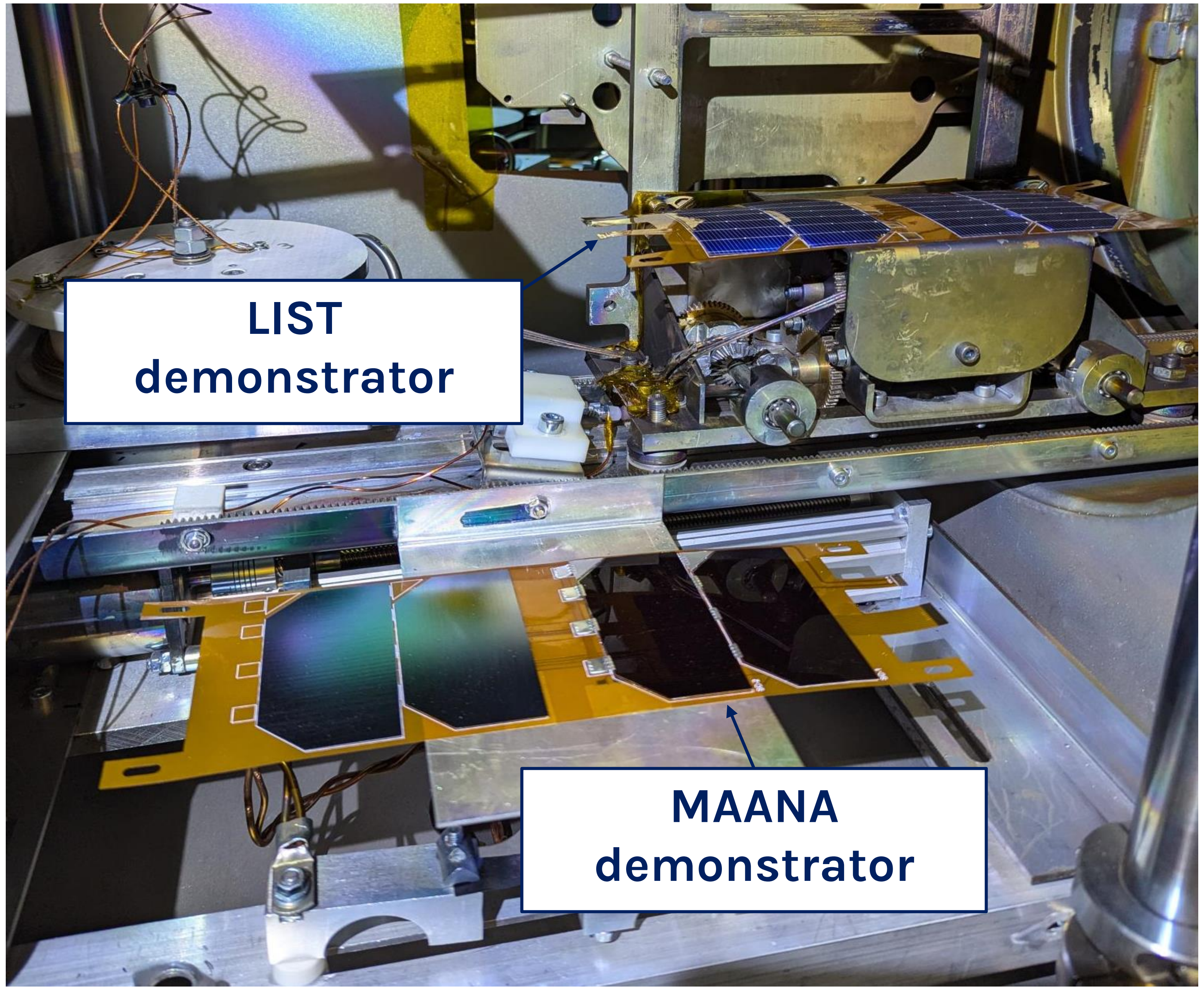


Sensors were tested by integration on prototype FPC. Thermal tests performed in environmental chamber at 1 atm for 10 cycles between -60°C and 120°C.

ASSEMBLY & INTEGRATION

Physical Inspection → Functional → TVAC Cold Functional → TVAC Hot Functional → TVAC Cycling (survival) → Physical Inspection

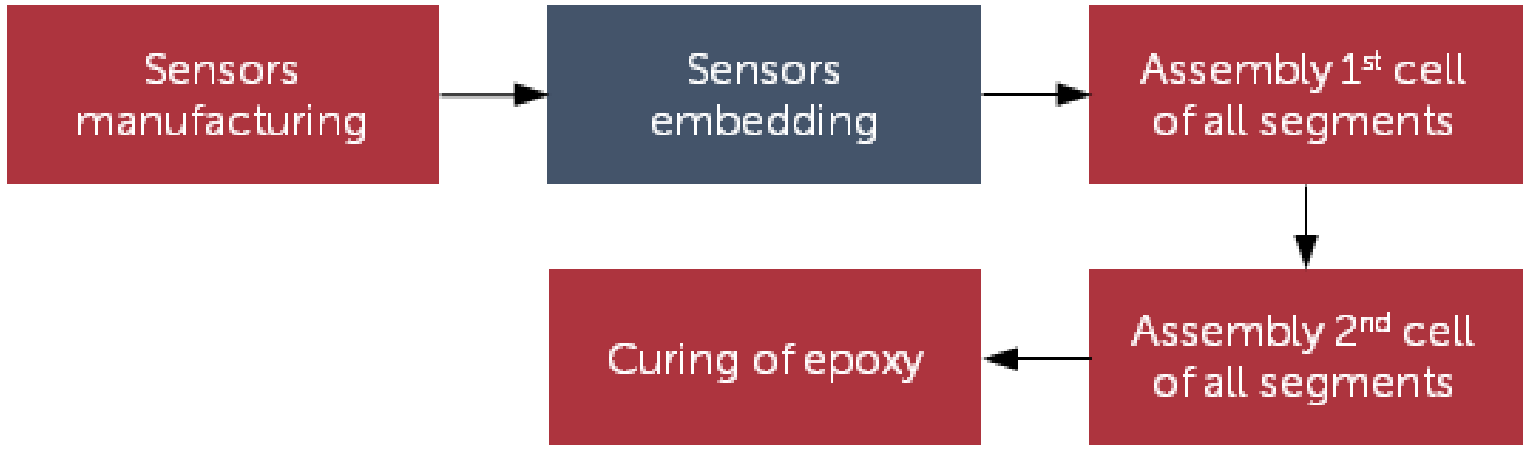


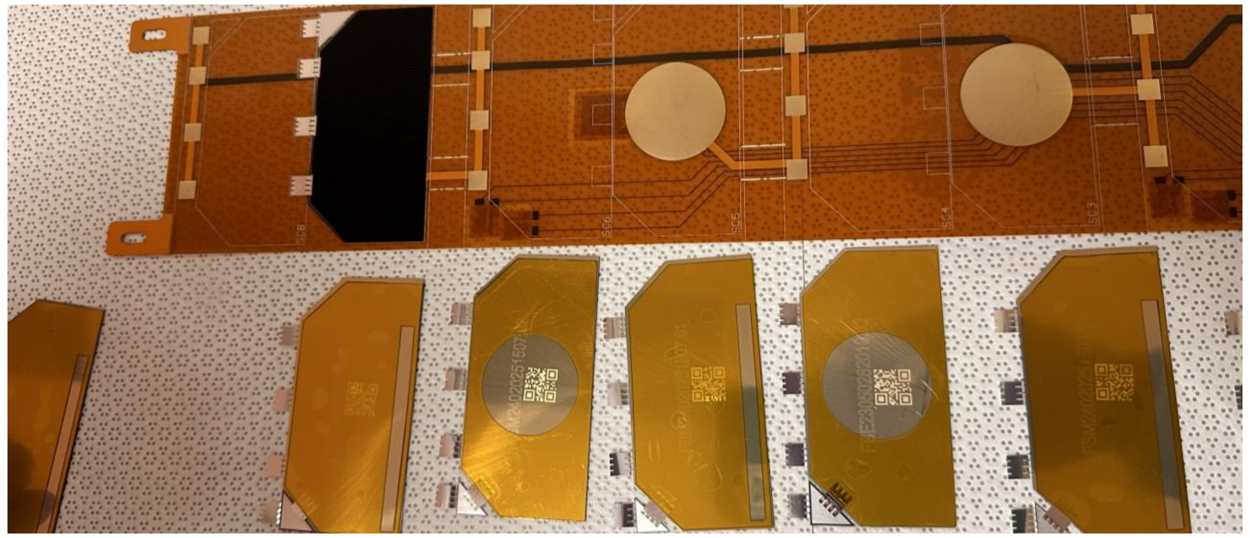


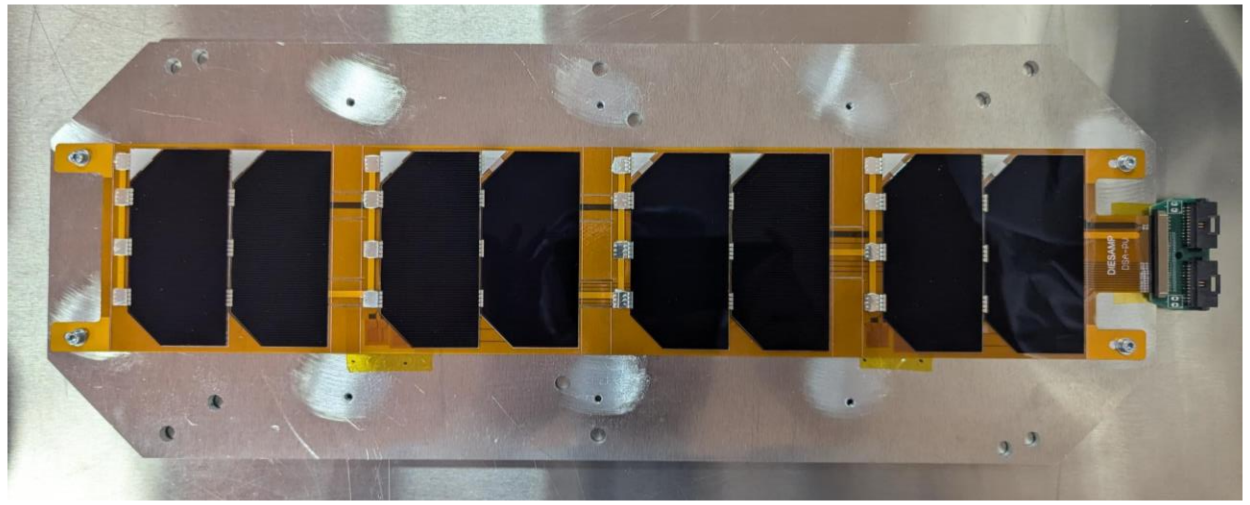
Sensors also tested in vacuum chamber from ambient pressure to 3x10-3 Pa (3x10-5 mbar) in <10 minutes.

