Module Prototyping for the Phase II Upgrade of the CMS Outer Tracker

Forum on Tracking Detector Mechanics – 27.06.18

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Marius Neufeld, Pia Steck

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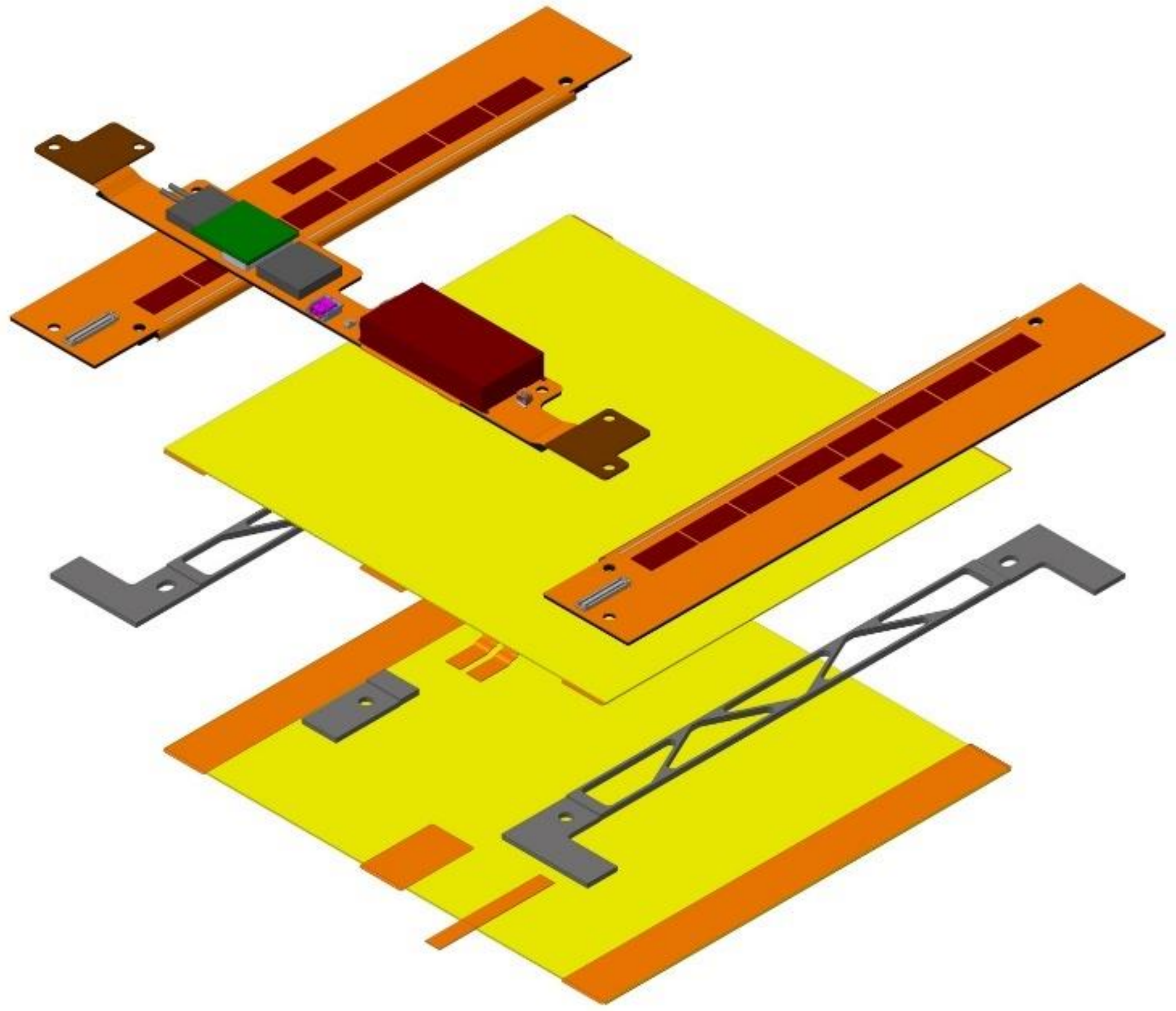
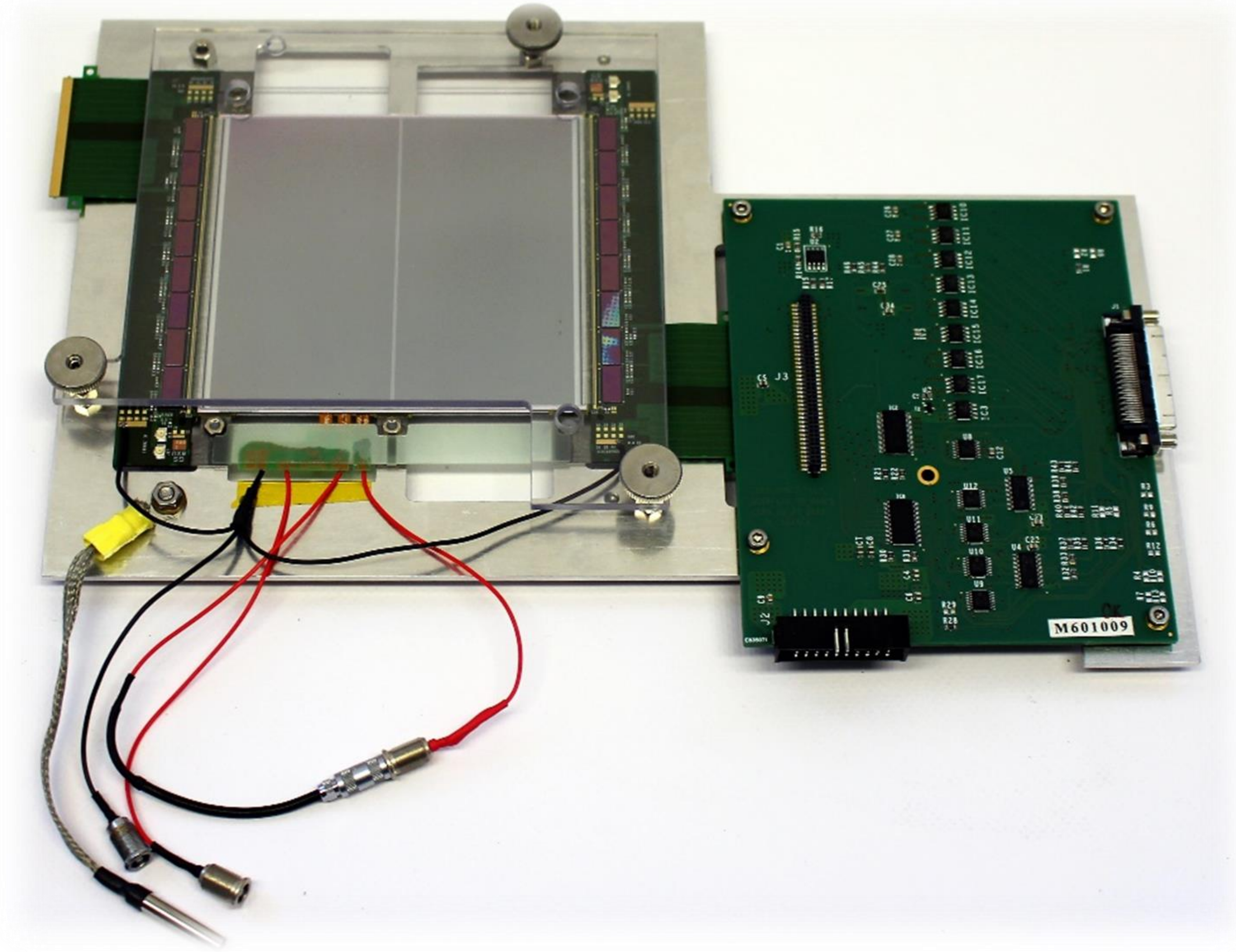
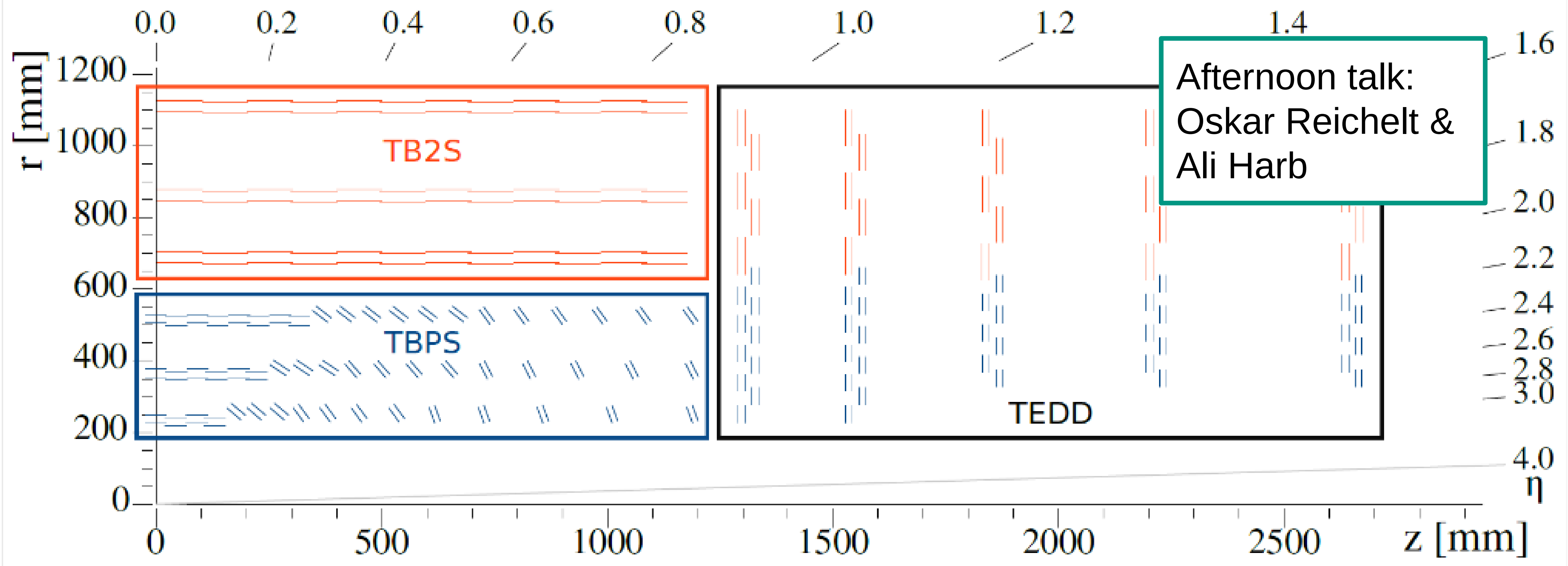




Content

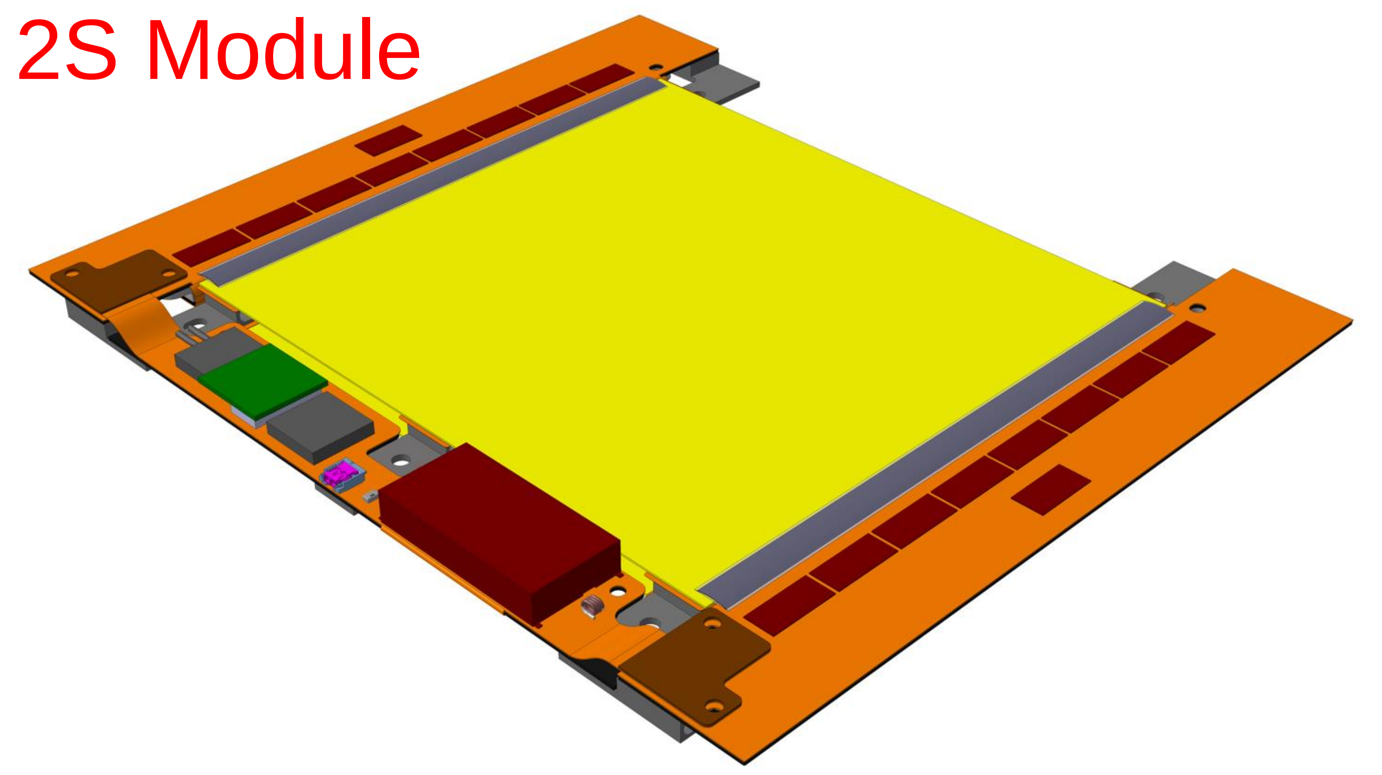
The Phase II Upgrade of the CMS Outer Tracker

- New silicon tracker of the CMS experiment for the HL-LHC by 2026
  - Increased granularity
  - Radiation tolerant to up to 10^{15} n_{eq}/cm^2
  - Reduced material budget
  - Sensors operated at –20°C
- Outer tracker will consist of ~13000 double-sided modules
  - 2S: strip/strip sensor
  - PS: pixel/strip sensor
- Contribution to Level 1 Trigger via p_T-module concept

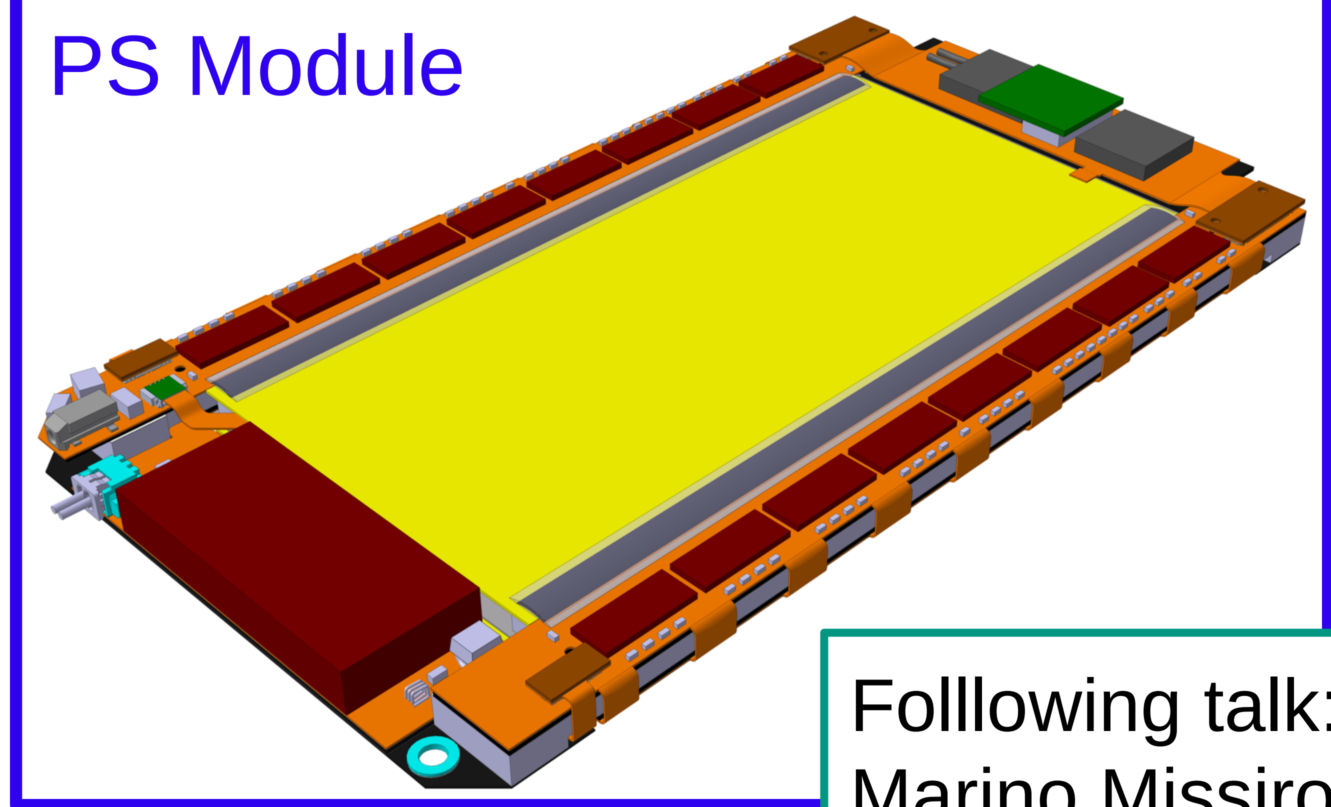


Afternoon talk:
Oskar Reichelt &
Ali Harb

2S Module



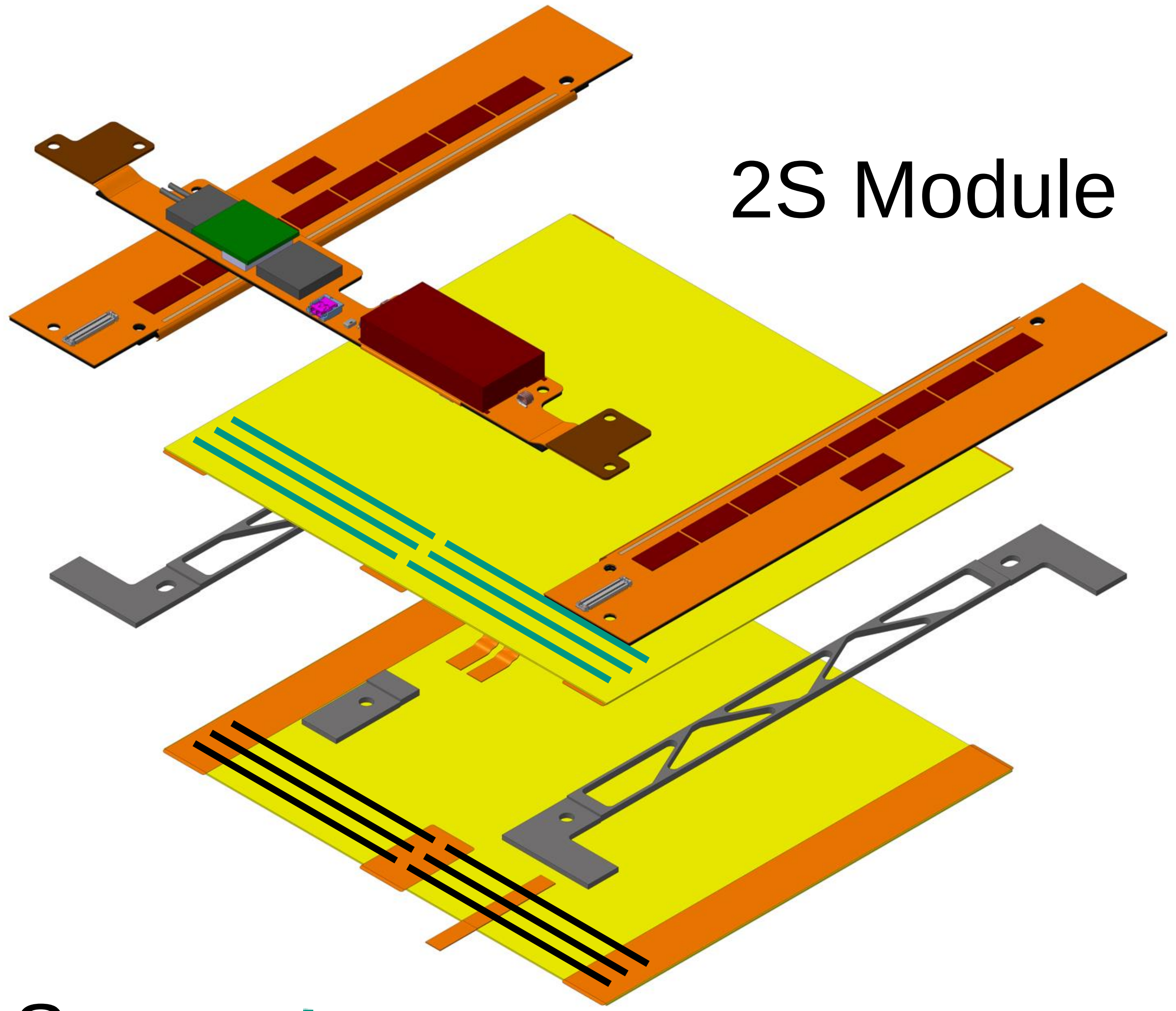
PS Module



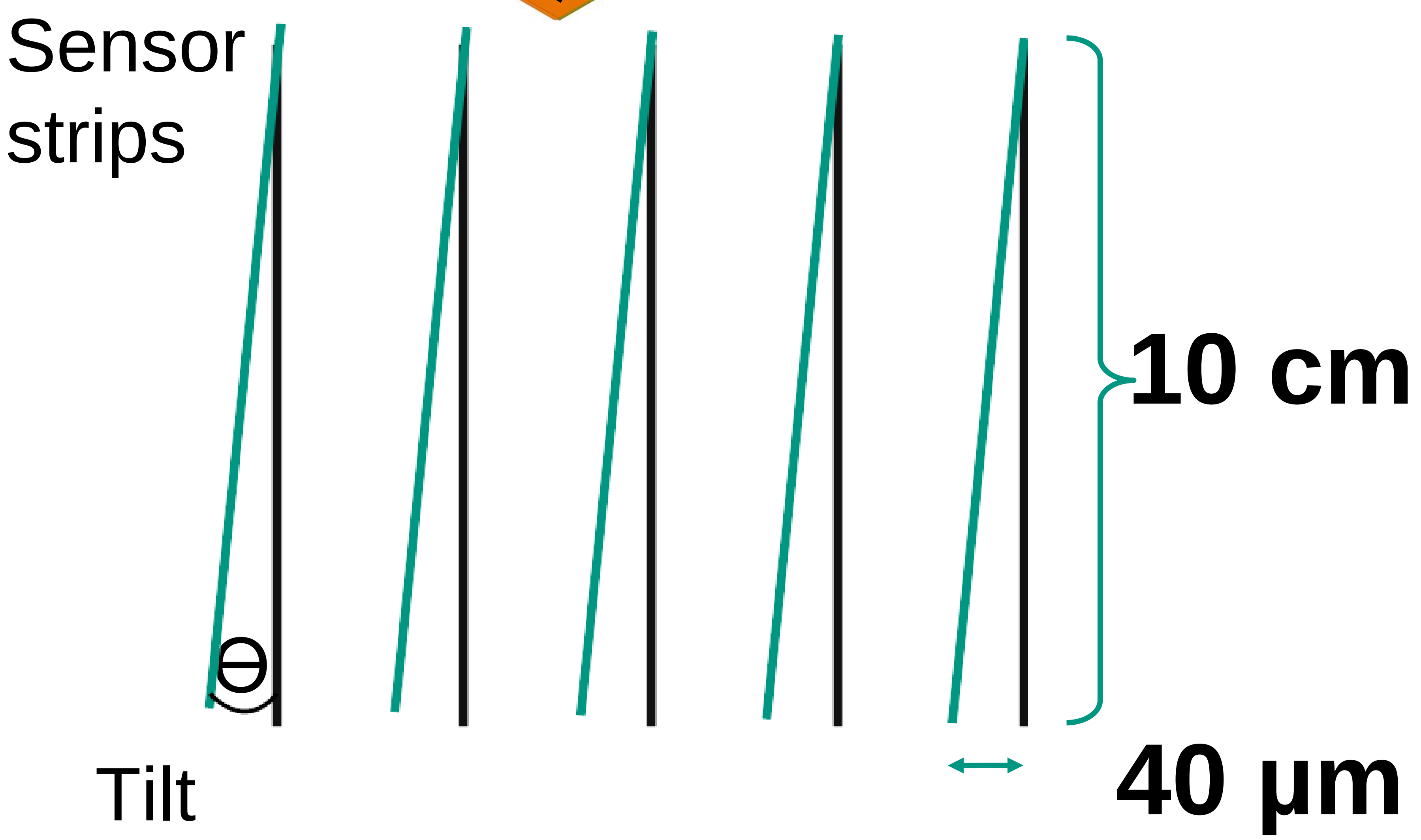
Folllowing talk:
Marino Missiroli

p_T-Module Concept

- Bending of tracks identified on double-sided sensor module by a coincidence logic
- High-p_T particle information contributes to Level 1 trigger
- Cut on p_T keeps trigger rates under control
  → **Alignment of superimposed strips in 2S Modules needs to be $|\Theta| < 400$ µrad to ensure functionality of coincidence logic**