ASSEMBLY & INTEGRATION

DSA-PV: assembly and integration



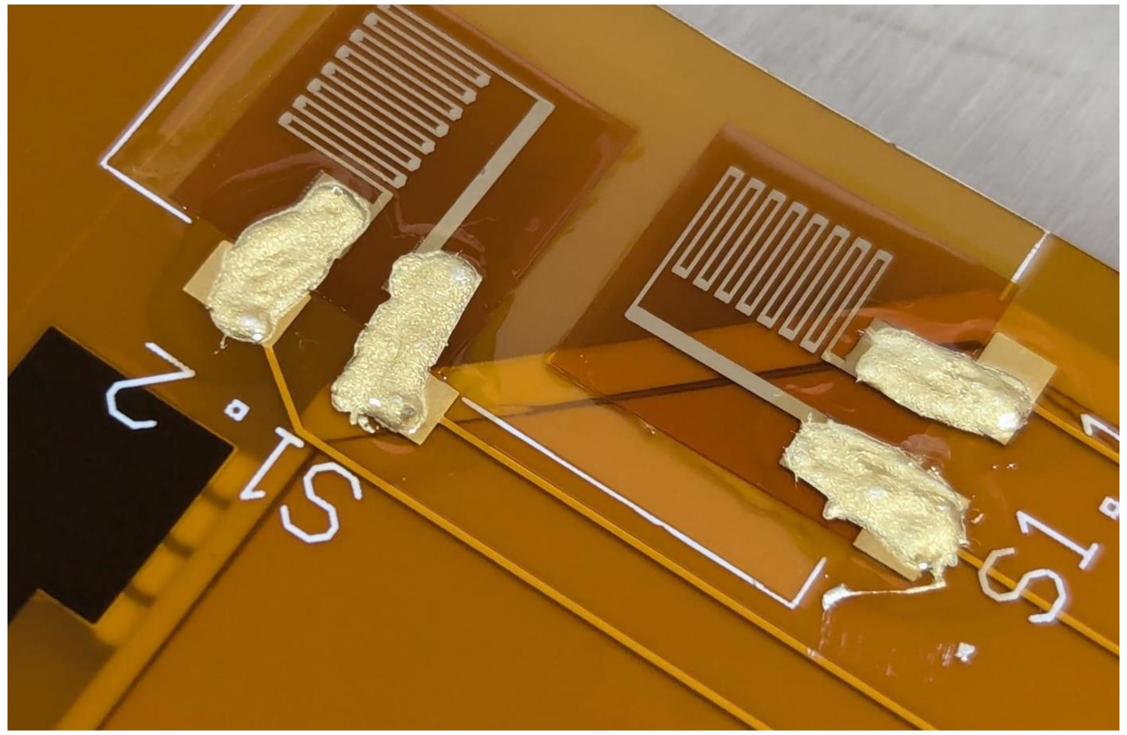


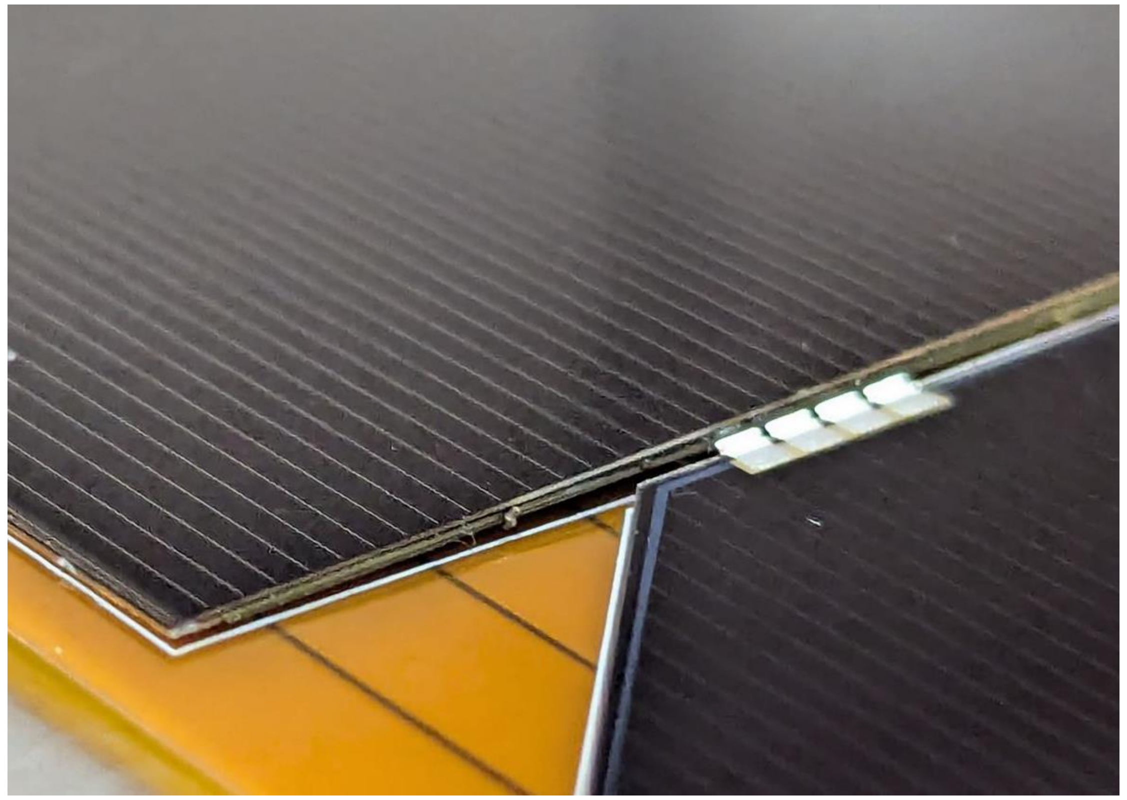


Name	A/I	Description
Sensors' manufacturing	A	The sensors are manufactured following the process outlined in section 5.4.1
Sensors' embedding	I	The sensors are integrated following the process outlined in section 5.4.1
Assembly 1st cell of each segment	A	Half of the PV cells are cleaned. Silicone adhesive pieces are cut and attached to the FPC surface. Bi-component silver epoxy is mixed. Epoxy is laid on the back contact surface of the first cell. The first cells of each segment is placed on top of the adhesive in correct position. Each cell is gently pressed to guarantee uniform spreading of the silver epoxy. The interconnection of the front connection of the first cells are attached on the FPC though silicone adhesive.
Assembly 2nd cell of each segment	A	The remaining PV cells are cleaned. Silicon adhesive pieces are cut and attached to the FPC surface. Bi-components silver epoxy. A small droplet of epoxy is applied on top of the interconnections of first cells and on the pads of the interconnections of the second cell. The second cells of each segment are placed on top of the adhesive in the correct position. The interconnections of the second cells are gently pressed on top of the epoxy droplets to guarantee electrical contact.
Curing of cell-to-FPC epoxy	A	The FPC with the PV cells on top is cured at 120°C (TBC) for 15 minutes (TBC). The breadboard is cooled down to room temperature.

ASSEMBLY & INTEGRATION

DSA-PV: inspection





Inspection

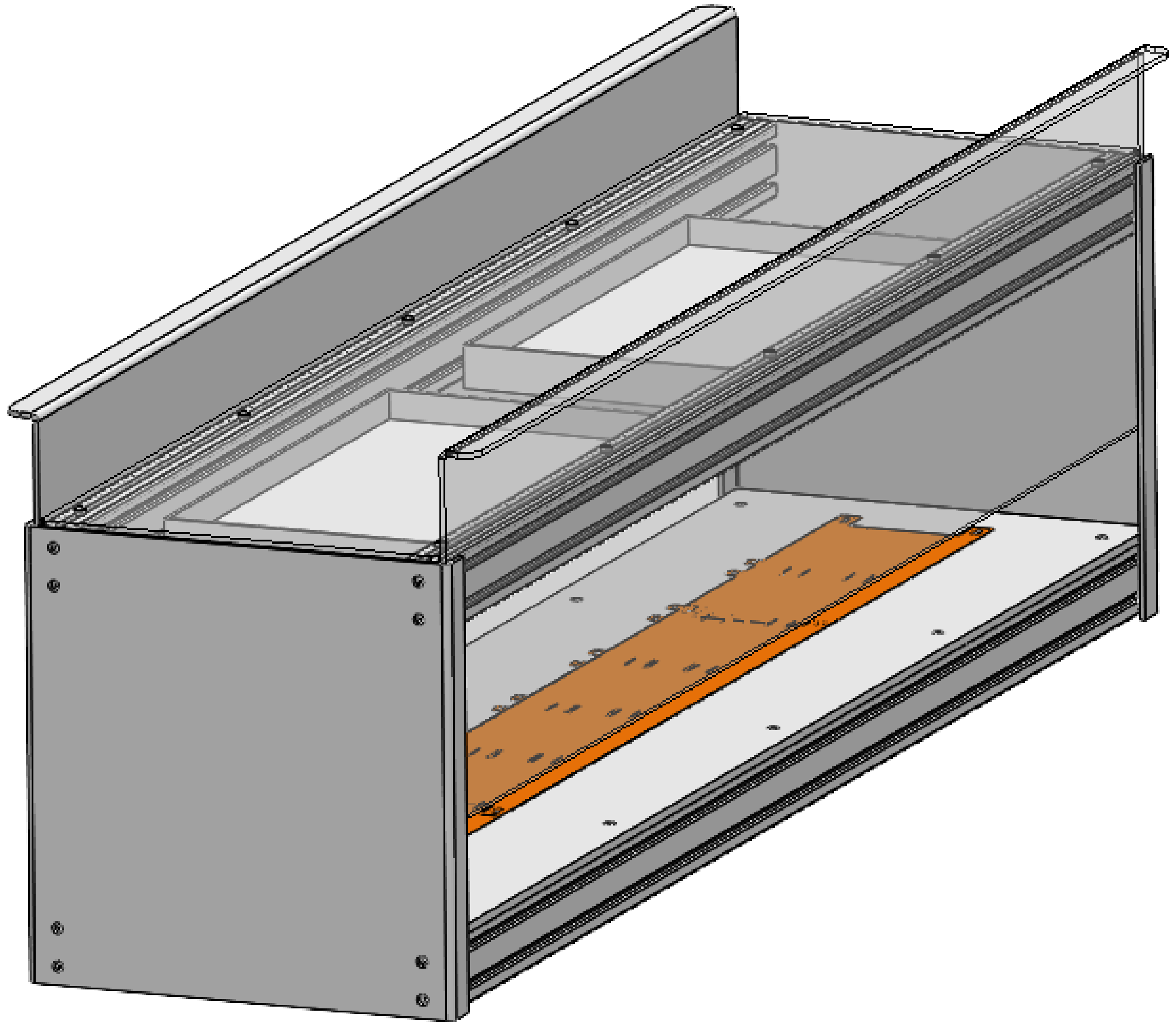
Pass/Fail criteria	**Status after testing**
The sensors are individually compliant to pass/fail criteria of "Physical Inspection".	Inspection successful. Two defects were found. 1) **The silver epoxy used to perform the electrical connection was not very flat** with some "spikes". These defects can induce localized stresses which may damage the cell during integration procedure. 2) **Yellowing of the silver epoxy detected after curing of cell's connection** (left of Figure 26). Resistance of the sensors consequently increased. As strain values of individual gauges in strain sensors are still close to each other, this change is considered acceptable.
The FPC does not show delamination, discontinuous pattern of the electrical circuits, damage or oxidation of the exposed contact pads, damage (cracking or wrinkling) of the Kapton substrate.	FPC does not show delamination of its structure. FPC does not show cracking nor wrinkling of its structure. Electrical circuit continuity checked with multimeter.
The FPC can be bent on the flexible junctions without any damage to the laminated structure.	The FPC was not bent to preserve as much flatness as possible, recommended for optimal execution of TVAC.
The sensors are properly glued to the laminated structure.	Sensors still glued and with electric contact to the FPC.
The PV cells do not show macro-cracks or damage to the cell substrate, to the cover glass, to the interconnectors and diodes. The PV cells are securely glued to the Kapton substrate without any evident sign of delamination.	Inspection successful. The **two cells near the strain sensors (cells #2 and #6) are slightly delaminated** at the start of the cell (right of Figure 26). The presence of non-flat surface due to excessive encapsulation of sensors incentivized delamination of the cell from the adhesive. The cells look anyway solidly attached to the PCB.
It is possible to connect the breadboard to the interfaces with the data management system and electrical load.	Correctly connected and data connection confirmed.

MAANA ELECTRIC

ASSEMBLY & INTEGRATION

DSA-PV: functional test

A **Light Box** based on LED has been used to test PV performance of a flexible solar array. The setup is conceptually similar to the one presented in the previous review (Pedivellano, 2023) but improved as it proved a completely closed (i.e. repeatable) test environment. The PV performance is read by an **electrical load** KORAD KEL 102.

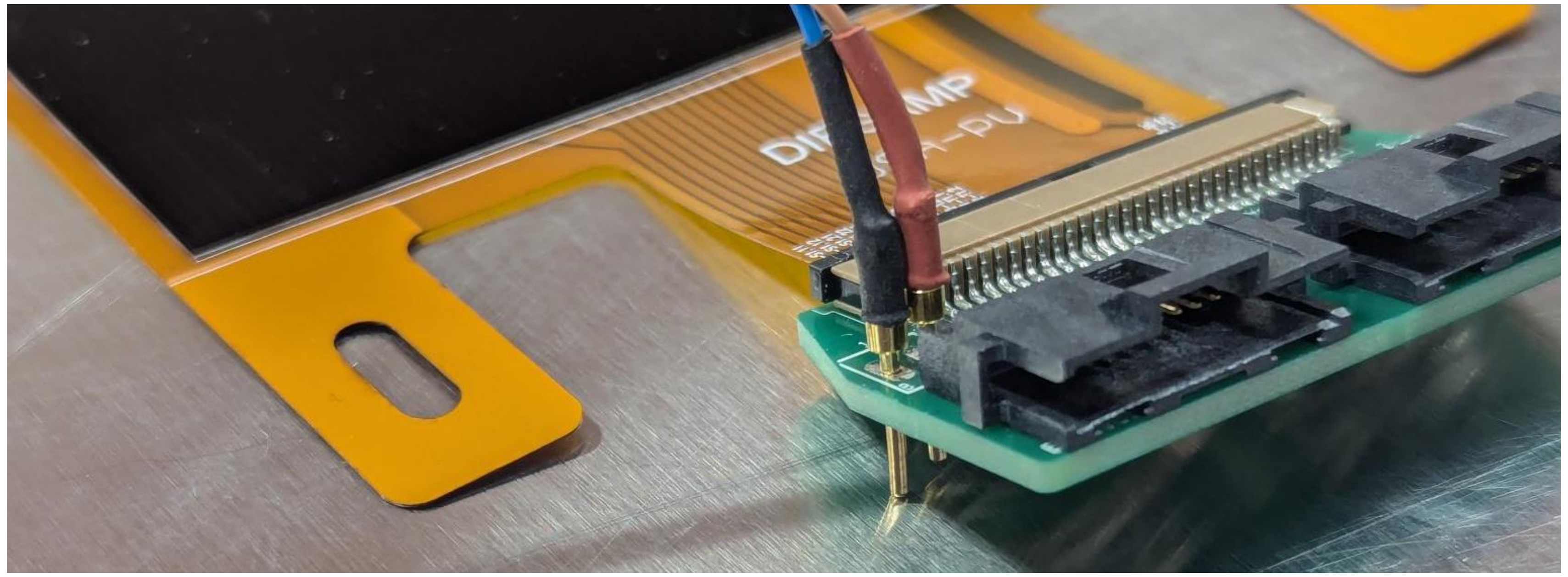


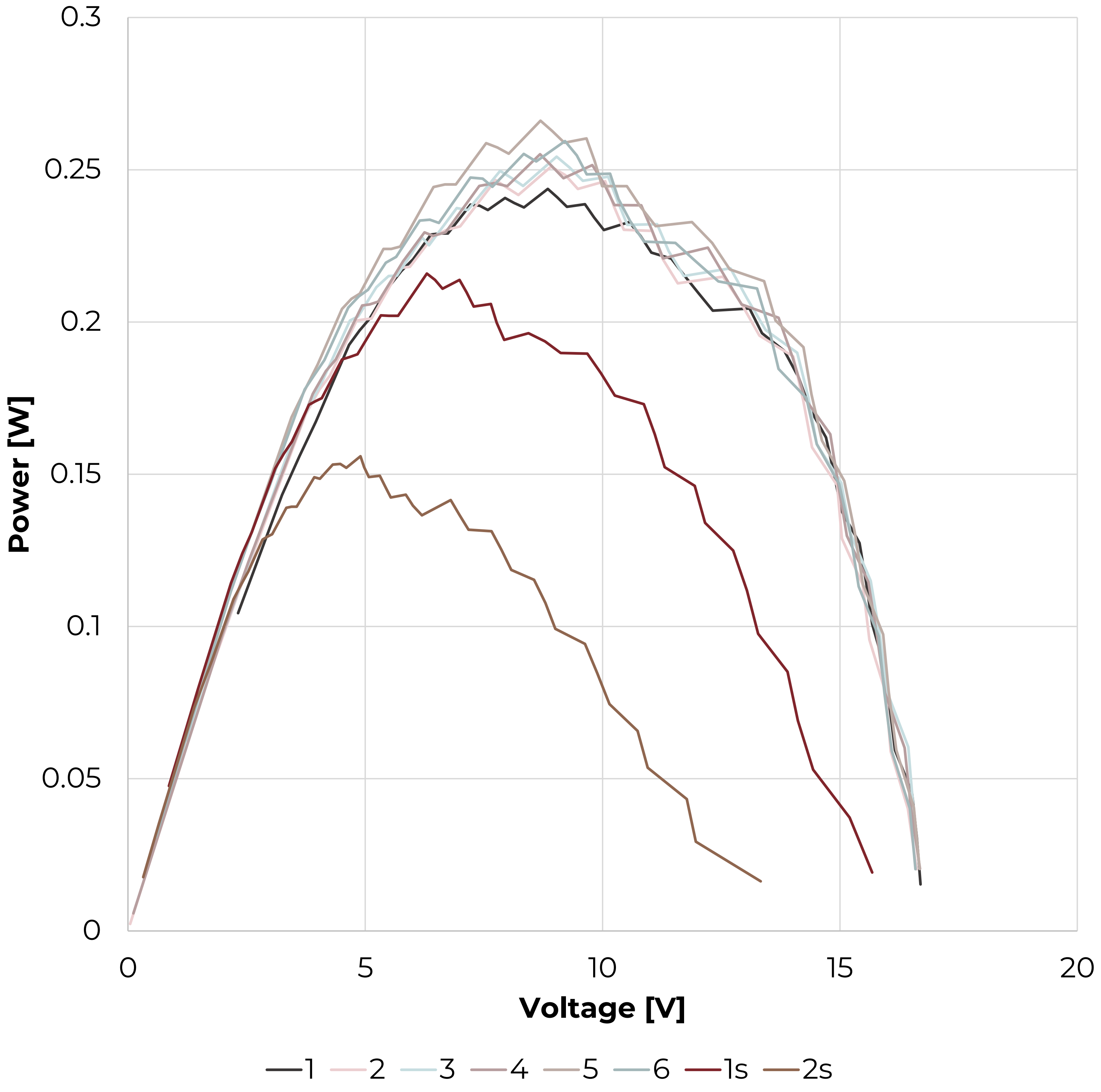
CAD of the Light Box to monitor PV performance degradation during testing campaign.

Electrical load KORAD KEL 102

ASSEMBLY & INTEGRATION

DSA-PV: functional test



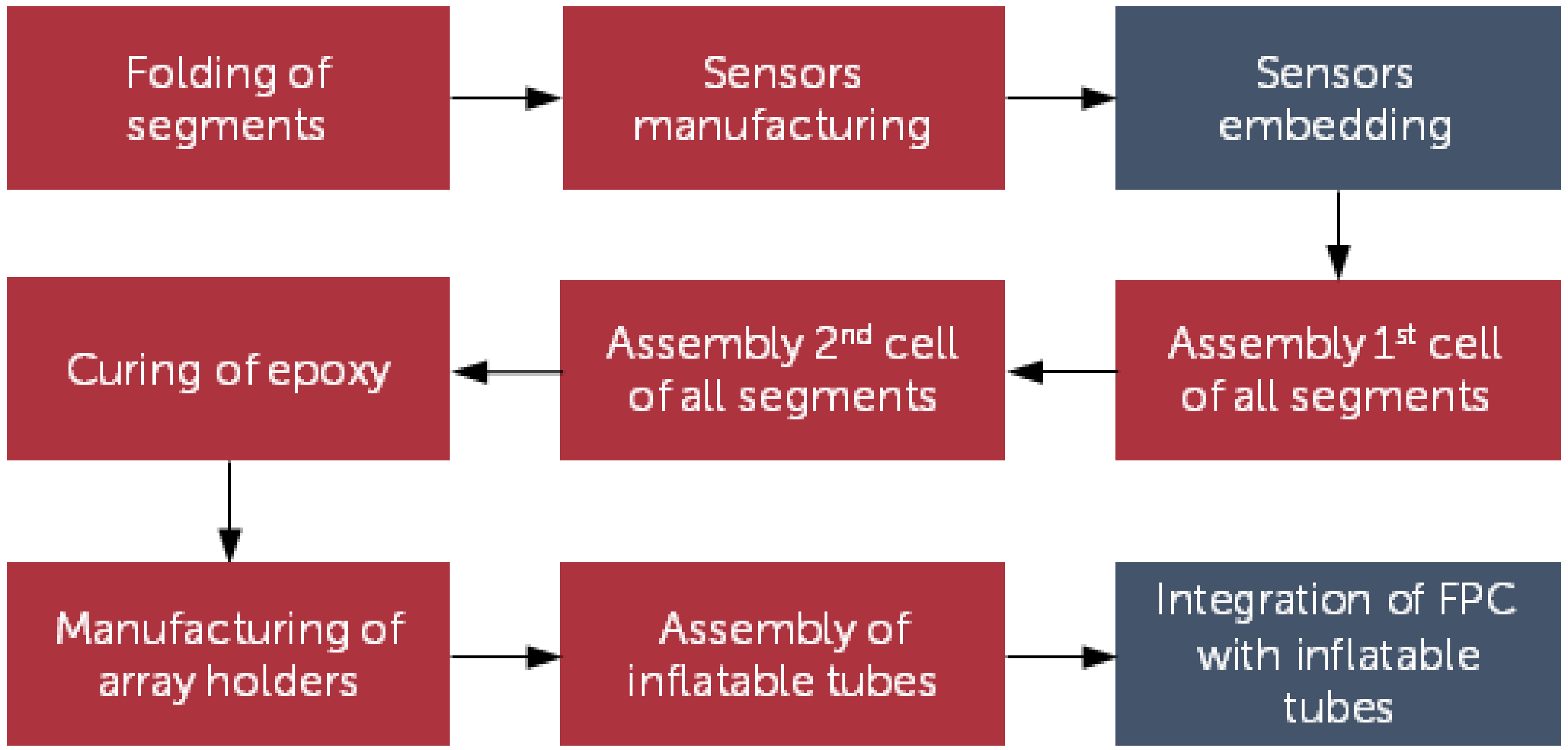


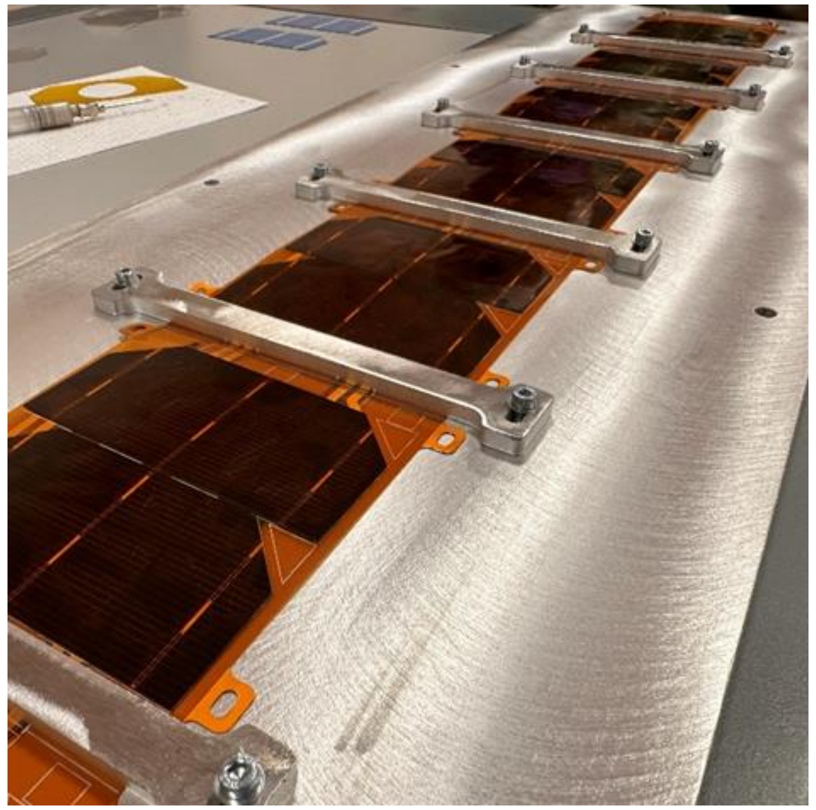
Repeatability of PV performance reading has been tested on 6 repetitions on DSA-PV. **Shading** 1 and 2 cells has been also performed to verify ability to detect failure.