2S Module



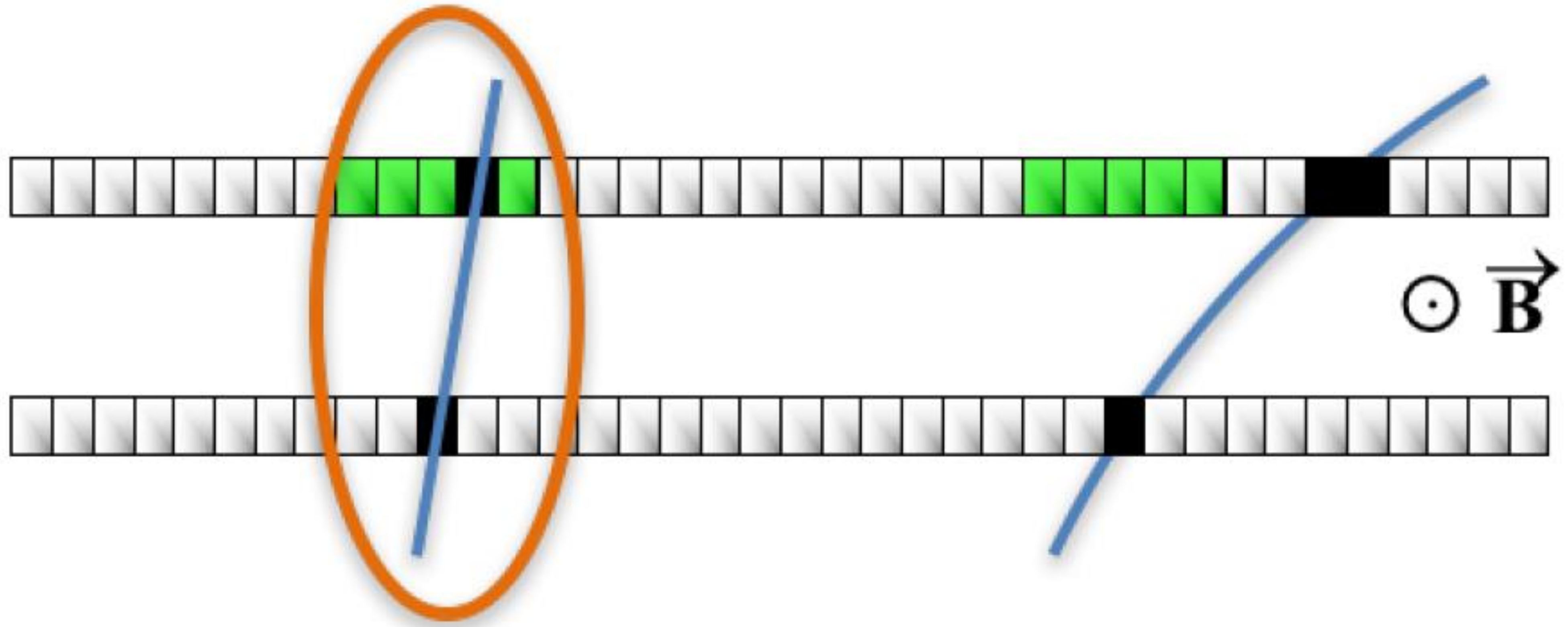
Sensor strips

Θ

Tilt

10 cm

40 µm



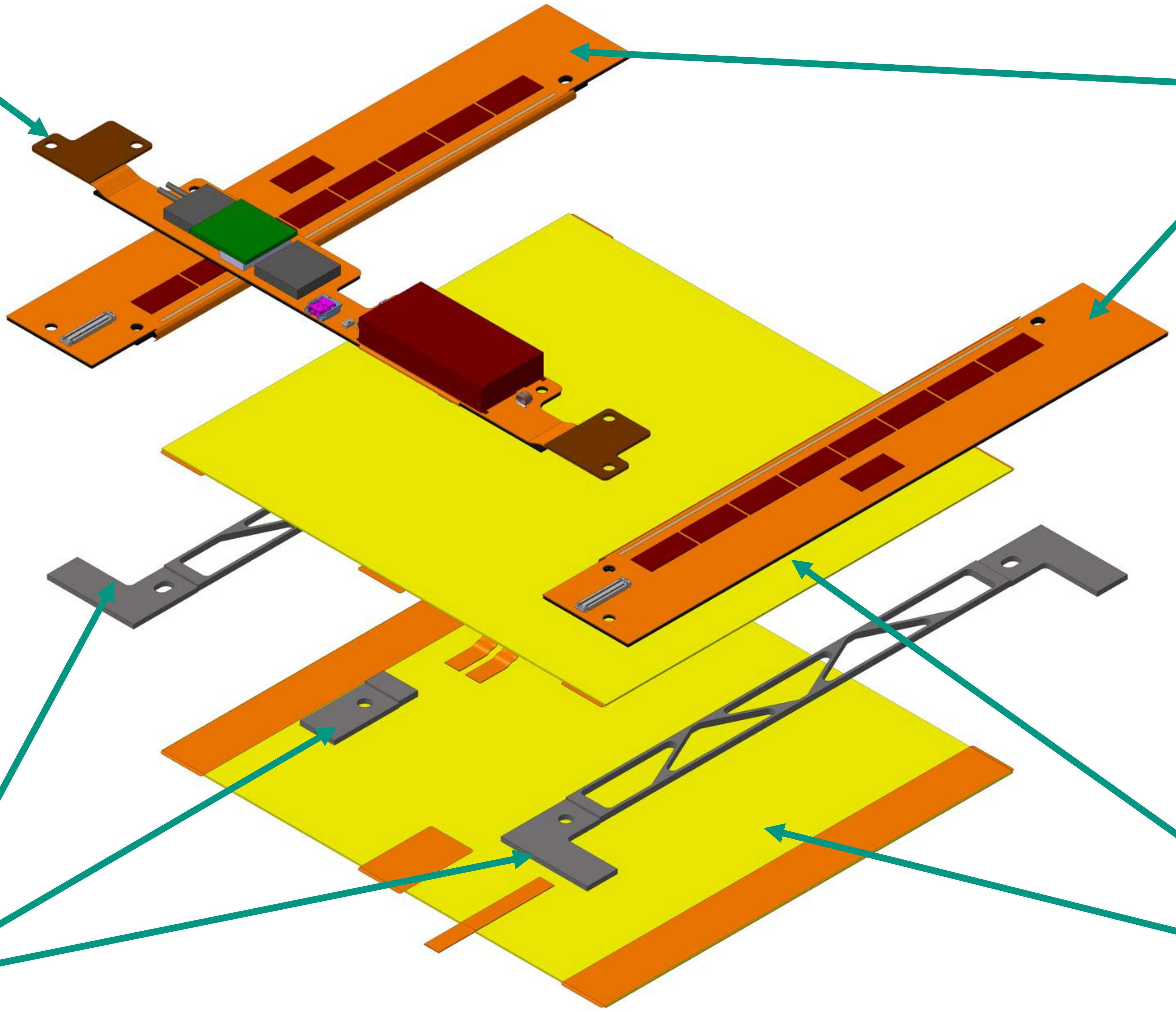
Top sensor

Bottom sensor

Production Plans

- Two-year production period end 2021 – end 2023
- ~13,000 PS and 2S Modules produced across 11 assembly centers
- Assembly centers pledged to build up to 2000 modules (KIT: 2000 2S Modules)
  - 400 working days: **5 modules/day** on average (plan at KIT: 8 modules/day peak production)
- 2S Module design almost complete, now focus on efficient assembly procedure
- Need stable and reliable production and test procedures to keep production time short and module quality high

2S Module for the CMS Outer Tracker



Service Hybrid

- Powering
- Data transmission

2 Front-end Flex Hybrids

- 8 CMS Binary Chips each
- 1 Concentrator Chip each
- Connected to both sensors

Spacer

- Carbon fiber reinforced aluminum
- Mechanical fixation

2 Silicon Strip Sensors

- 2 x 1016 strips (5 cm) each
- Bottom strip to top strip alignment of <400 µrad

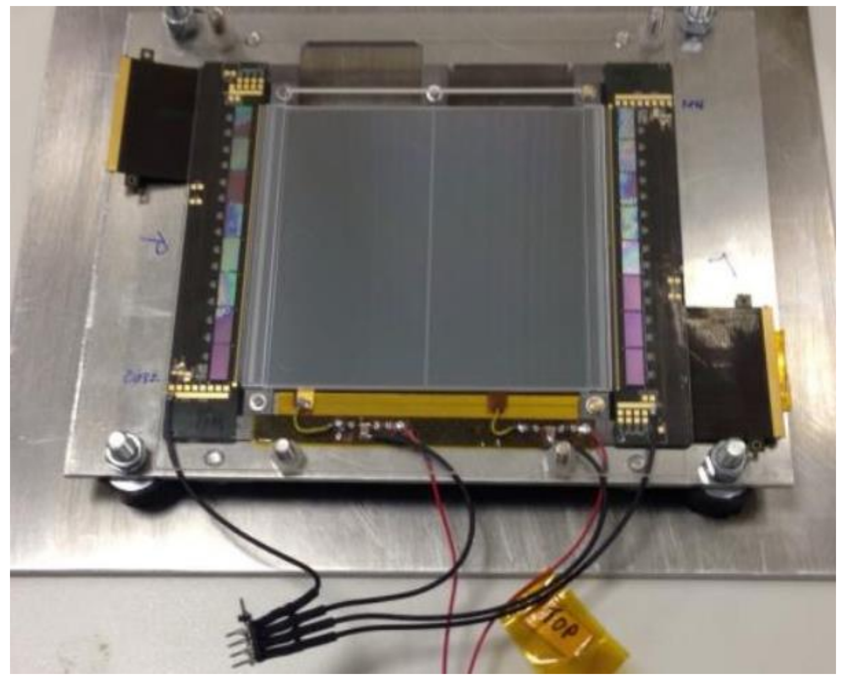
Module Prototyping

- CMS outer tracker module working group of about 30 members developed and continuously improved module baseline design and tooling during the past years

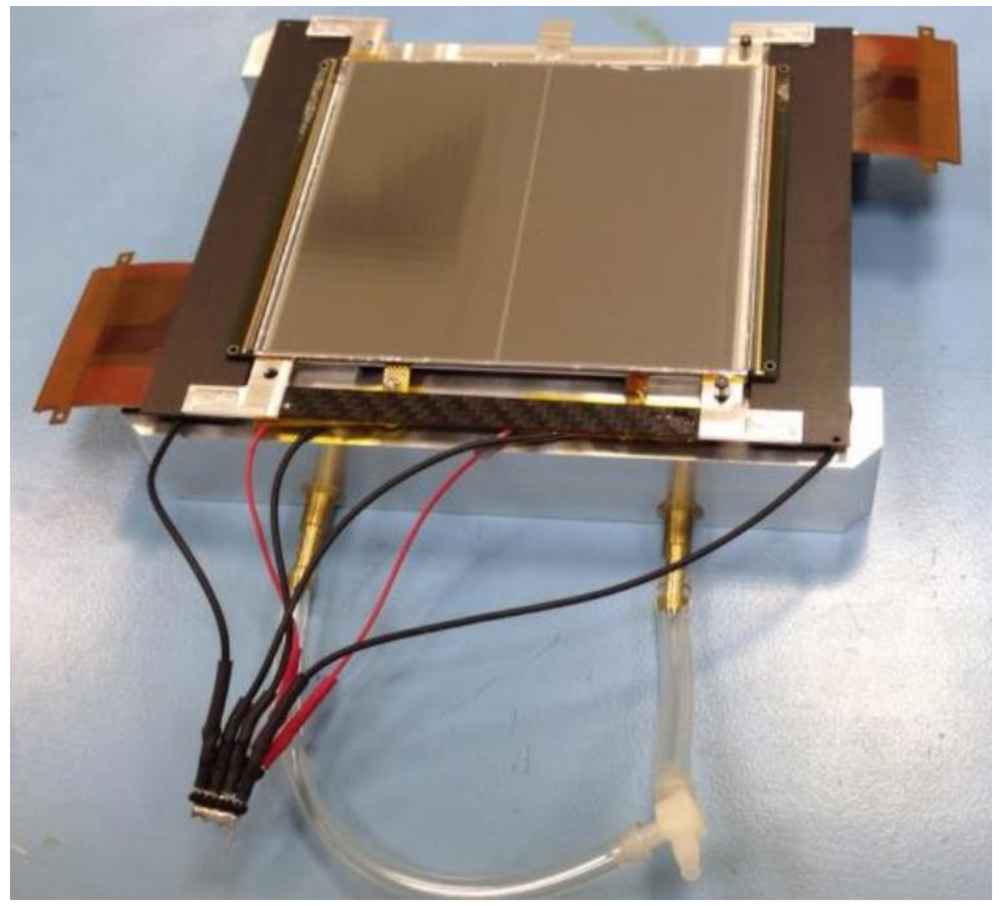
- 2S Module baseline design was proven to work by several functional modules built at CERN

- Beginning of 2018: New parts available
→ **Production centers can enter the prototyping phase**