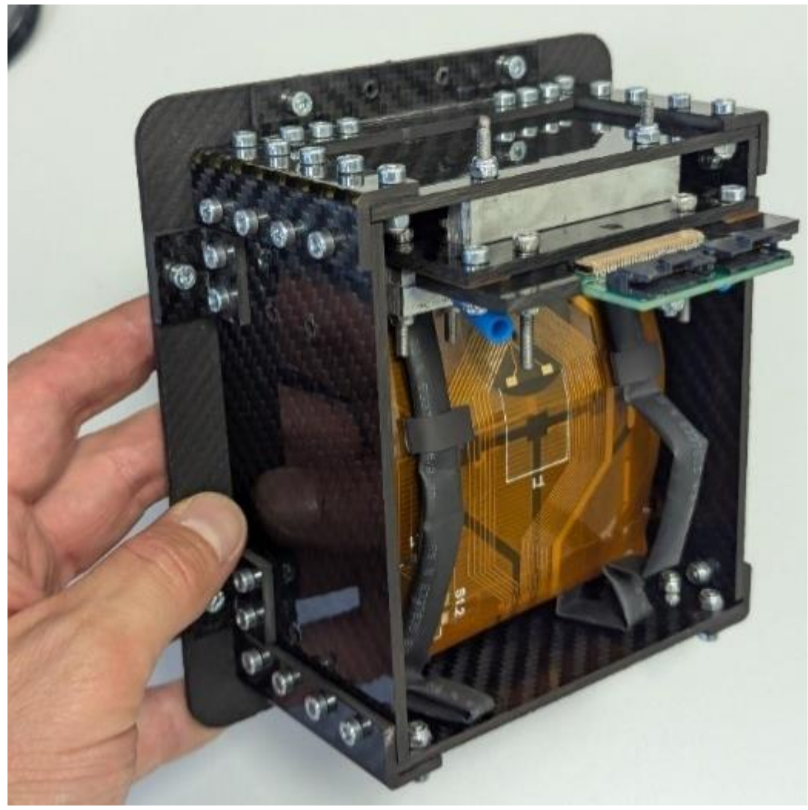
MAANA ELECTRIC

ASSEMBLY & INTEGRATION

DSA-M: assembly and integration



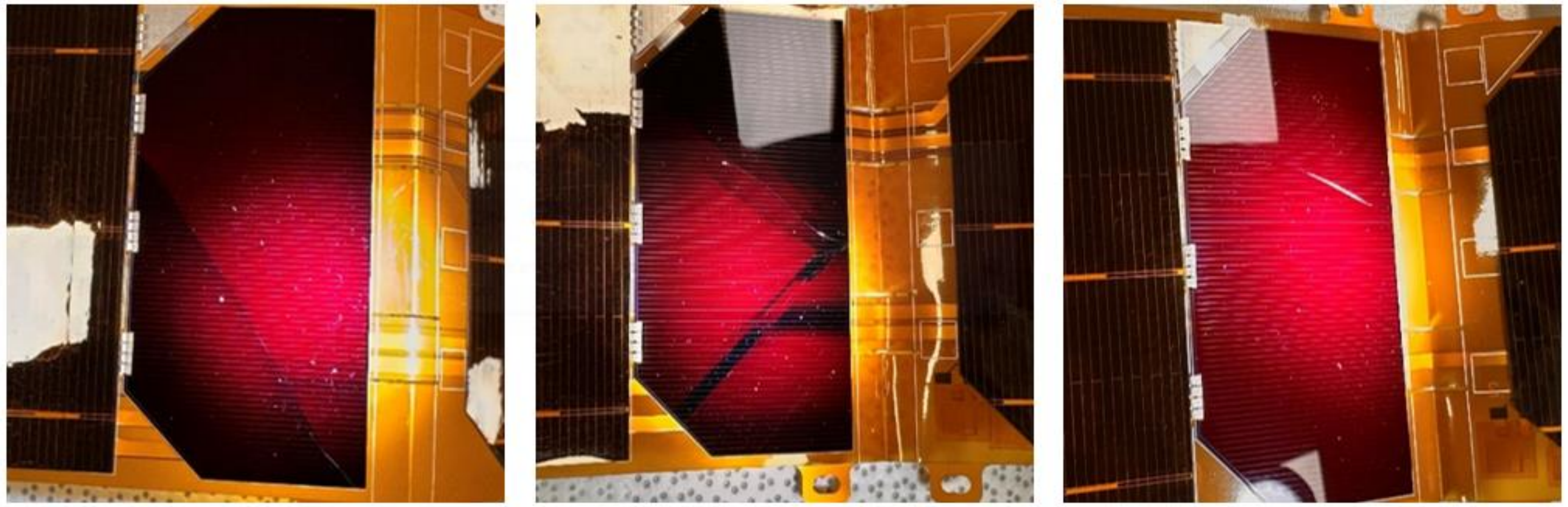




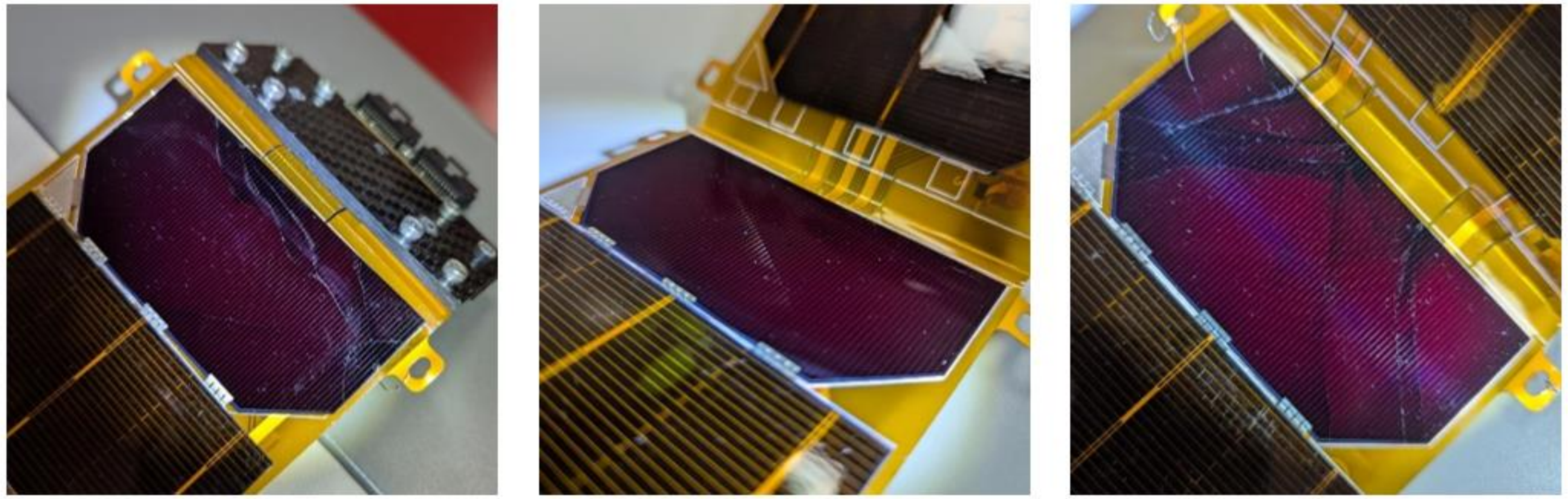
Name	A/I	Description
Folding of segments	A	The FPCB is bended on the folding lines leaving the bridges free to bend following their natural curvature.
Sensors' manufacturing	A	As in Sensors integration.
Sensors' embedding	I	As in Sensors integration.
Assembly 1st cell of each segment	A	As for DSA-PV. The interconnections of the front connection are pressed on the epoxy droplet to guarantee electrical contact.
Assembly 2nd cell of each segment	A	The mechanical cells are cleaned. Silicon adhesive pieces are cut and attached to FPC surface. The 2nd cells of each segment are placed on top of the adhesive in the correct position.
Curing of epoxy	A	As in DSA-PV.
Manufacturing of array holders	A	The two array holders are printed with ABS 3D printing machine. Pneumatic threads are machined and assembled.
Assembly of inflatable tubes	A	The tubes are inserted in pneumatic thread and heated up to adhere. Pneumatic interface is closed on the inflatable tube. The end of the inflatable tube is glued with silicone adhesive and secured in the front holder. The gas-supplying system is interfaced with the rear holder and is activated to check if the two tubes exhibit any buckling during inflation. If so, the length of the tubes between the two holders must be re-assessed.
Integration of FPC with inflatable tubes	I	The integrated FPCs are secured to the front and rear holders. The gas-supplying system is gently activated to check the matching between the tubes assembly and the FPCs assembly. If the tubes exhibit buckling or the FPCs look under-deployed, the tolerance of positioning of the front holder and the FPCs assembly shall be assessed.

ASSEMBLY & INTEGRATION

DSA-M: inspection



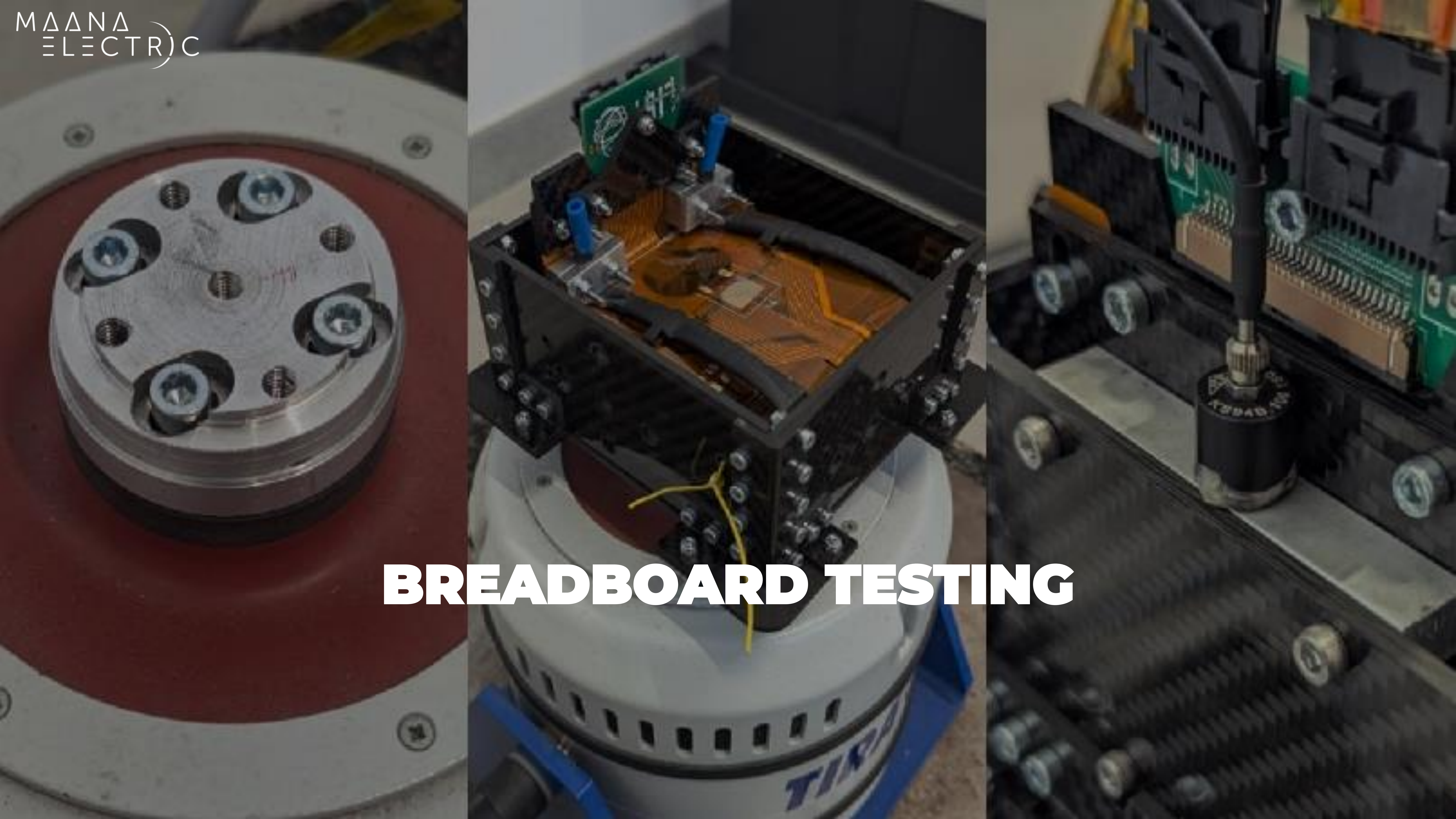
Cracks induced in the cells #3, #4 and #8 after folding manually the array



Cracks in cells #1, #7 and #8 were experienced after the packing of the array

Physical Inspection	
Pass/Fail criteria	Status after testing
The sensors are individually compliant to pass/fail criteria of “Physical Inspection”.	Inspection successful. **Yellowing of the silver epoxy was again detected** (as for DSA-PV) after curing of cell’s connection. Resistance of the sensors again increased as already reported for DSA-PV. The change is considered acceptable as the resistances of strain sensors remained close.
The FPC does not show mechanical and electrical incompliances,	Inspection successful.
The FPC can be bent on the flexible junctions and sensors are properly glued to the laminated structure.	Inspection successful.
The PV cells are securely glued to the substrate and do not show damage to the cell substrate, to the cover glass, to the interconnectors and diodes.	**Damages were reported on cells after bending and packing**.
The inflation tubes have good adhesion with the pneumatic holders and do not show any sign of damage (cuts or perforation) on the walls.	Inspection successful.
The data management system, electrical load and gas-inflation system can be interfaced.	Inspection successful.

MAANA ELECTRIC

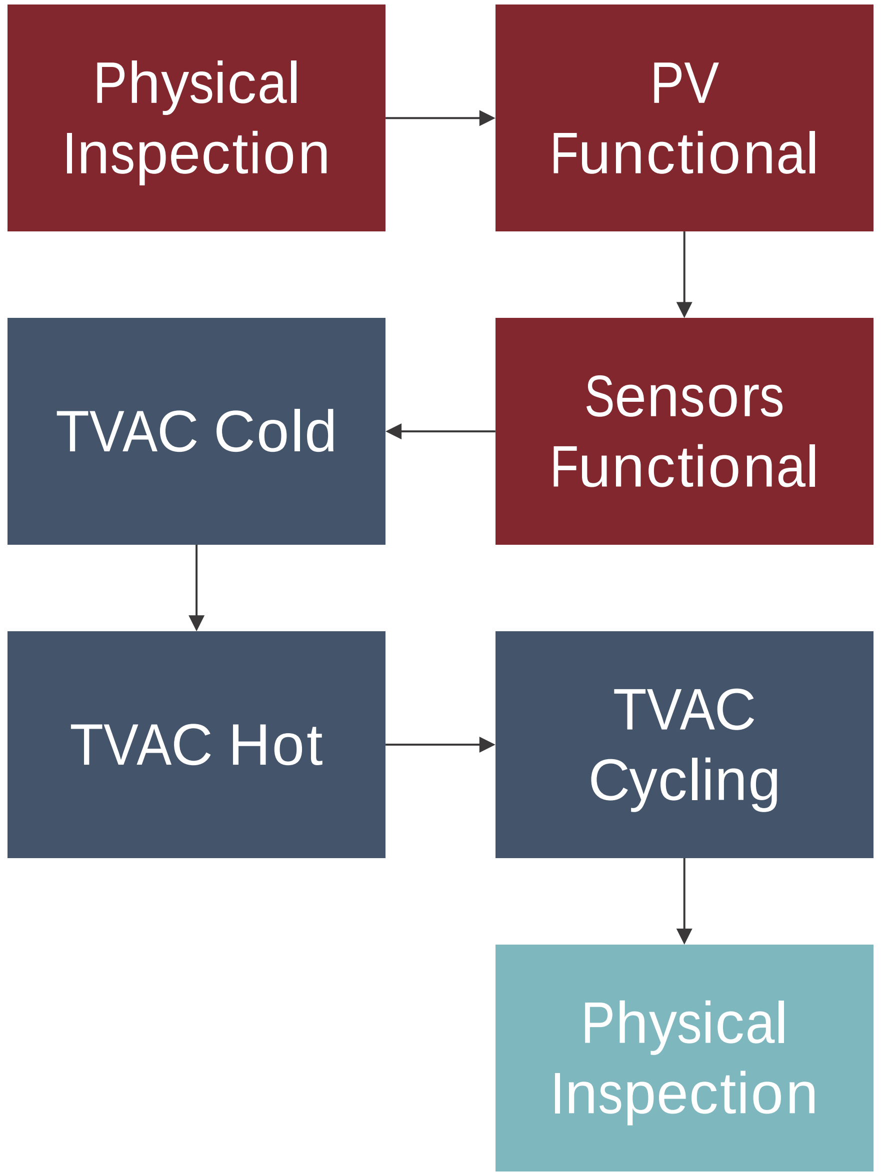


BREADBOARD TESTING

BREADBOARD TESTING

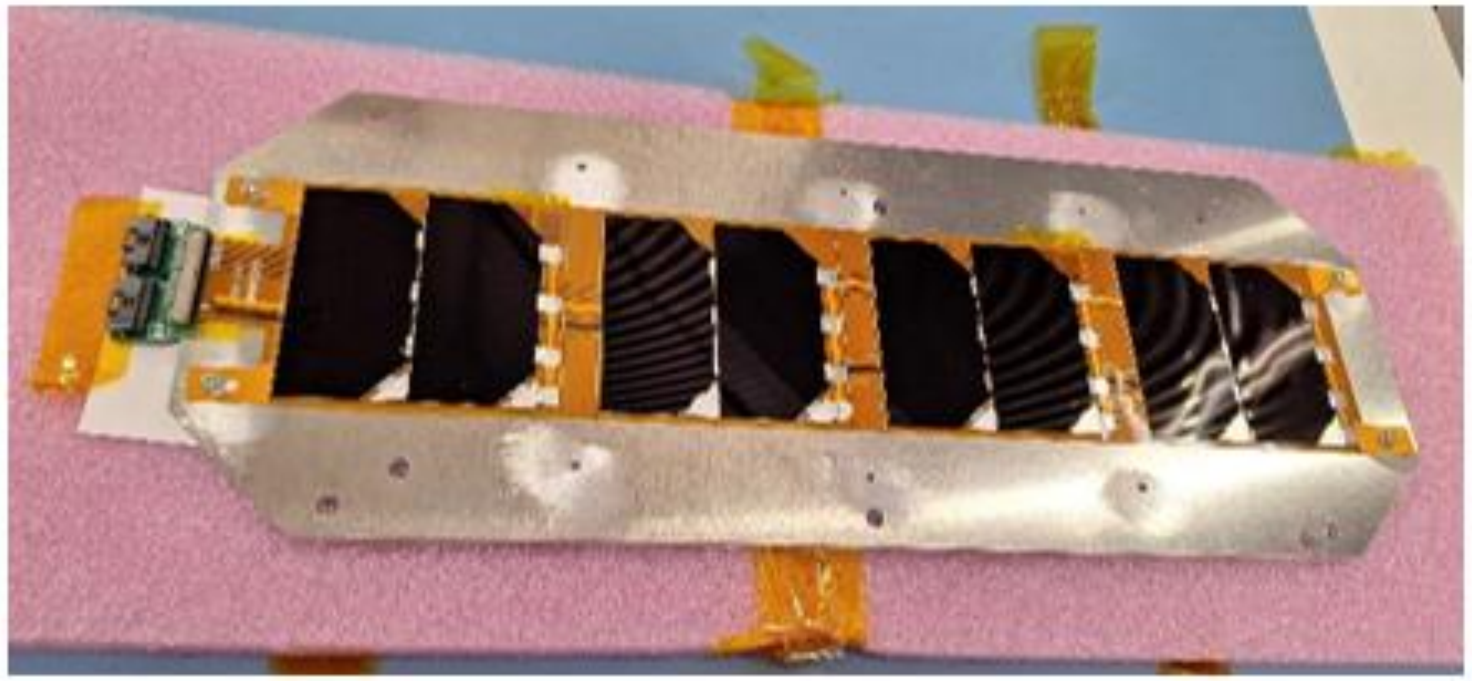
DSA-PV: Test plan

<table>
<tr><th>Name</th><th>Description</th><th>Environment</th><th>Pass/Fail criteria</th></tr>
<tr><td>TVAC Cold</td><td rowspan="2">The test is checked-in with Sensors Functional and PV functional tests. The breadboard is tested in TVAC at the specified temperature (TRP of set temperature ±5°C). The dwell time is set to 1 hour. Temperature ramp at ≤2°C/min. After, Physical Inspection is performed as well as Sensors Functional and PV Functional tests in laboratory environment.</td><td>TVAC (-60°C)</td><td rowspan="3">•The breadboard passed a Physical Inspection, PV Functional and Sensors Functional tests before testing.
•The temperature profile is followed with respect to set temperature, TRP and dwell time.
•The sensors function with required performance and accuracy during the test.
•The breadboard passed a Physical Inspection, PV Functional and Sensors Functional tests before testing.
•The performance of the sensors is the same of those recorded before the TVAC testing, within uncertainty of precision.</td></tr>
<tr><td>TVAC Hot</td><td>TVAC (+120°C)</td></tr>
<tr><td>TVAC Cycling</td><td>The test is checked-in with Sensors Functional and PV Functional tests. The breadboard is tested in TVAC at the specified temperature following a cycle between minimum and maximum temperature (TRP of set temperature ±5°C). The dwell time is set to 1 hour. Temperature ramp at ≤2°C/min. The test is performed for 4 cycles. After, Physical Inspection is performed as well as Sensors Functional and PV Functional tests in laboratory environment.</td><td>TVAC (-60°C÷120°C)</td></tr>
</table>

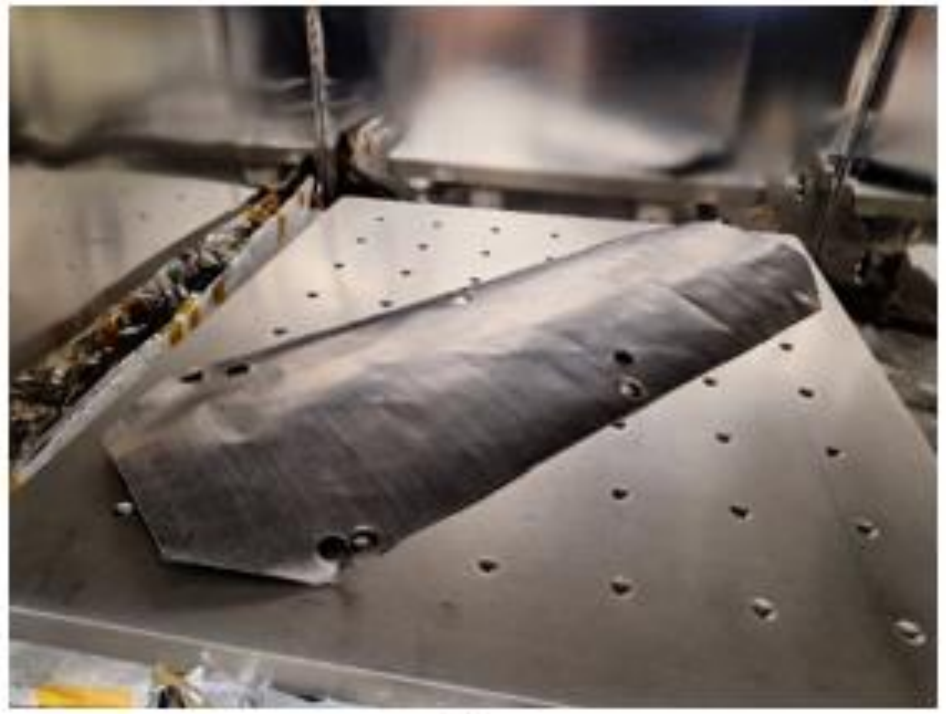


BREADBOARD TESTING

DSA-PV: testing setup

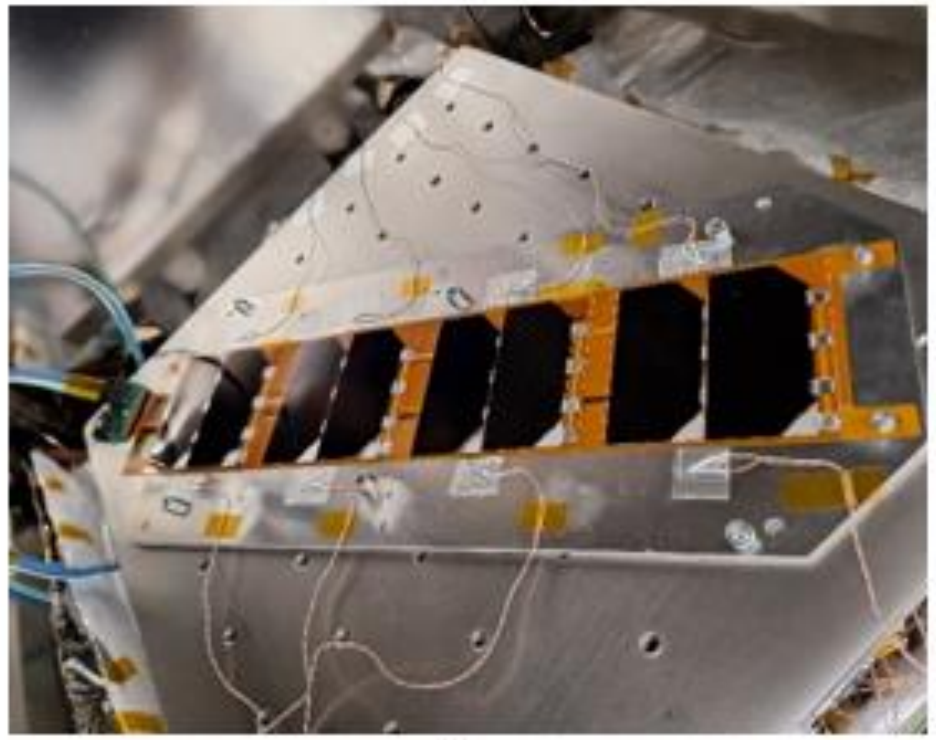


(a)

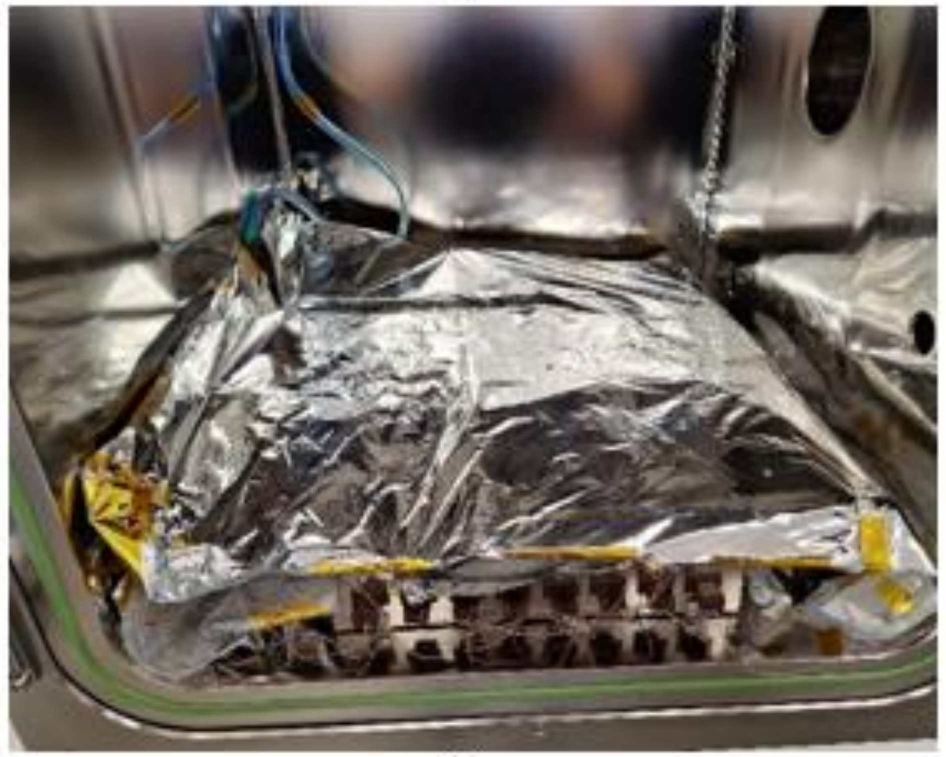


(b)

(c)



(d)