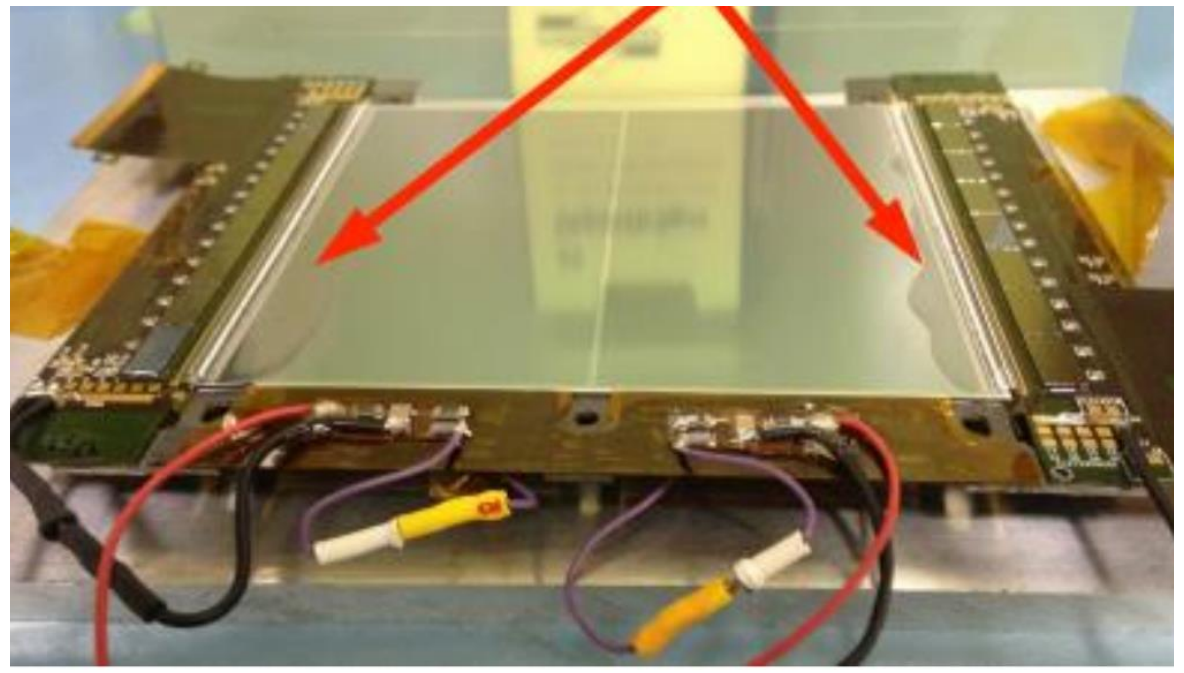
Module #1



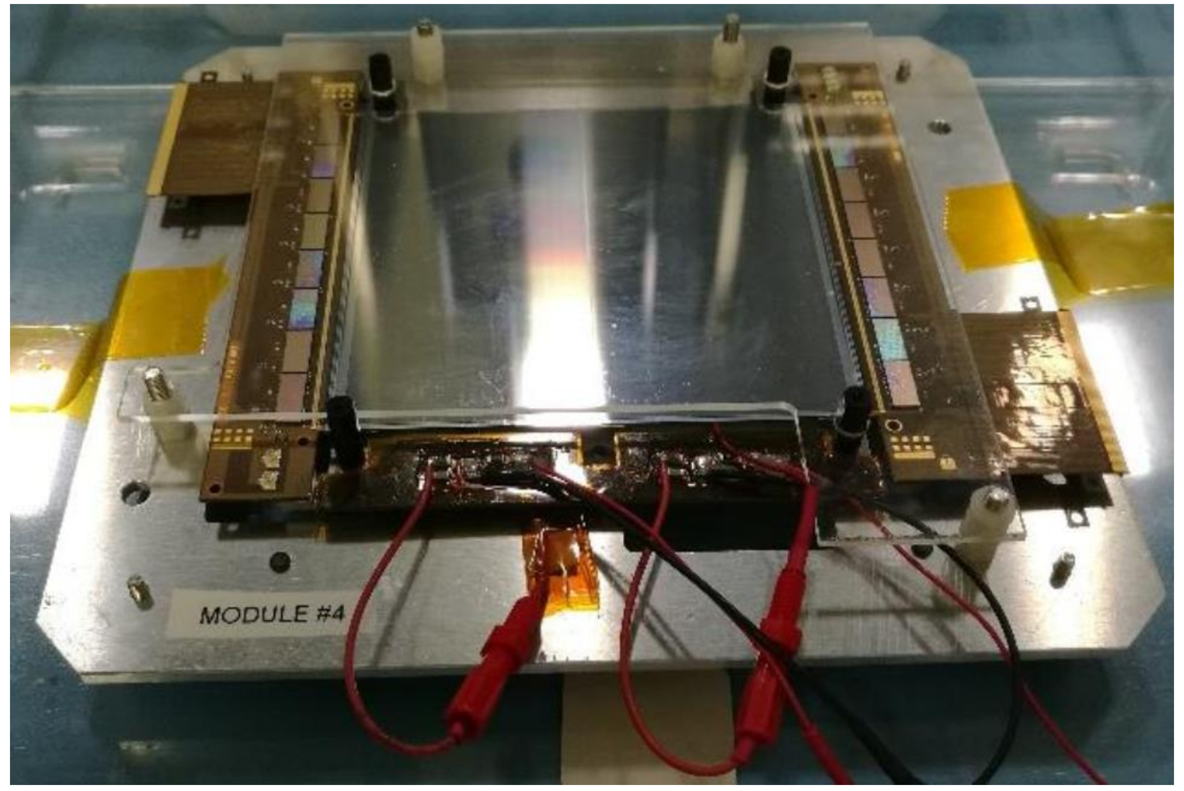
Module #2



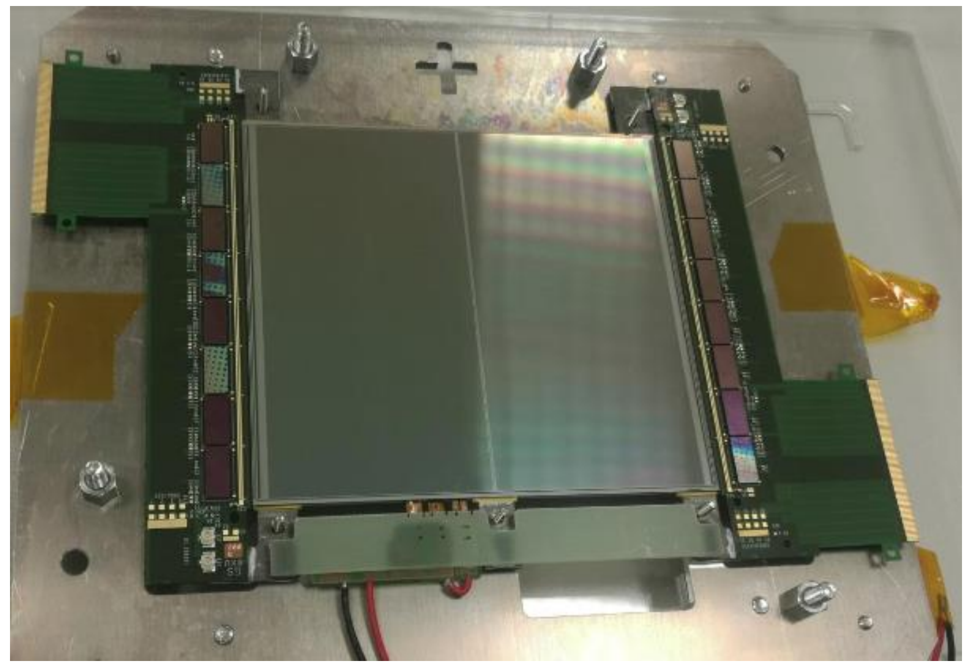
Module #3



Module #4

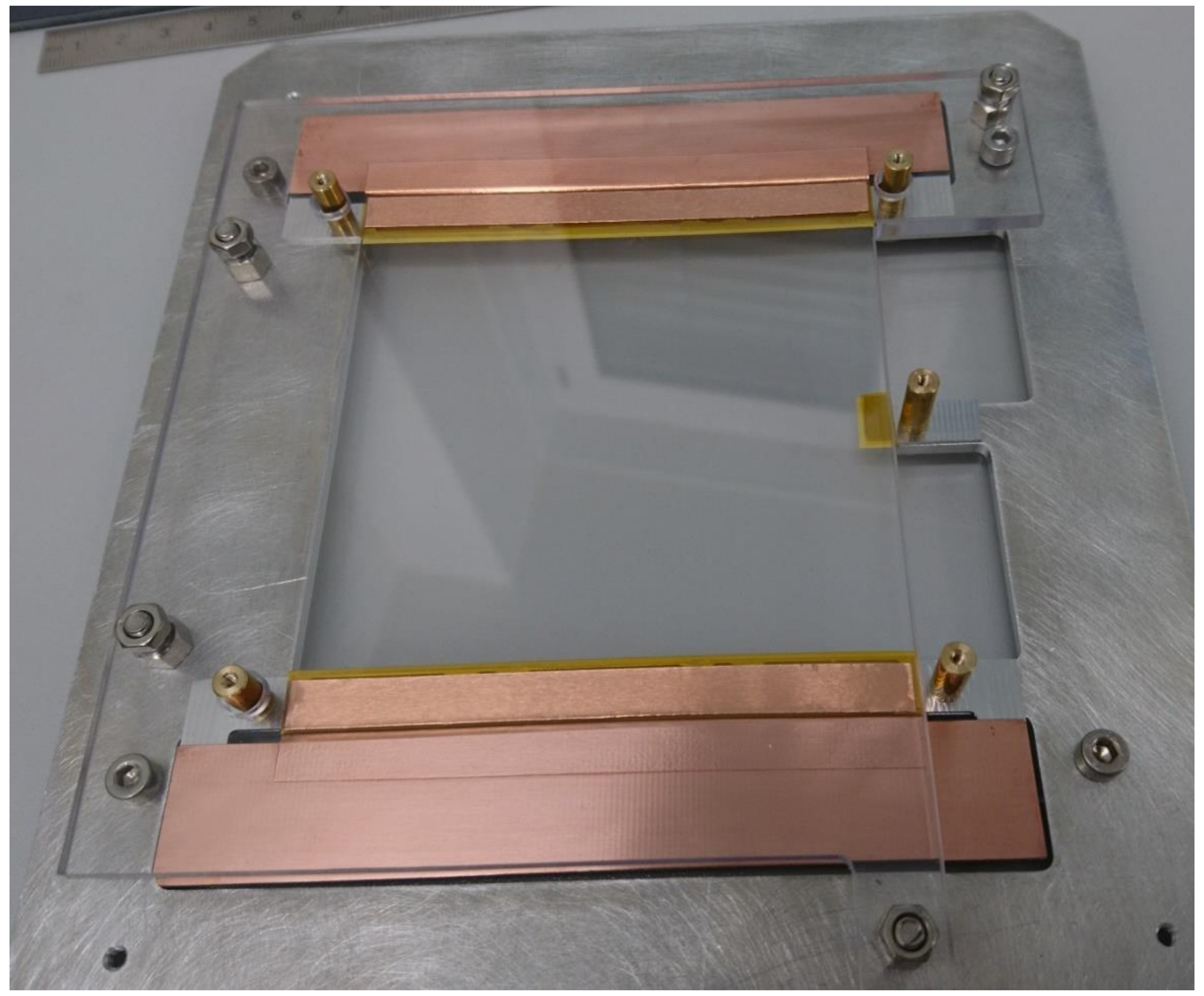


Module #5

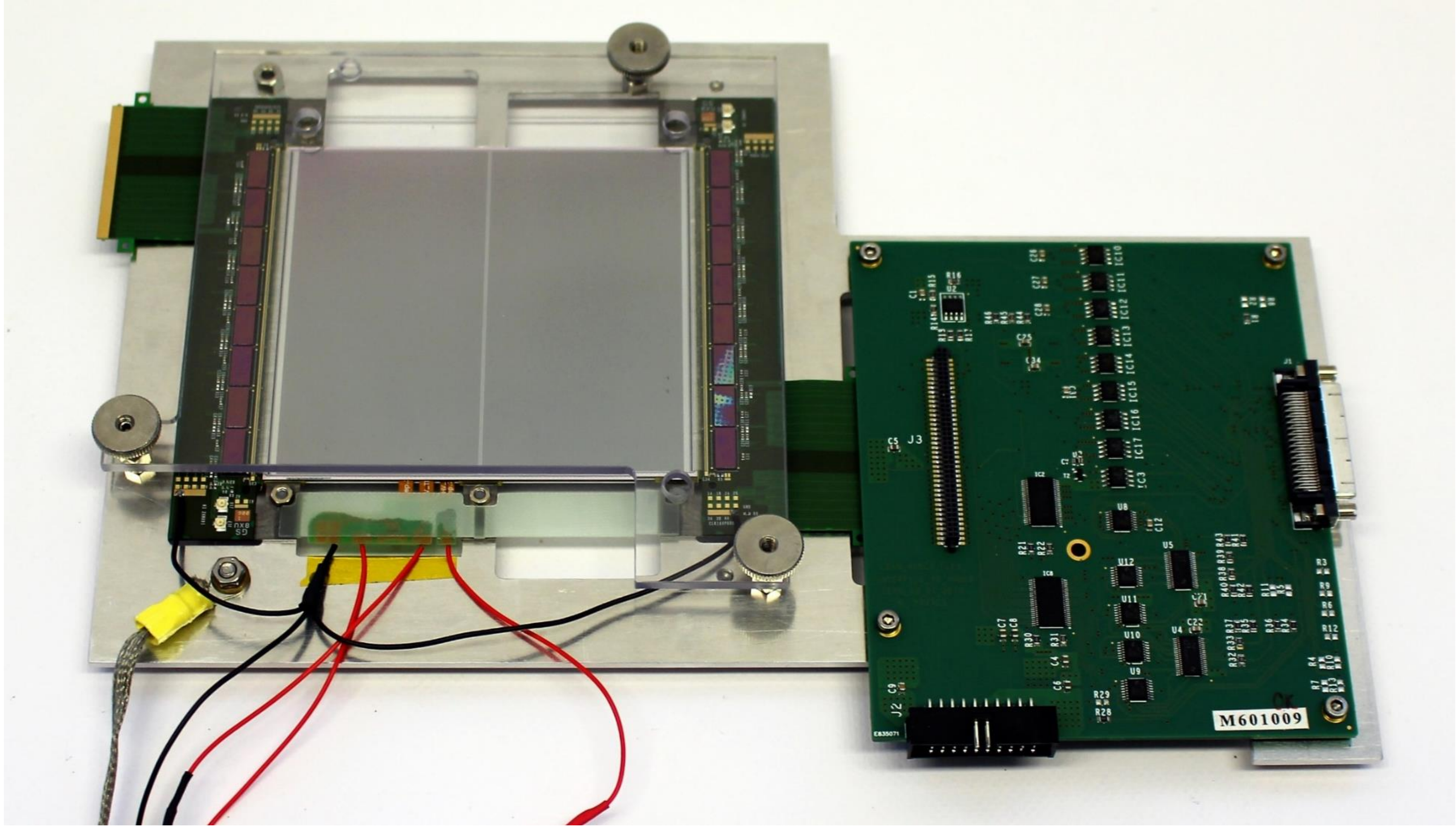


Module Prototyping – KIT

- To qualify assembly procedure KIT built dummy modules with substitute materials in 2017

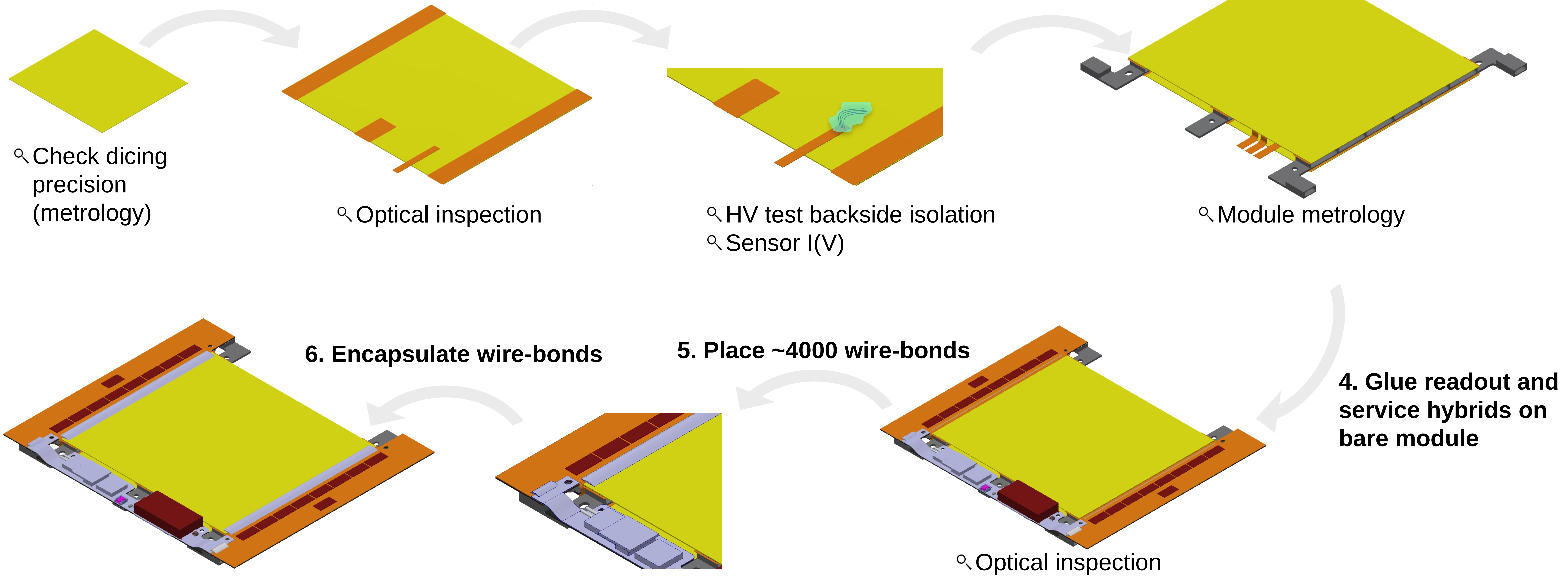


- In Jan 2018, the first functional KIT 2S Module was assembled



Module requirements	To evaluate
Mechanical precision	Precision of jig-based assembly procedure
Thermal performance	Thin, fully wetted glue connections
High voltage stability	Placement of thin polyimide strips
Readout quality	Ensure high bonding quality

Assembly and Test Procedure of 2S Modules



🔍Check dicing precision (metrology)

1. Glue polyimide HV isolation and attach HV tails on sensor backside

🔍Optical inspection

2. Wire-bond and encapsulate HV tails

🔍HV test backside isolation
🔍Sensor I(V)

3. Glue sensors on Al-CF brides

🔍Module metrology

4. Glue readout and service hybrids on bare module

🔍Optical inspection
🔍HV/LV test

5. Place ~4000 wire-bonds

🔍Module test

6. Encapsulate wire-bonds

🔍Module test

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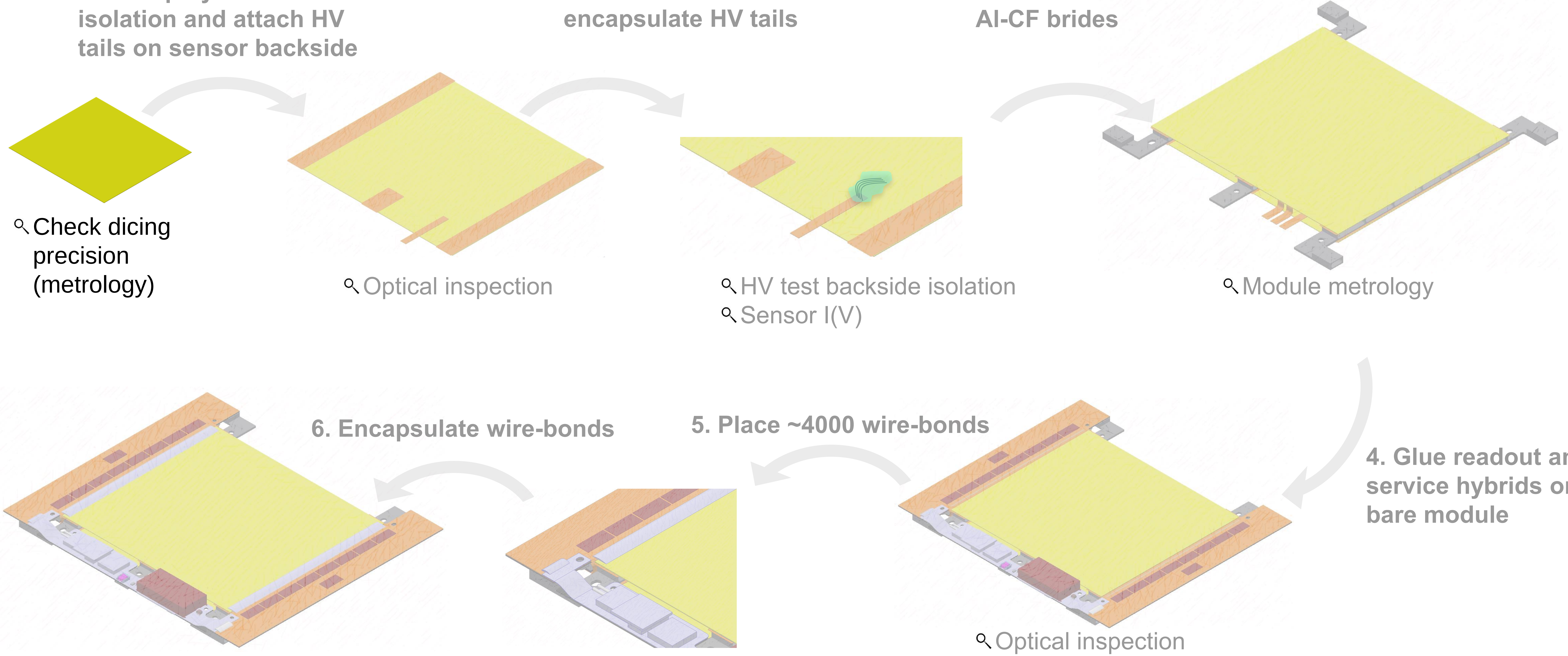