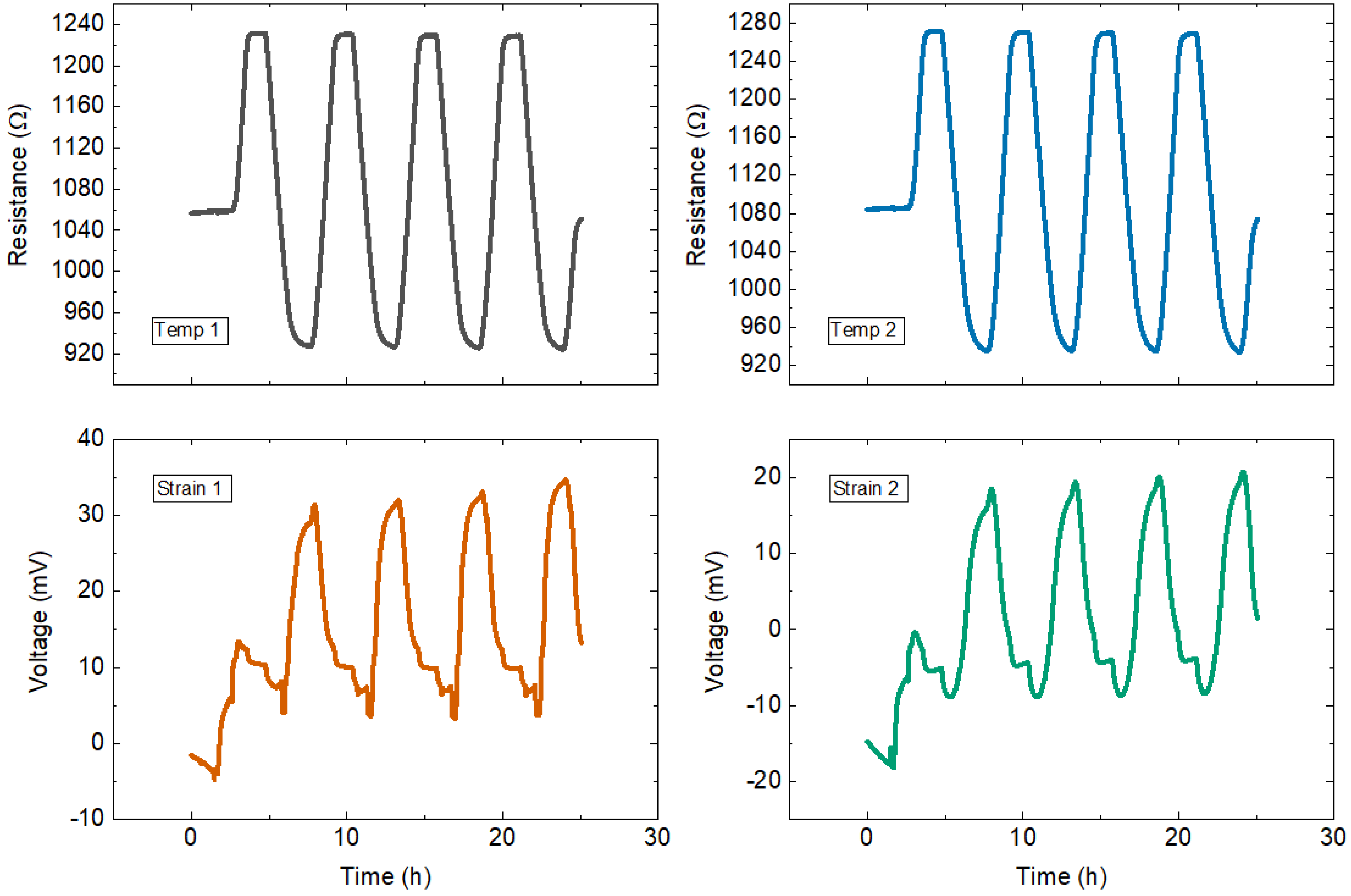
(e)

Testing was performed at external service provider **Lunar Outpost LU**. TVAC set-up with the DSA-PV demonstrator.

a) The DSA-PV integrated on a thermal plate.
b) Thermal filler (Sigraflex® graphize foil) which was placed between the two thermal plates.
c) Flange with the KF50 feedthrough.
d) The DSA-PV integrated on thermal plate with attached thermocouples.
e) The whole set-up covered with MLI.

BREADBOARD TESTING

DSA-PV: Tests results

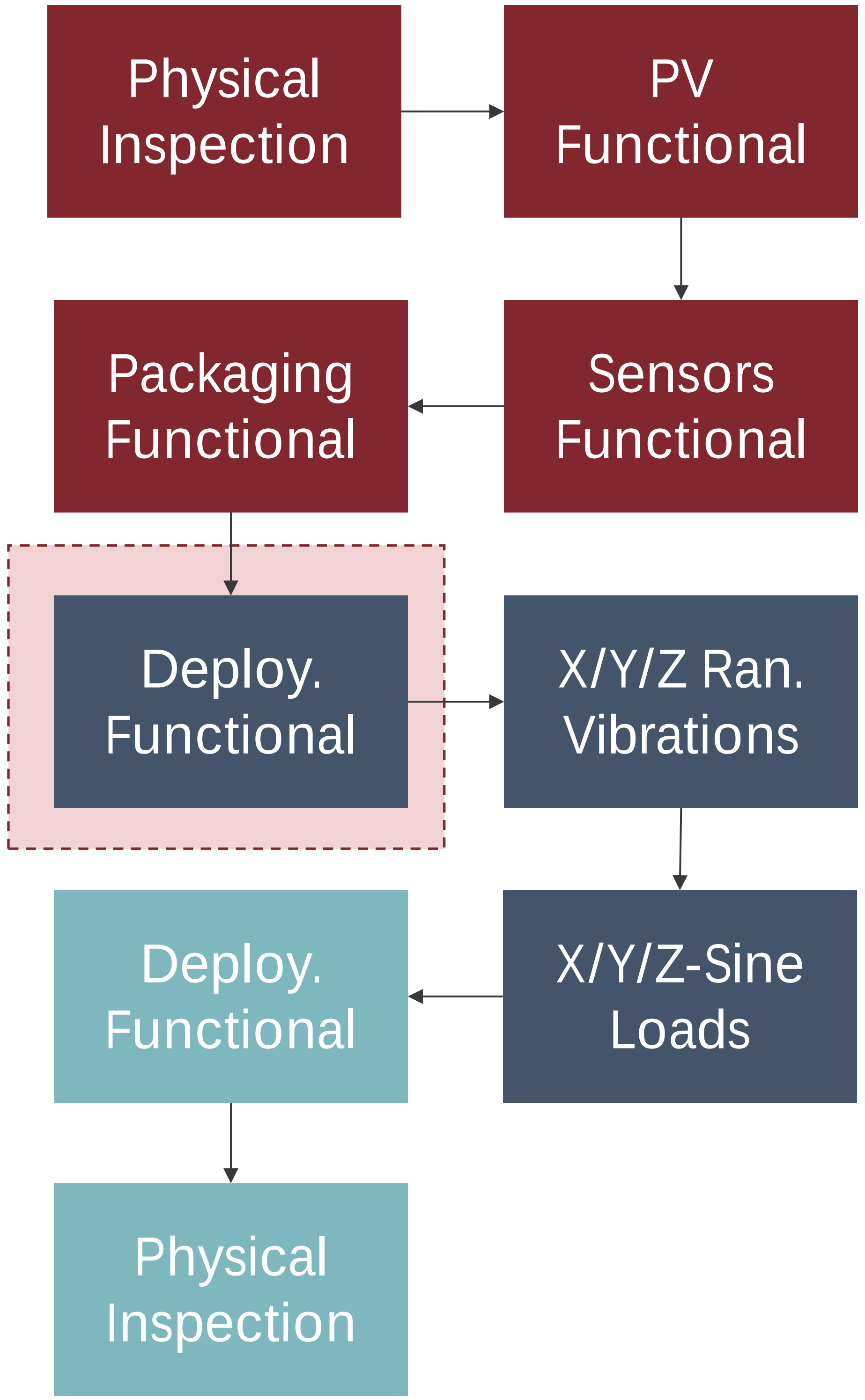


Pass/Fail criteria	Status after testing
The breadboard passed a Physical Inspection, PV Functional and Sensors Functional tests before testing.	All tests were successfully performed.
The temperature profile is followed with respect to set temperature, TRP and dwell time.	Temperature profiles according to the test plan. Slight deviation of pressure (~10^{-4} mbar instead of 10^{-5} mbar) during TVAC hot and TVAC cold is considered a minor deviation.
The sensors function with required performance and accuracy during the test.	Real-time data taken during testing revealed expected behavior. **Drift of the resistance values was observed during TVAC hot** in one of the temperature sensors, while it was very minor in the others.
The breadboard passed a Physical Inspection, PV Functional and Sensors Functional tests after testing.	All tests were successfully performed.
The performance of the sensors is the same of those recorded before the TVAC testing, within uncertainty of precision.	Temperature and strain sensors give very similar resistance and voltage reading before and after the tests. The exception is one of the temperature sensors, which shows a resistance drift during first TVAC hot test.

BREADBOARD TESTING

DSA-M: Test plan

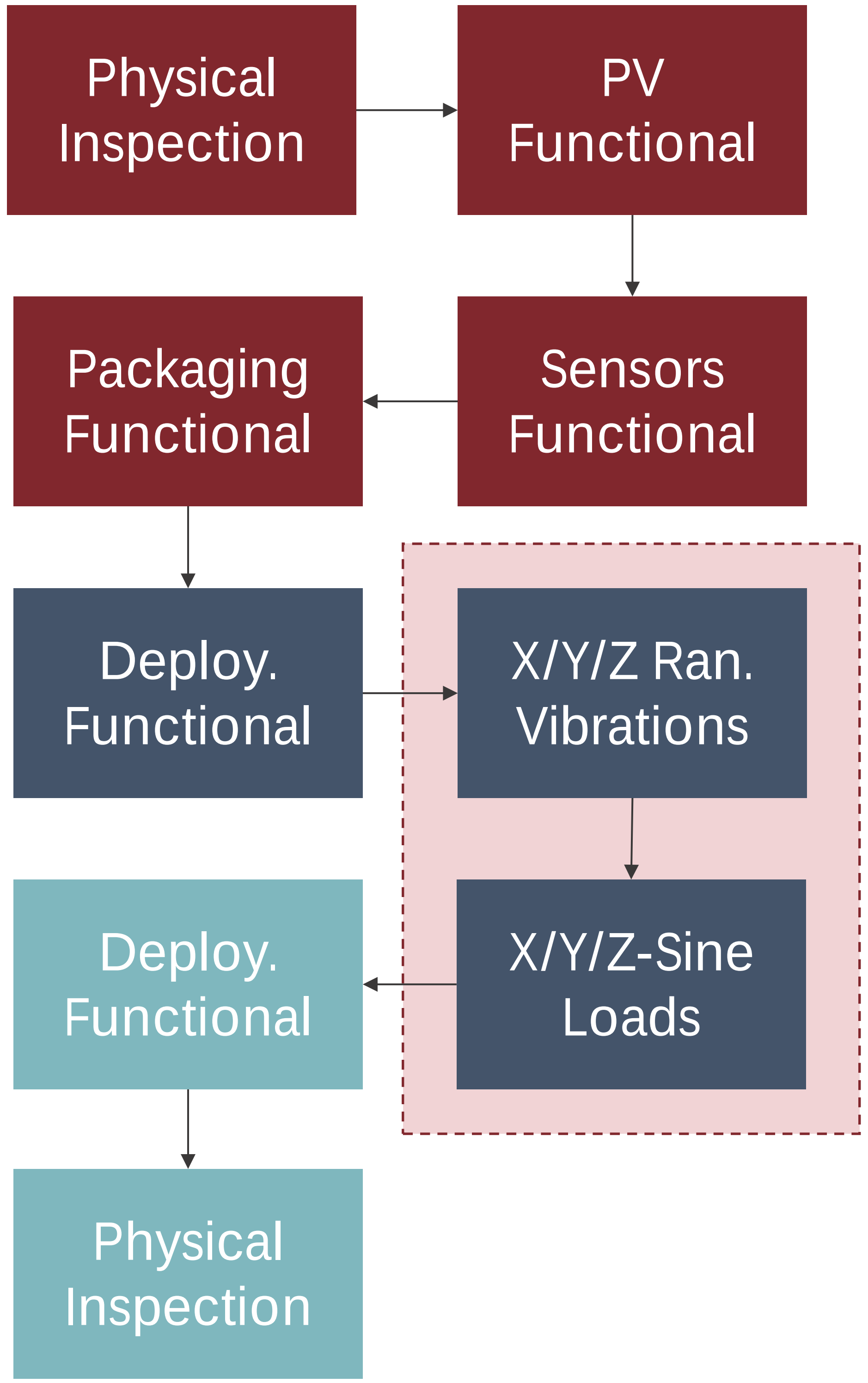
Name	Description	Environment	Pass/Fail criteria
Deployment Functional	The test is checked-in with Sensors Functional and PV functional tests. The DSA-M is integrated on the CubeSat structure. A Functional test is performed as in “Sensors Functional” while the DSA-M is in being deployed from the CubeSat structure. The configuration is held until equilibrium configuration is reached. After, Physical Inspection is performed as well as Sensors Functional and PV Functional tests in laboratory environment.	Laboratory	• The temperature sensors deliver information about the baseline environment. • The sensors can read with required accuracy the value of the baseline environment. • The strain sensors can uniquely identify folded vs. stowed configurations. • Check-out inspection and tests do not highlight any difference in the sensors’ status before and after execution of the Functional test. • Check-out inspection does not highlight any degradation of the PV assembly, of the FPC and inflation mechanism.



BREADBOARD TESTING

DSA-M: Test plan

<table>
<tr><th>Name</th><th>Description</th><th>Environ.</th><th>Pass/Fail criteria</th></tr>
<tr><td>Random Vibrations</td><td rowspan="2">The test is checked-in with Sensors Functional and PV functional tests. The DSA-M is integrated on the CubeSat structure which is then mounted on the dispenser mock-up (mounted on the shaker) simulating the mechanical interface with the launcher. The test is performed operating the shaker on the desired axis. After, Physical Inspection is performed as well as Sensors Functional and PV Functional tests in laboratory environment.</td><td>Single-axis run. vibrations</td><td rowspan="2">• The temperature sensors deliver information about the baseline environment.
• The sensors can read with required accuracy the value of the baseline environment.
• The strain sensors can uniquely identify the vibratory environment vs. static folded or stowed configurations.
• Check-out inspection and tests do not highlight any difference in the sensors' status before and after execution of the Functional test.
• Check-out inspection does not highlight any degradation of the PV assembly, of the FPC and inflation mechanism.</td></tr>
<tr><td>Sine load</td><td>Single-axis sine load</td></tr>
</table>



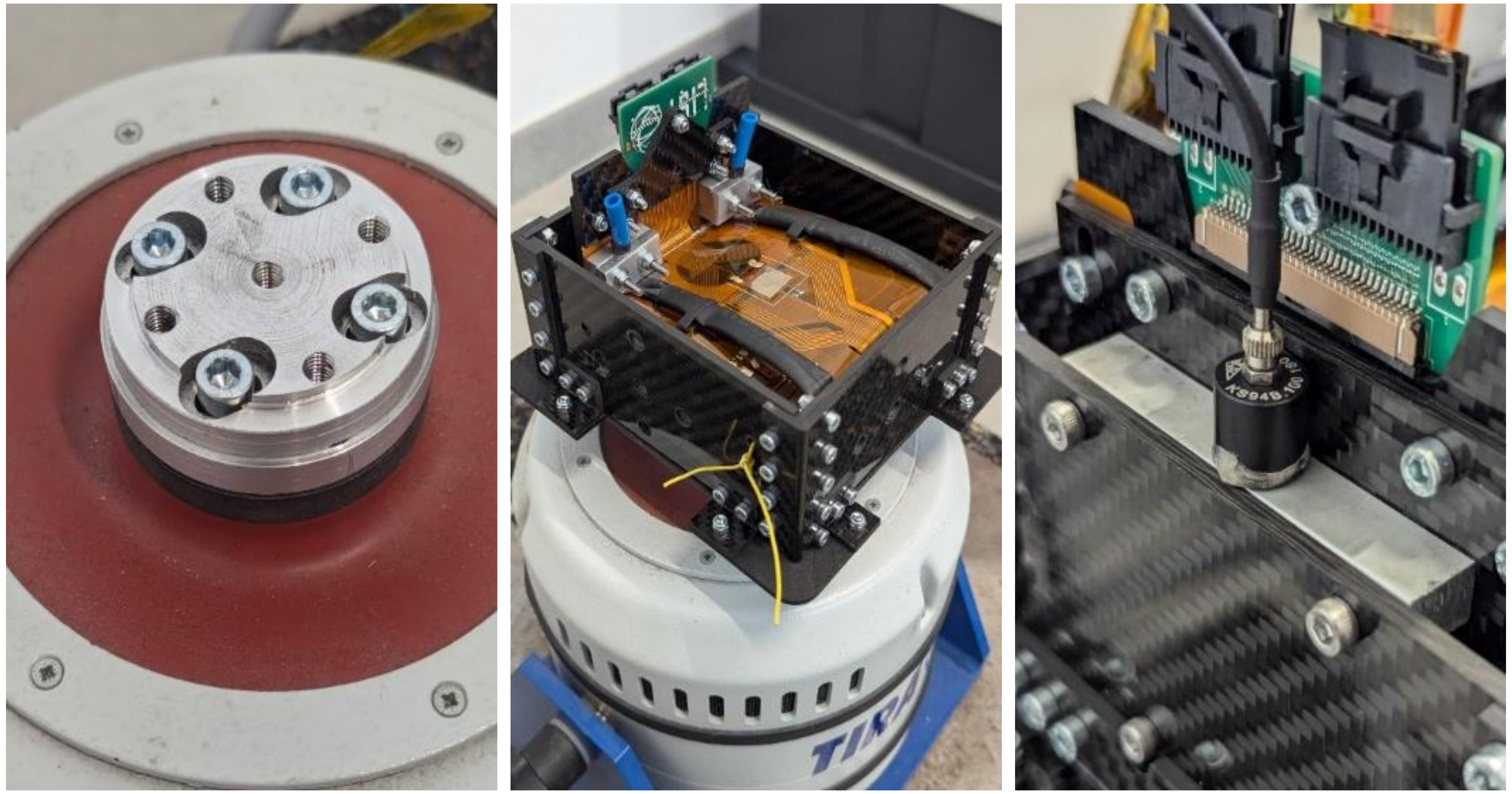
BREADBOARD TESTING

DSA-M: Tests setup

Deployment test

Setup of deployment test: the DSA-M mounted in stowed configuration (top-left), a highlight of the data interface of the DSA-M (bottom-left), the DSA-M released from stowed configuration (top-right) and the DSA-M deployed with inflation

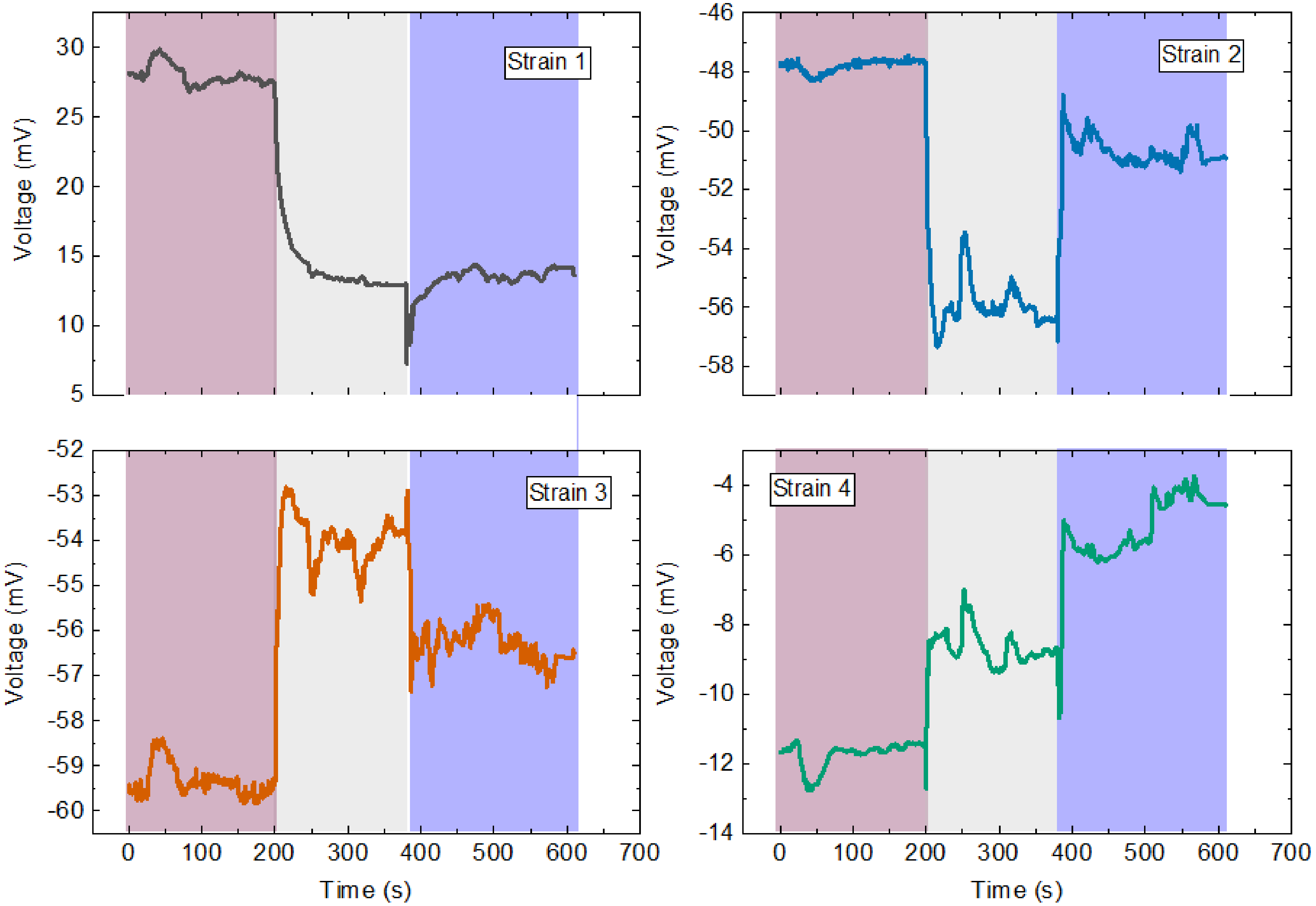
Random and sine vibration



Setup of x-axis vibratory test od DSA-M: the mechanical interface (left), the DSA-M mounted (center), the accelerometer (right)

BREADBOARD TESTING

DSA-M: Deployment test

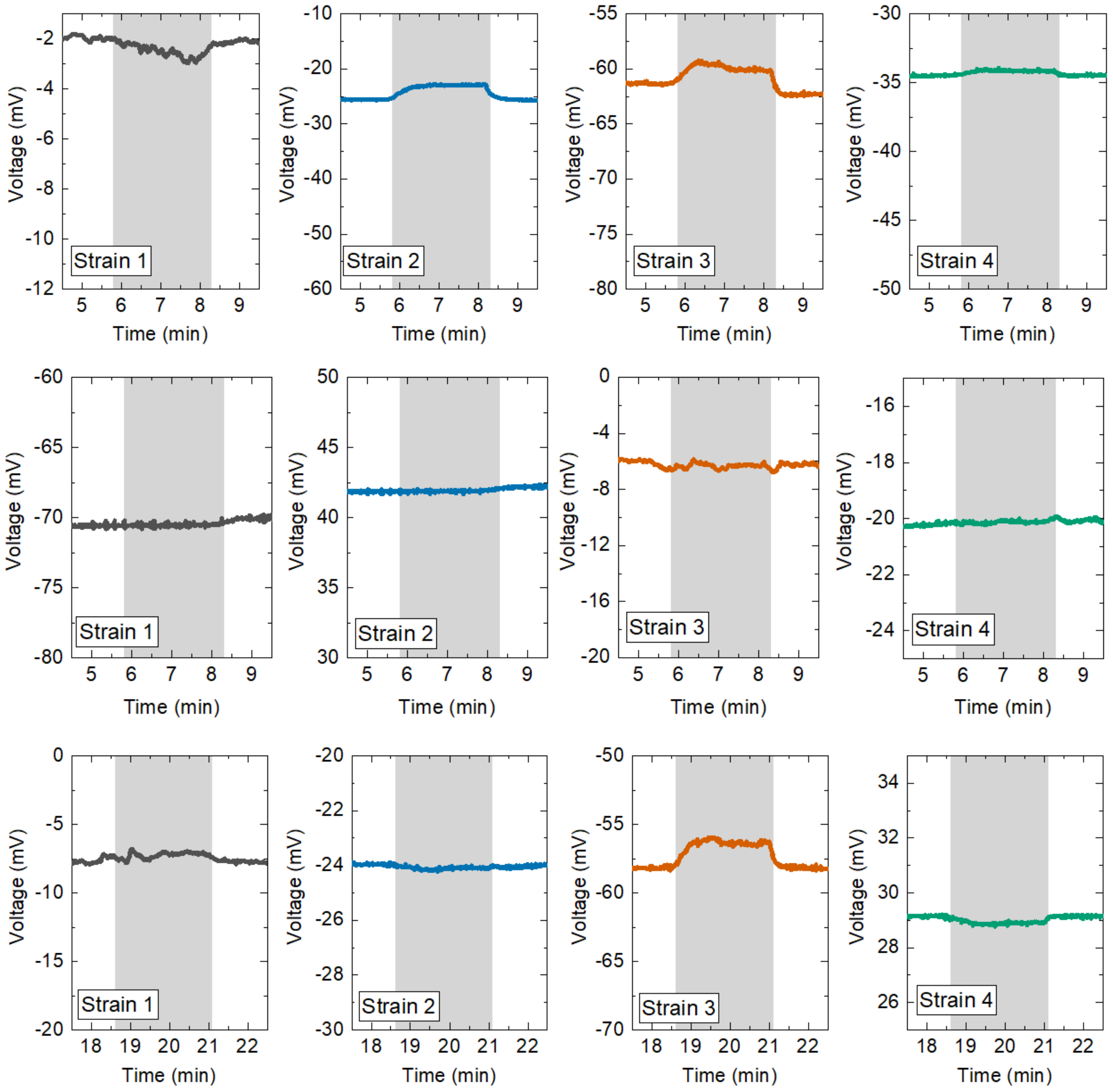


Strain sensors reading during deployment test. Different colors denote different stages of deployment: "pressed", "released" and "inflated".

Pass/Fail criteria	Status after testing
The temperature sensors deliver information about the baseline environment.	Test successful.
The sensors can read with required accuracy the value of the baseline environment.	Temperature sensors showed only minor drift of the resistance values.
The strain sensors can uniquely identify folded vs. stowed configurations.	Test successful.
Check-out inspection and tests do not highlight any difference in the sensors' status before and after execution of the Functional test.	Inspection successful.
Check-out inspection does not highlight any degradation of the PV assembly, of the FPC and inflation mechanism.	Inspection successful. Pre-existing damage did not propagate. Comparison between pre- and post-test PV functional confirms that the deployment did not degrade the performance of the panel.

BREADBOARD TESTING

DSA-M: Random and sine vibrations tests



Readings of the strain sensors during random vibrations test on the x (top), y (center) and z (bottom) axes. Grey area highlights the time of vibrations.