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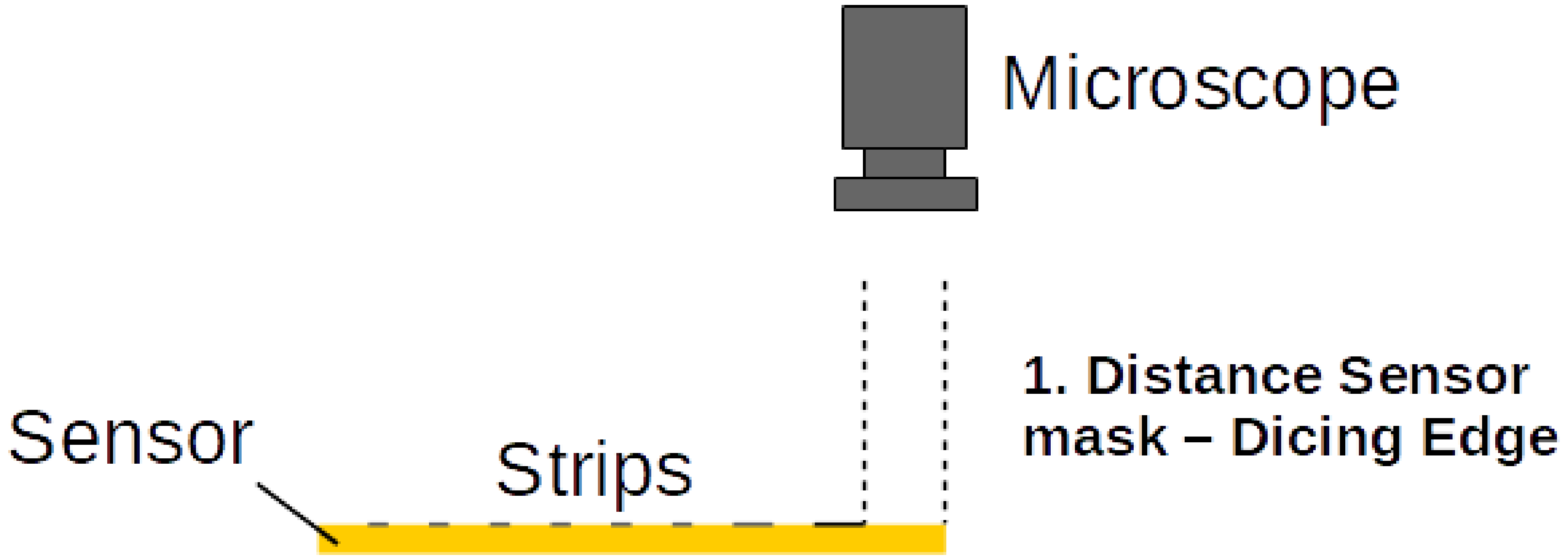
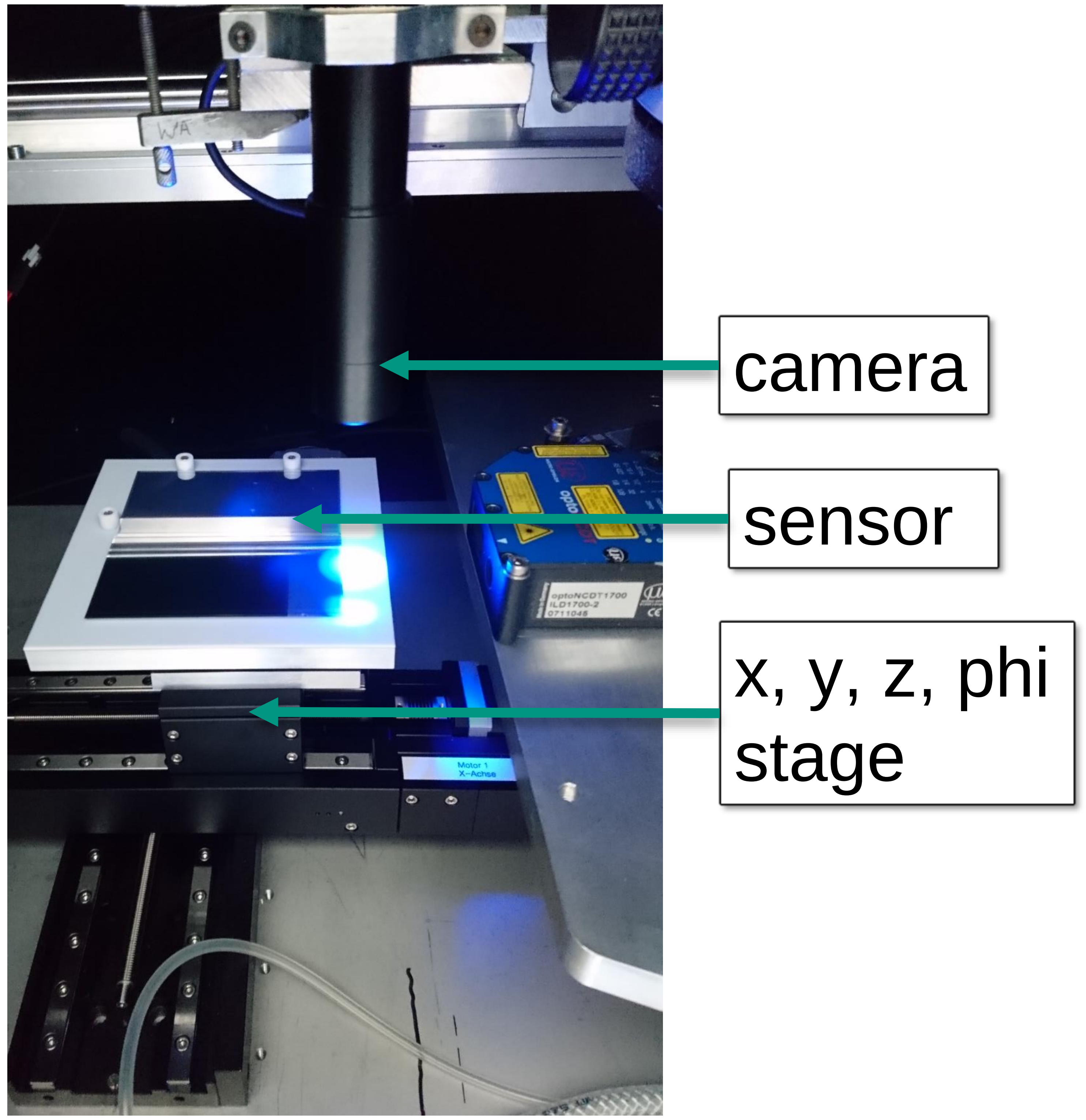
Sensor Dicing Precision – Station

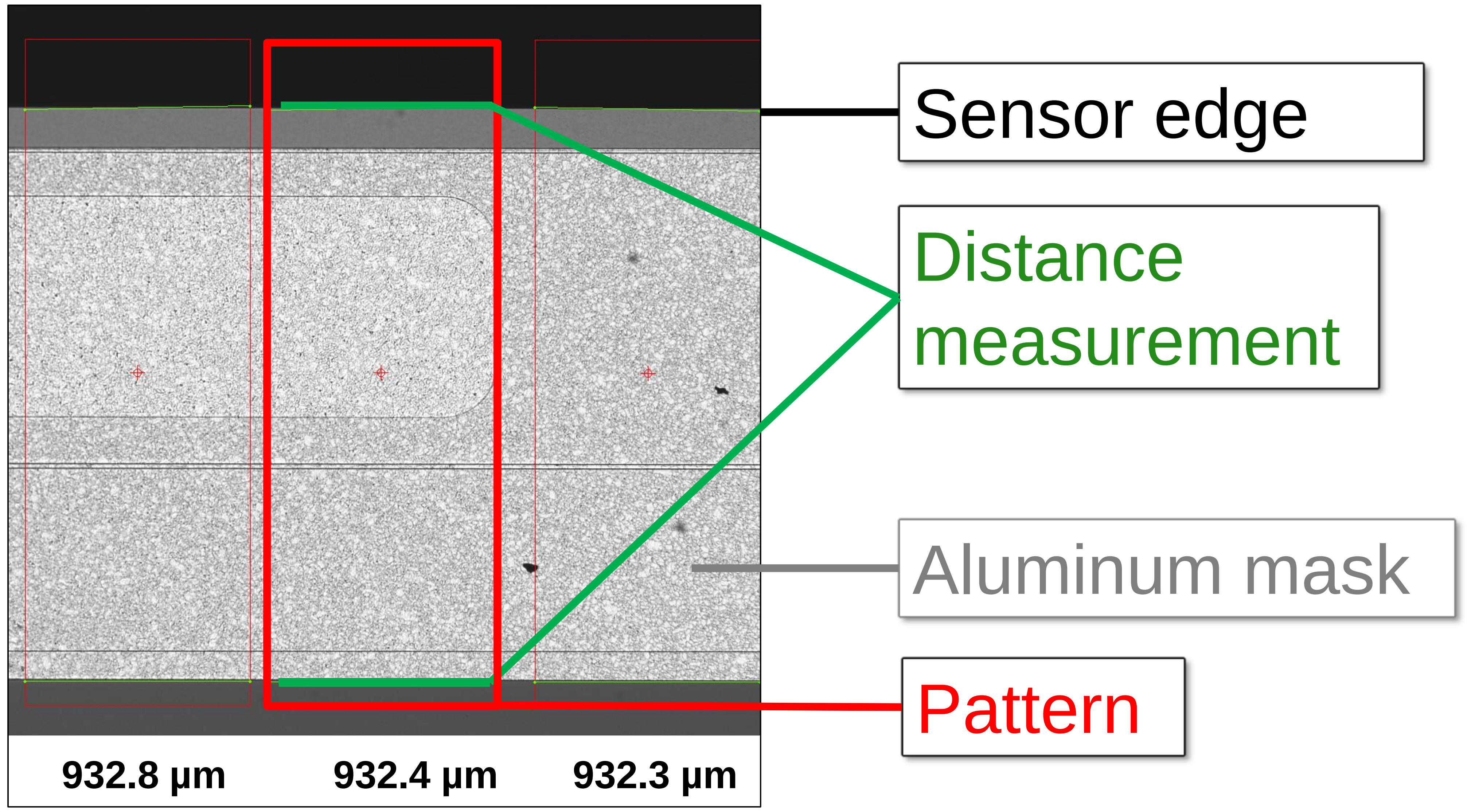
- High precision on sensor dicing necessary for sensor alignment
- Check dicing angles on each sensor before module assembly in a semi-automatic measurement station
- Vendor specification: **angle <100 µrad** (10 µm dicing wide area)
- 5MP camera mounted above sensor jig



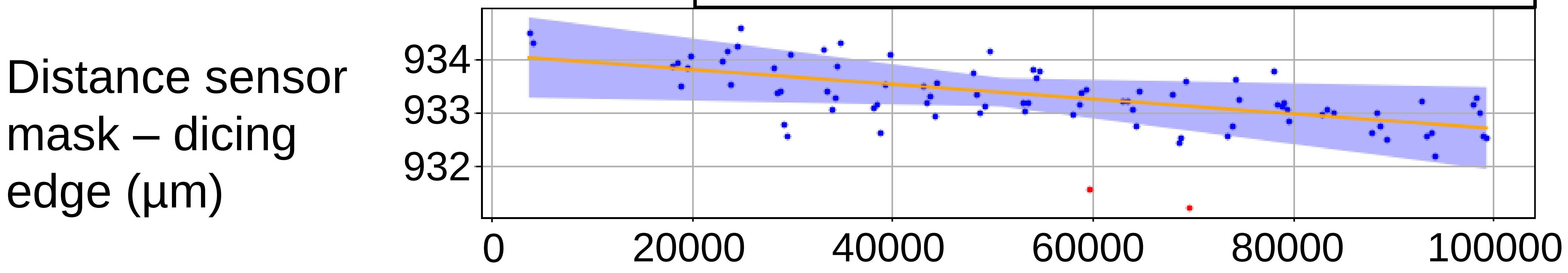


Sensor Dicing Precision – Measurement

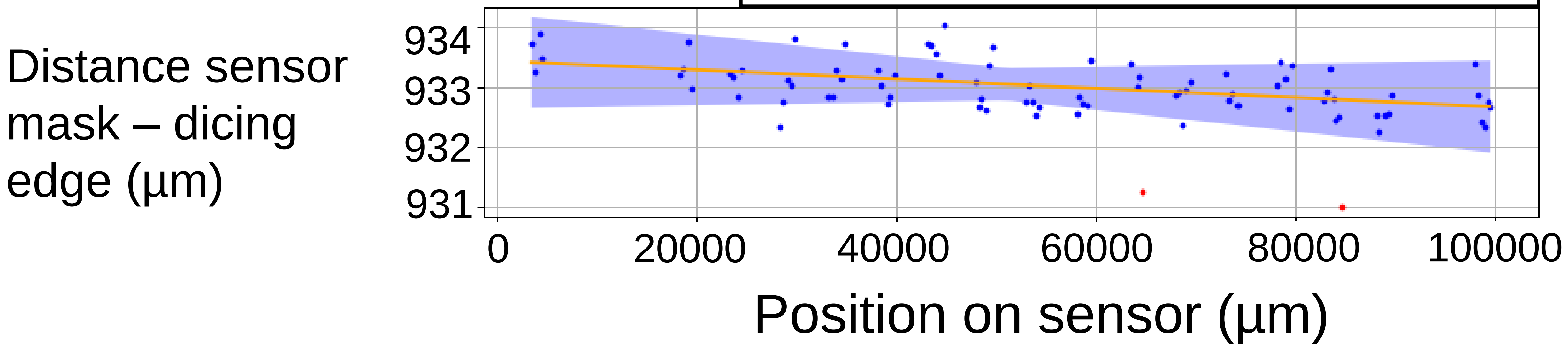
- Pattern recognition software measures distance between dicing edge and sensor mask
- Multiple measurements within each picture
- Fit (slope) on distances along the sensor side gives dicing angle

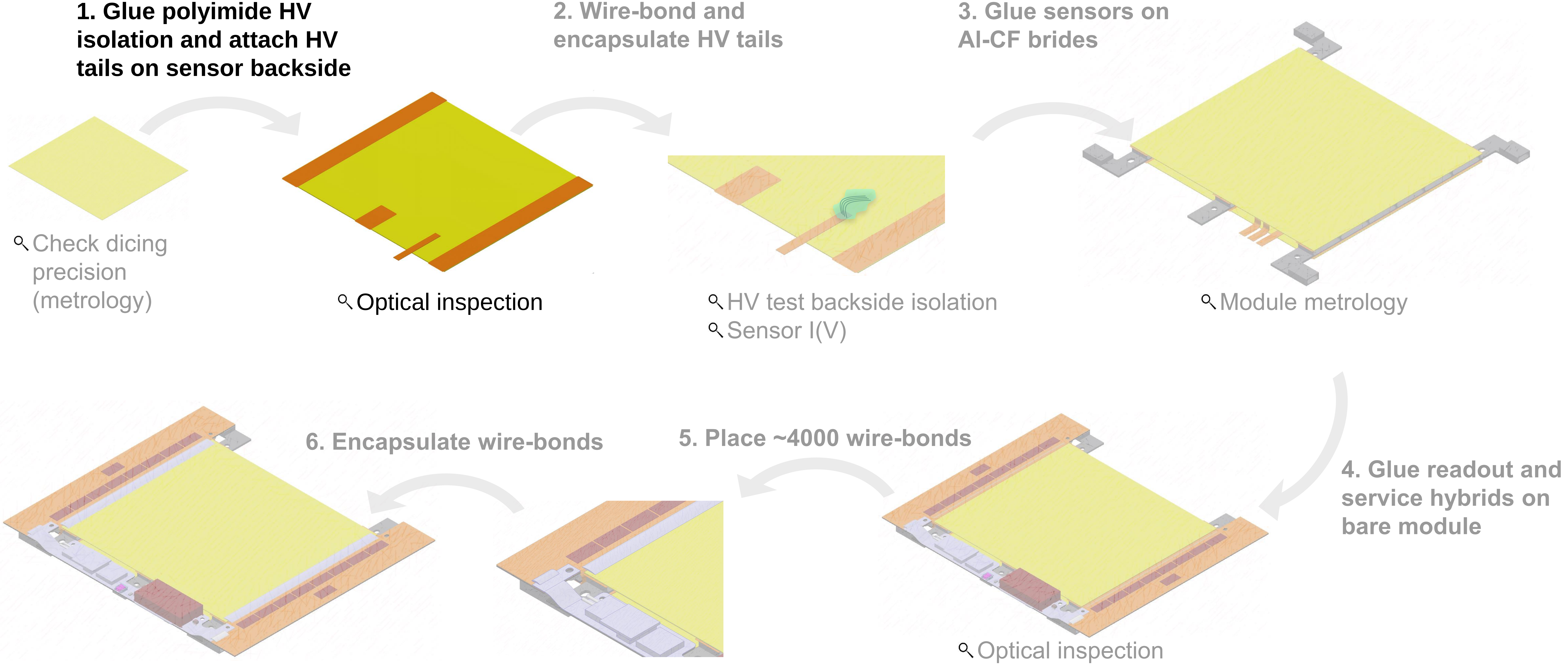


Bottom sensor: **– 9 ± 11 µrad**



Top sensor: **– 15 ± 11 µrad**





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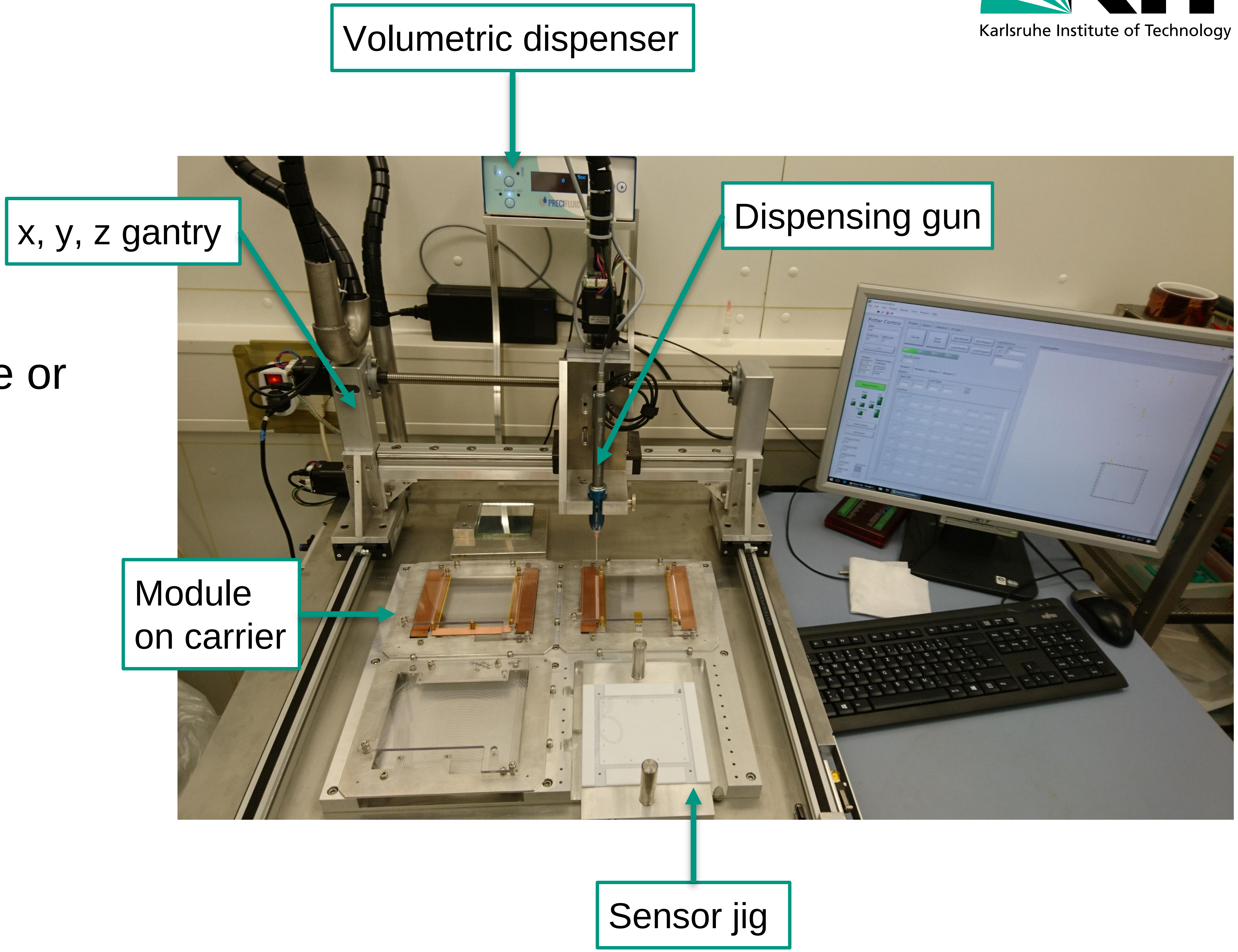
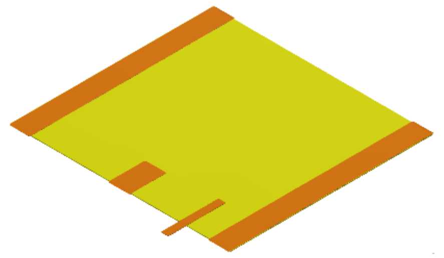
Dispensing Gantry

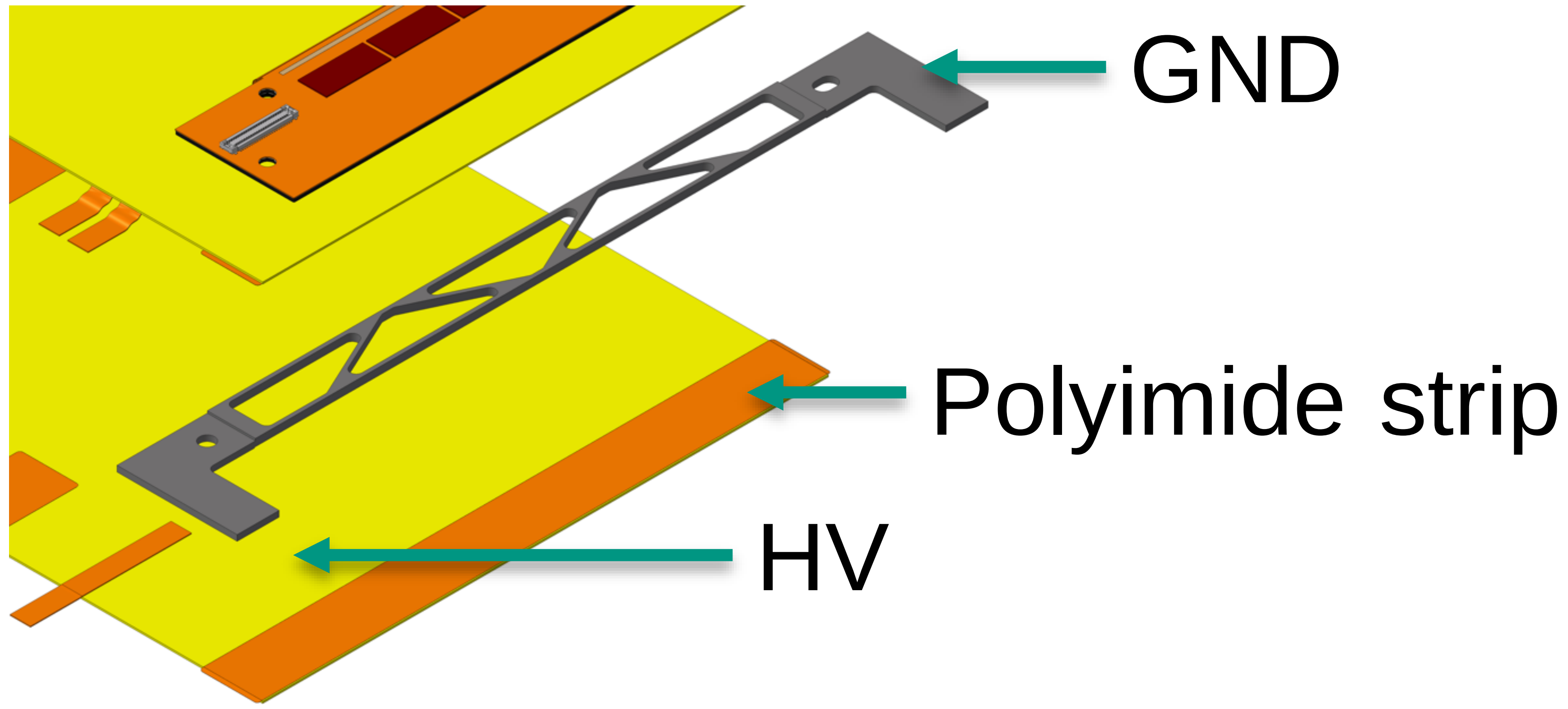
- Volumetric dispenser applies glue or wire-bond encapsulation material
- Space for 4 modules or sensors
- Controlled via LabVIEW

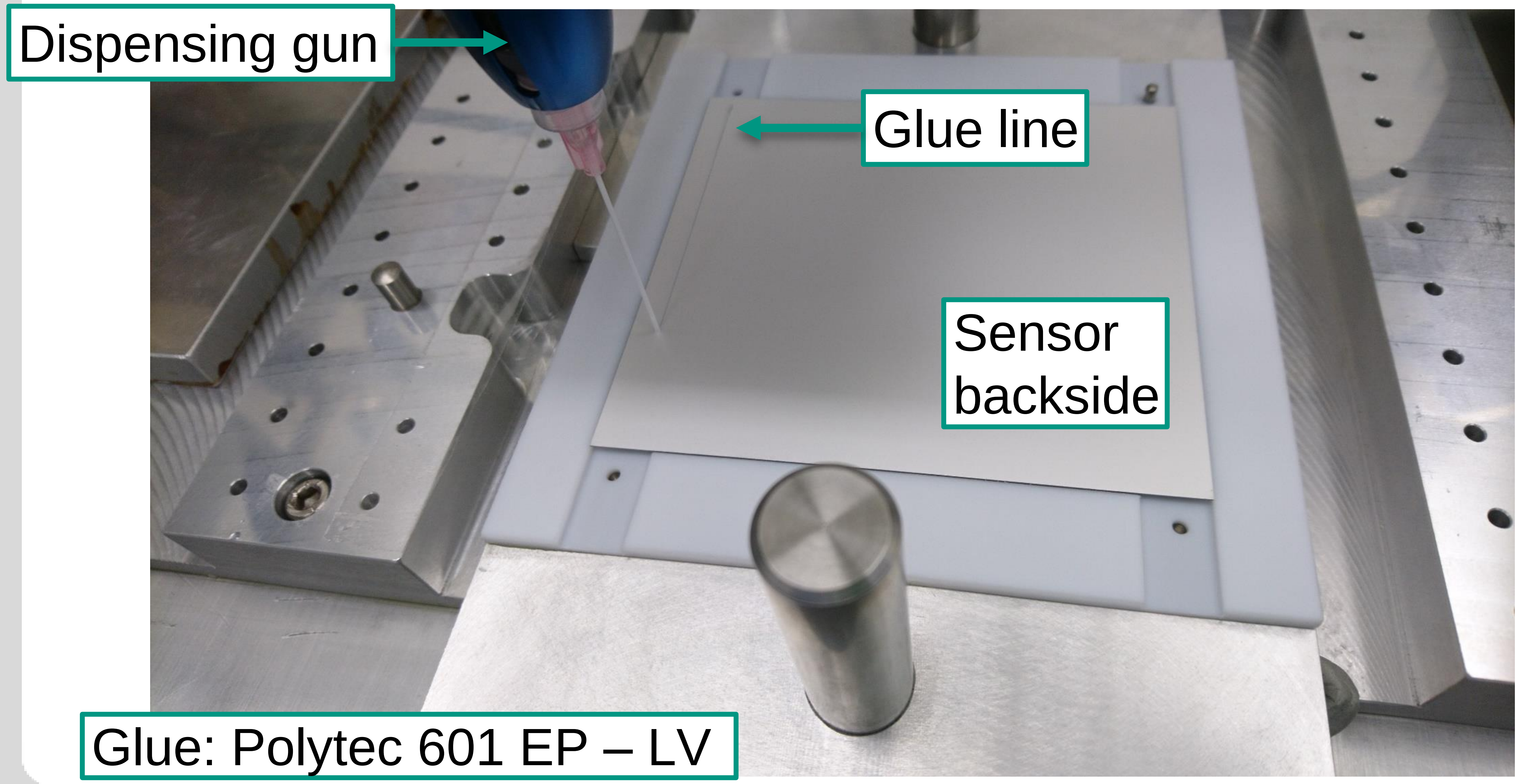


Polyimide Backside Isolation

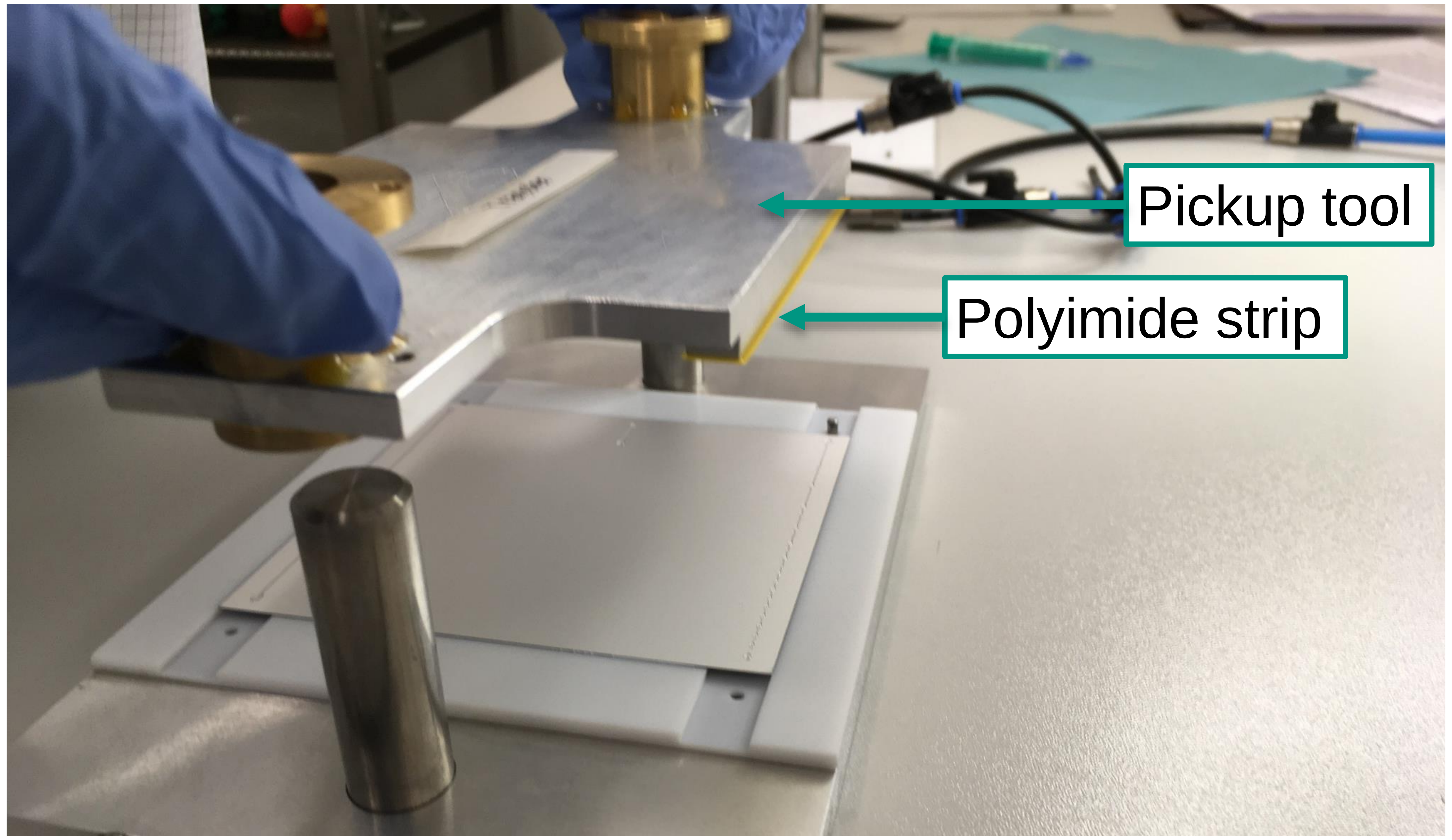


- Sensor backside must be isolated against Al-CF bridges
- 25 µm thick Polyimide strip (Kapton MT+, λ = ~1 W/m/K)
- Volumetric dispenser on gantry applies thin glue lines
- Strips precisely placed with pickup tool (350 µm window)