Pass/Fail criteria	Status after testing
The temperature sensors deliver information about the baseline environment.	Test successful.
The sensors can read with required accuracy the value of the baseline environment.	Test successful.
The strain sensors can uniquely identify the vibratory environment vs. static folded or stowed configurations.	Both strain sensors #3 and #4 identify the vibratory environment in both x and z directions. Instead, strain sensor #2 identifies the environment for test in x direction, while sensor #1 is not able to distinguish the environment from static reading. It must also be remarked that no sensor was able to identify vibrations in the y direction.
Check-out inspection and tests do not highlight any difference in the sensors' status before and after execution of the Functional test.	Visual inspection successful. The sine tests executed before and after the random vibration tests do not highlight any sensible difference in sine response,.
Check-out inspection does not highlight any degradation of the PV assembly, of the FPC and inflation mechanism.	Visual inspection successful. Pre-existing cracks did not propagate during the test. The sine tests performed before and after each random vibration test are congruent for all three axis.

FUTURE DEVELOPMENTS

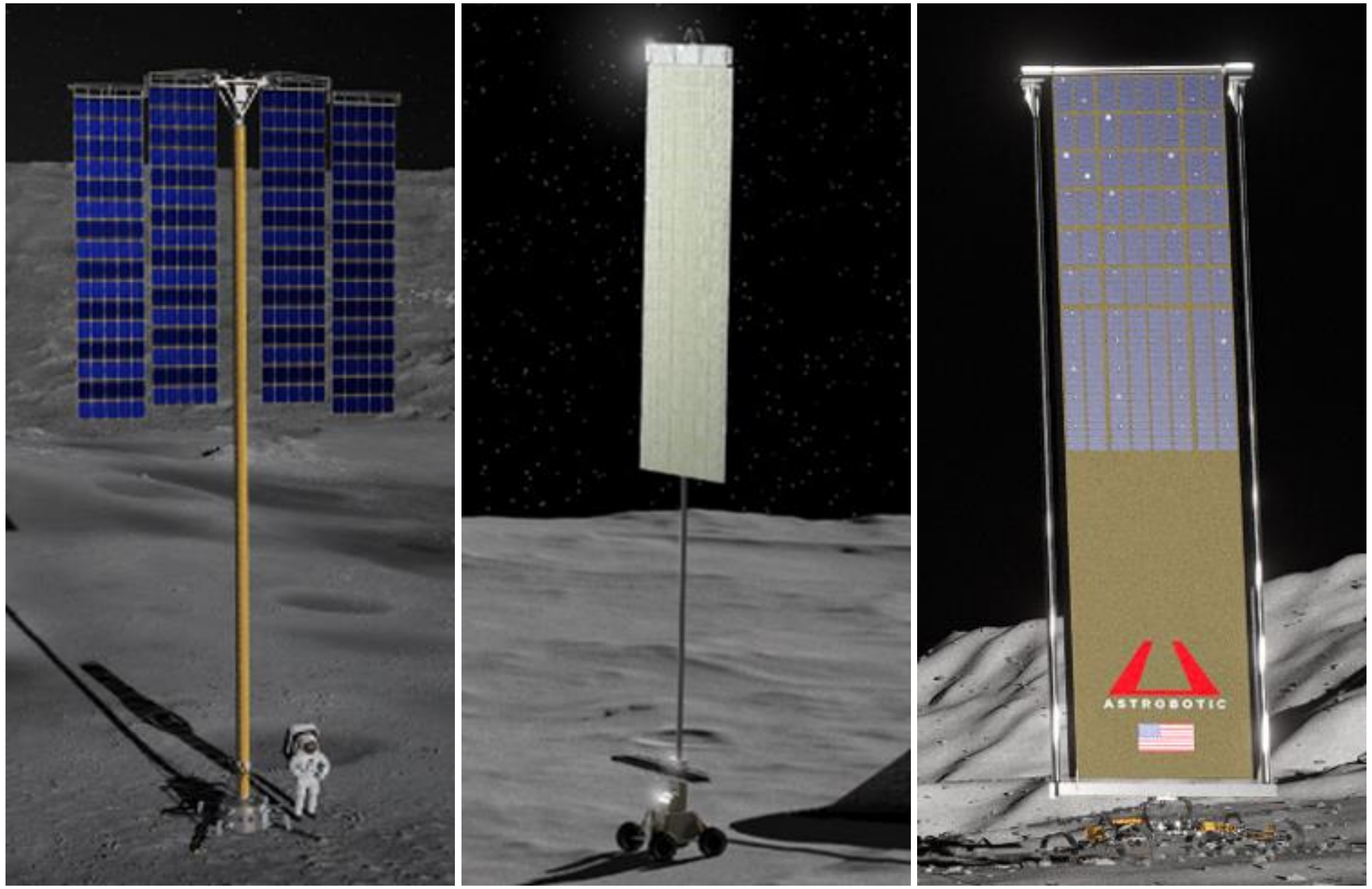
FUTURE DEVELOPMENTS

Product applicability to space missions

Conventional applications

Deployable solar array of several reference missions: ISS' SAW (top left), UltraFlex (top center), ROSA (top-right), iROSA deployed in front of SAW (bottom left) Eurostar Neo (bottom center) and SLIM (bottom right).

Lunar-surface segment



Solar arrays developed in the frame of the VSAT project: Honeybee Robotics' LAMPS (left), Lockheed Martin's Multi-mission Modular (MM) Solar Array (center-left), Astrobotics' VSAT (center-right). The 50kW scaled-up VSAT-XL by Astrobotics is shown on the right.

FUTURE DEVELOPMENTS

Development roadmap

Future development will include **technical improvement** of array (switch to thin and flexible PV cells encapsulated in polymeric films) and sensors' manufacturing (e.g. automatization of manual operations and switch to light annealing) and sensors' performance (e.g. eliminating resistance drift and temperature sensitivity of strain sensors).

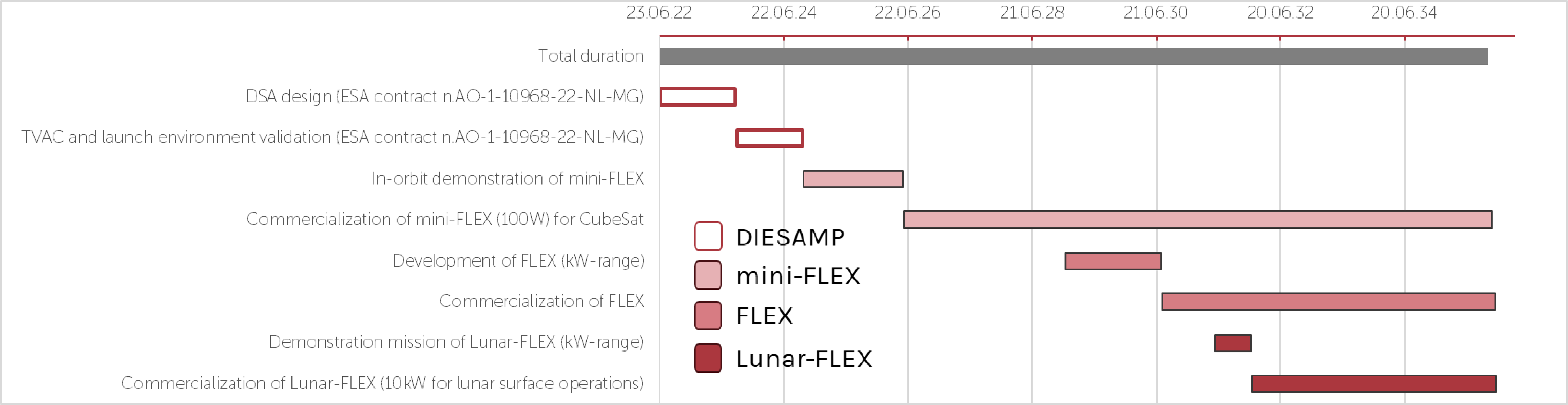
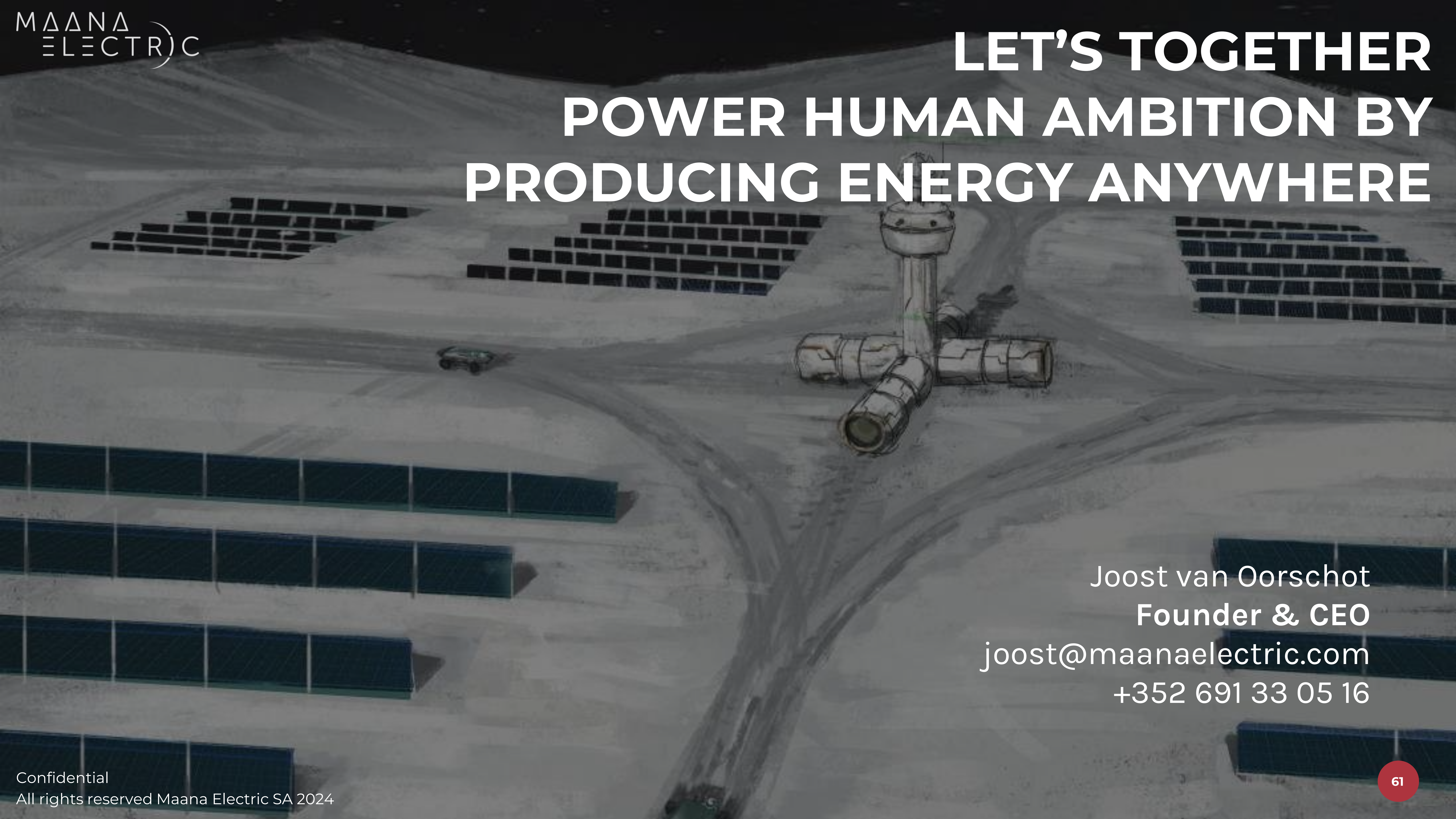


Diagram of the preliminary roadmap for FLEX products line



MAANA ELECTRIC

LET'S TOGETHER POWER HUMAN AMBITION BY PRODUCING ENERGY ANYWHERE

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BACK-UP SLIDES

TARGET TESTING CONDITIONS

CF1: To monitor array temperature

CF2: To monitor array strain field

CF3: To provide structural unity

Property	Value	Unit
Pressure	10^{-5}	mbar
Temperature (hot)	+120	°C
Temperature (cold)	-60	°C

Relevant thermal vacuum environment

Sine Load	Band [Hz]	Amplitude [g]
Longitudinal	2÷50	1.0
	50÷100	0.9
Lateral	2÷25	0.8
	25÷100	0.6

Relevant launcher environment for sine loads

Frequency [Hz]	PSD [g^2/Hz]
20	0.0044
100	0.0044
300	0.01
700	0.01
800	0.03
925	0.03
2000	0.00644
GRM	5.13

Relevant launcher environment for random vibrations

VERIFICATION STRATEGY

METHODS	LEVELS	STAGE
Inspection Test	Equipment (sensors) Breadboard (PV/M)	Breadboard (TRL5)

REQUIREMENT CATEGORY	SENSORS			DSA-PV			DSA-M		
	CF1	CF2	CF3	CF1	CF2	CF3	CF1	CF2	CF3
Functional performance	I,T	I,T	N/A	I,T	I,T	I,T	I,T	I,T	I,T
External Interfaces	I,T	I,T	N/A	I,T	I,T	I,T	I,T	I,T	I,T
Mechanical testing									
Sine load	N/A	N/A	N/A	N/A	N/A	N/A	T	T	T
Random vibration	N/A	N/A	N/A	N/A	N/A	N/A	T	T	T
Thermal testing									
Thermal vacuum (hot)	T	T	N/A	T	T	T	N/A	N/A	N/A
Thermal vacuum (cold)	T	T	N/A	T	T	T	N/A	N/A	N/A
Thermal vacuum (cycling)	T	T	N/A	T	T	T	N/A	N/A	N/A