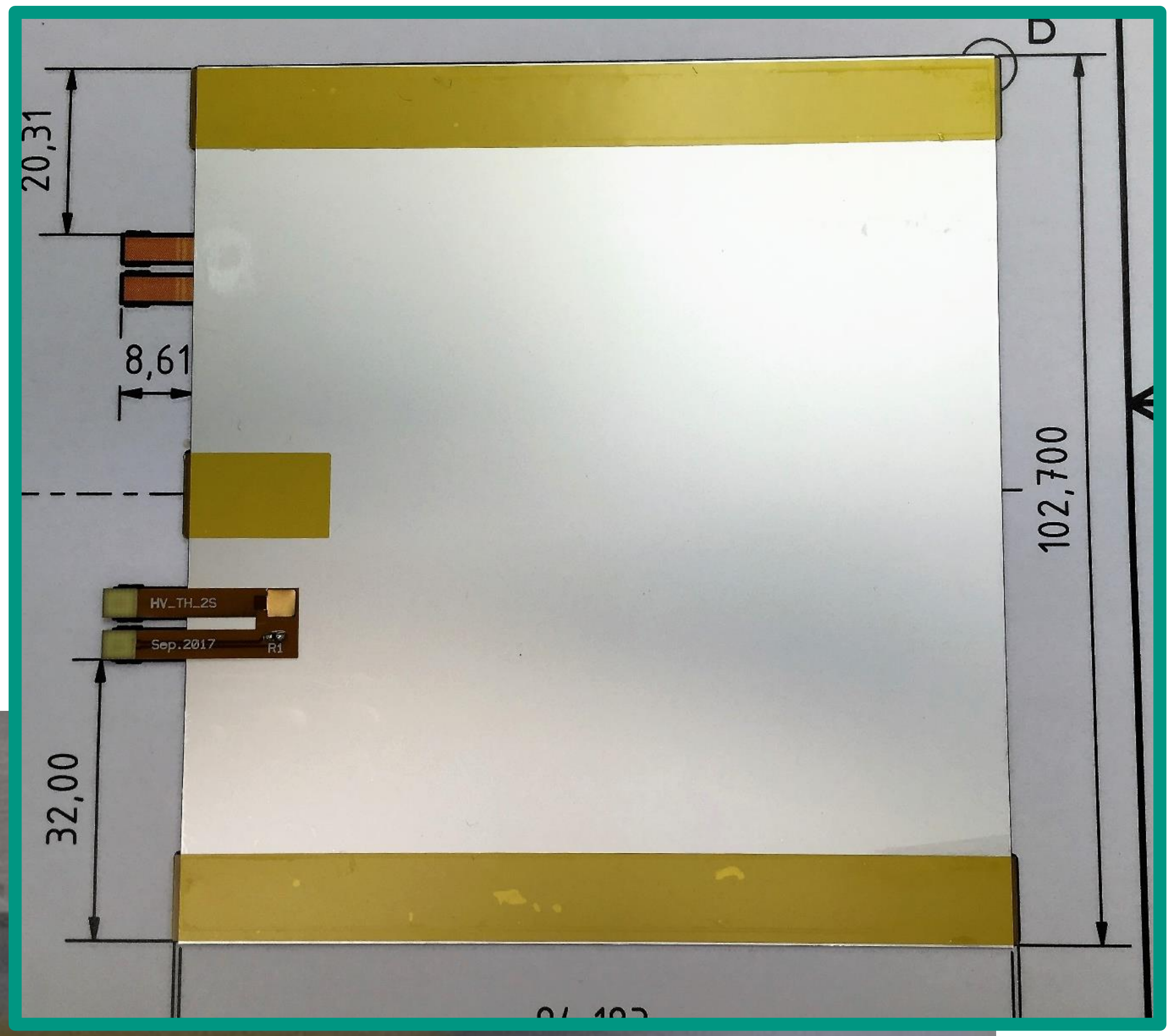
Glue: Polytec 601 EP – LV

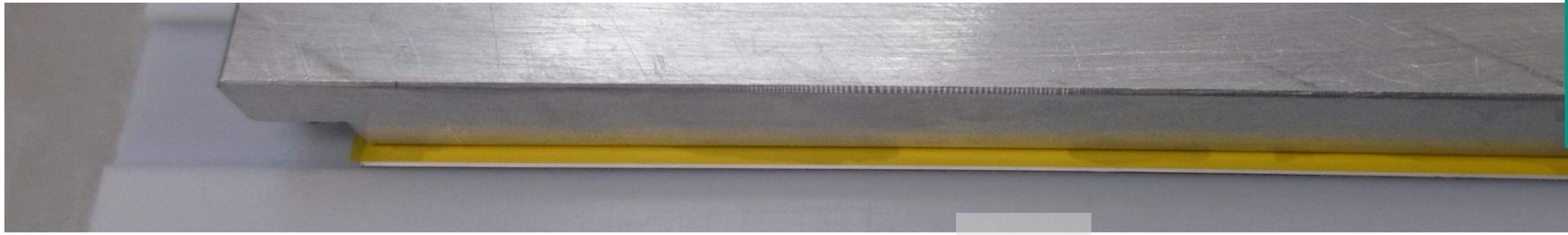


Polyimide Backside Isolation

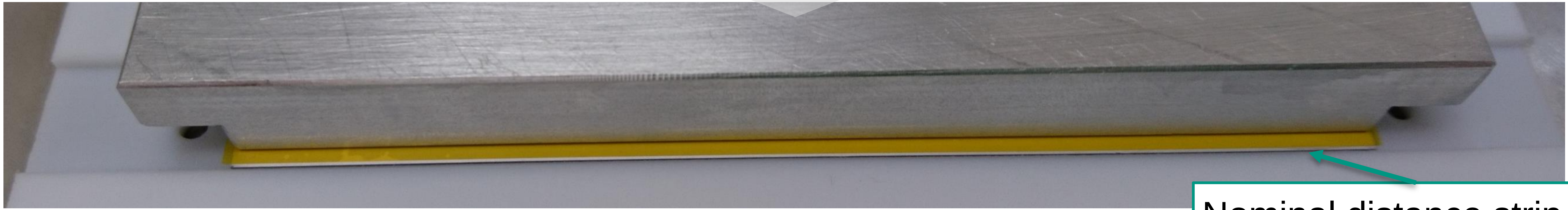
- Glue layers as narrow as **6 µm** possible
- **Full glue wetting** between sensor and strip by capillary forces

Improves thermal performance

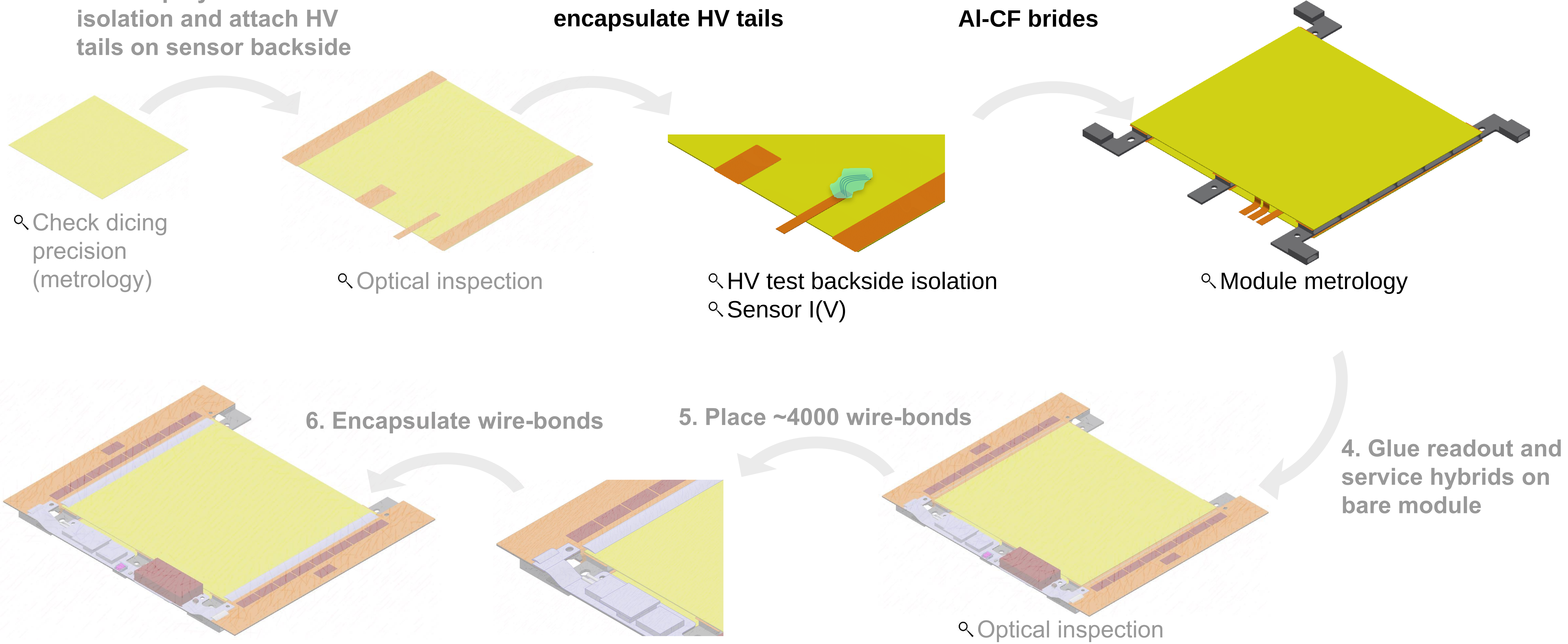




~5 min



Nominal distance strip to sensor edge: 150 µm



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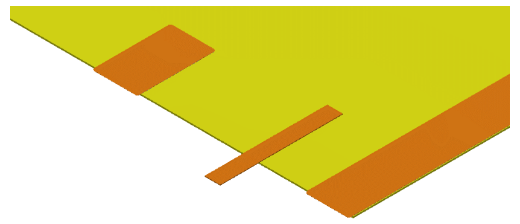
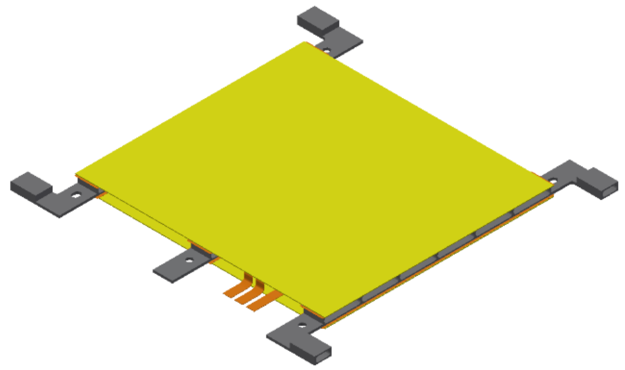
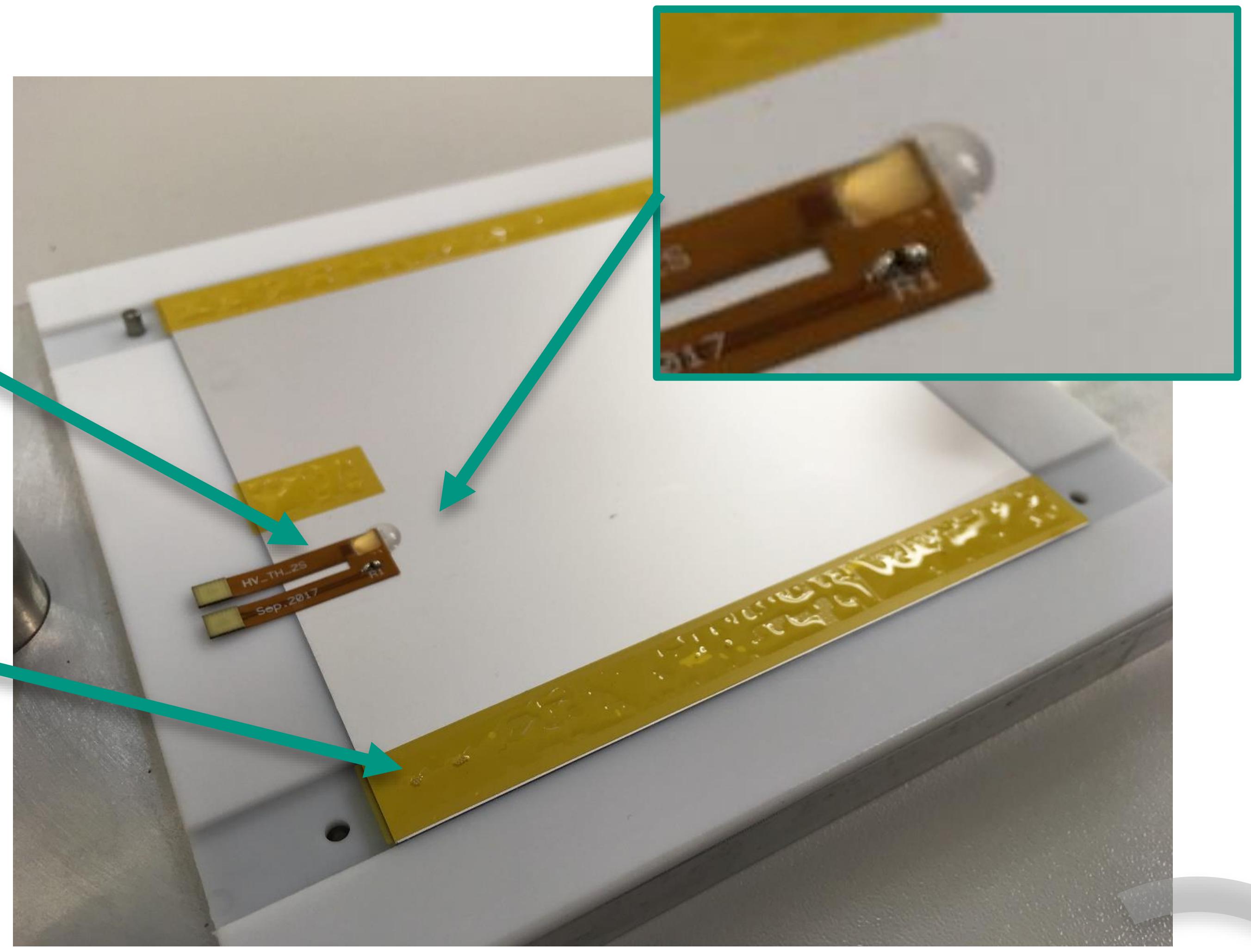
Bare Module Assembly

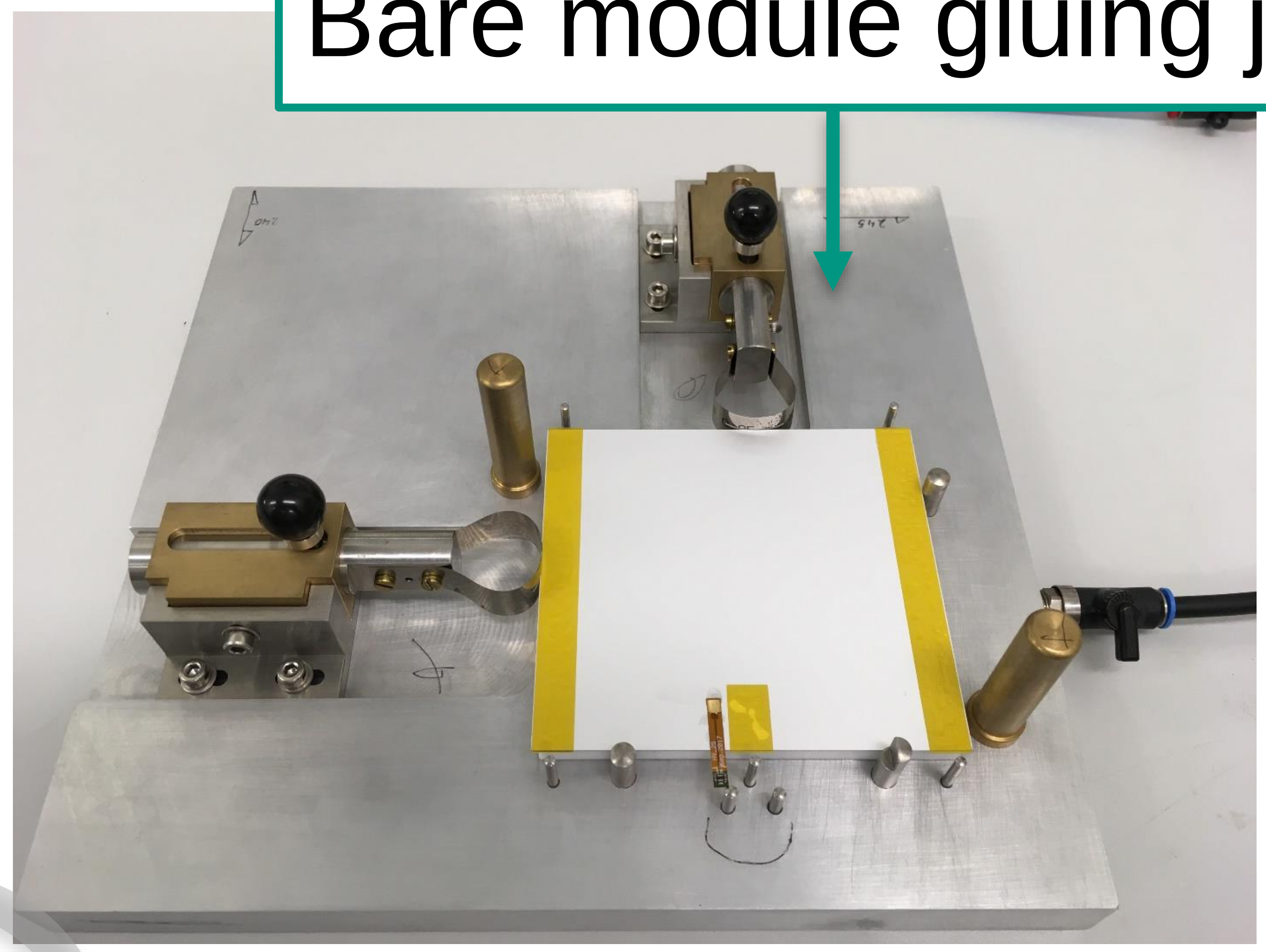


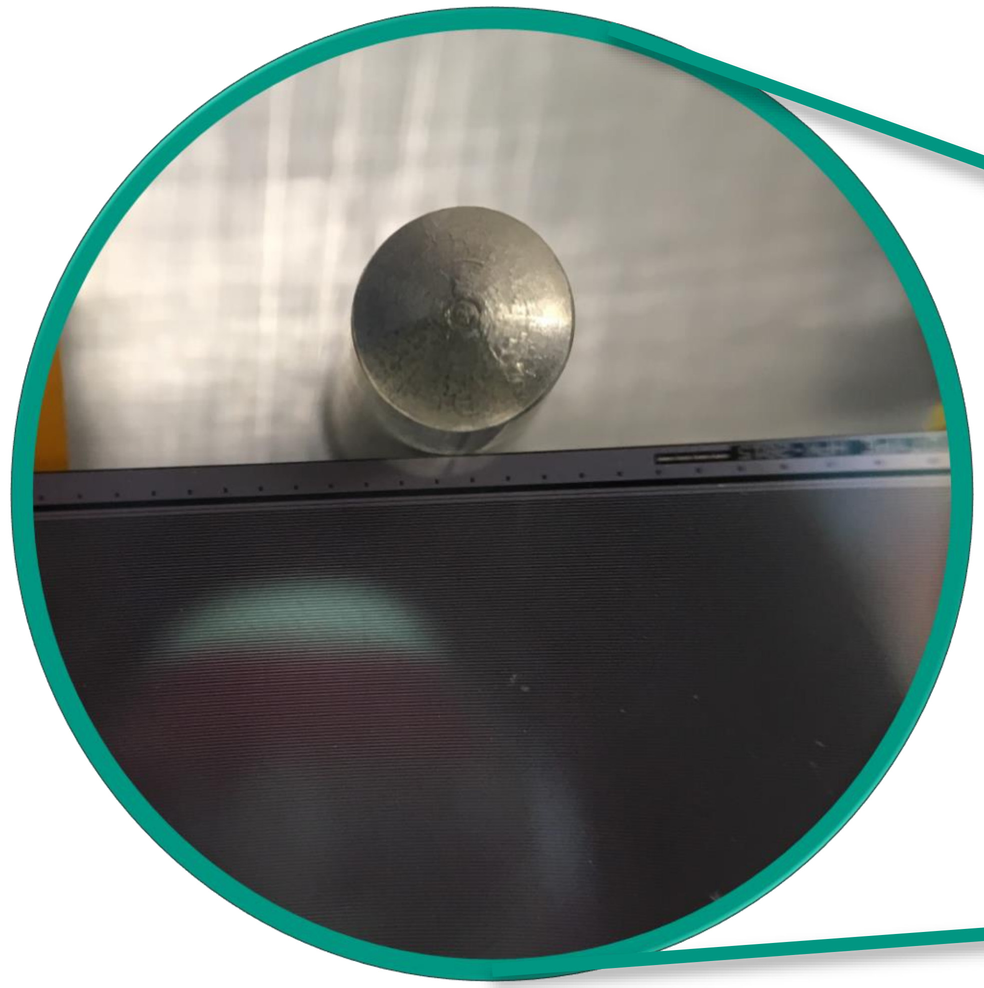


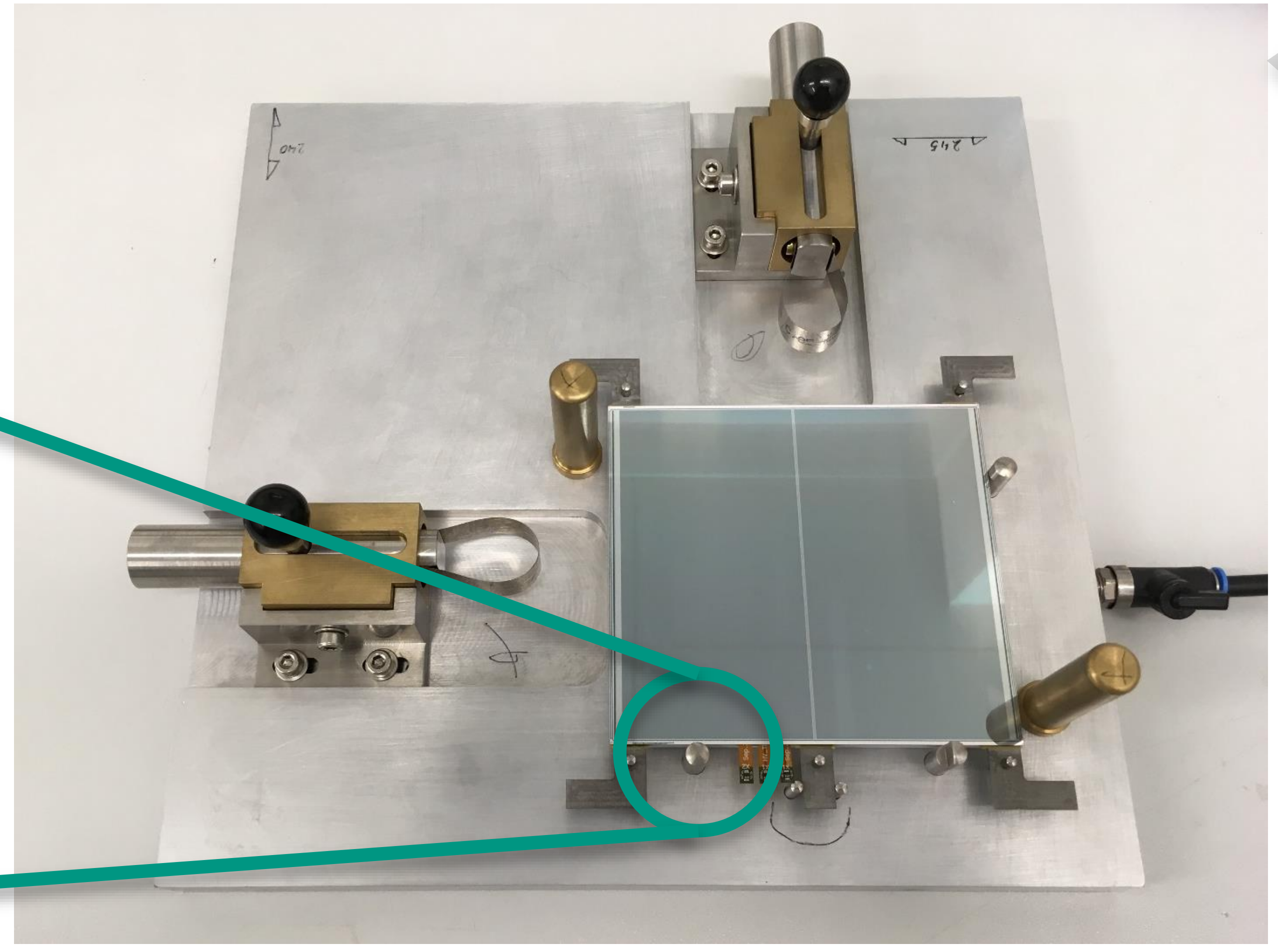
- Attach, wire-bond and encapsulate HV tails
- Apply glue with a rubber stamp on polyimide strip
- Align sensors and Al-CF bridges on a jig with alignment pins

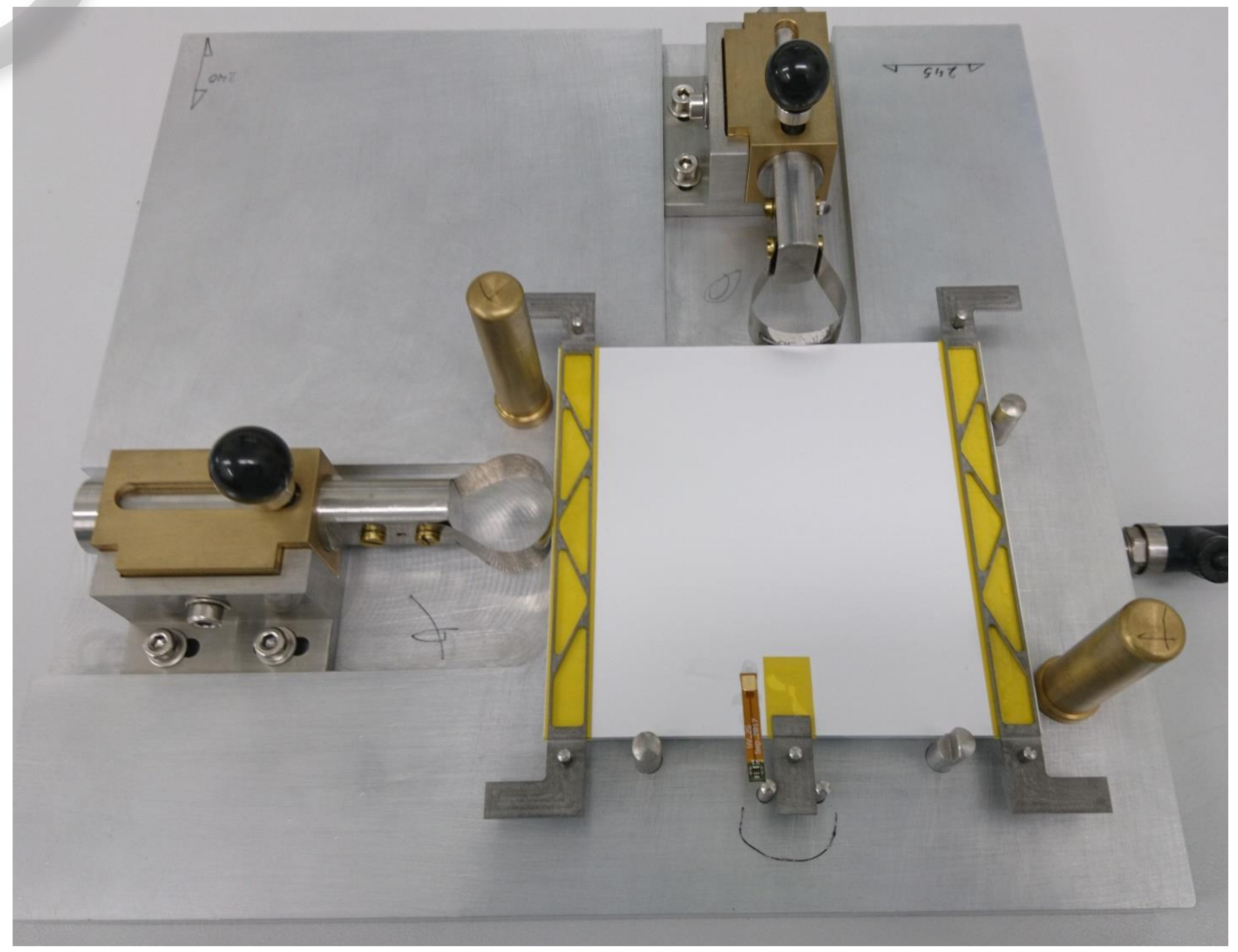


Bare module gluing jig



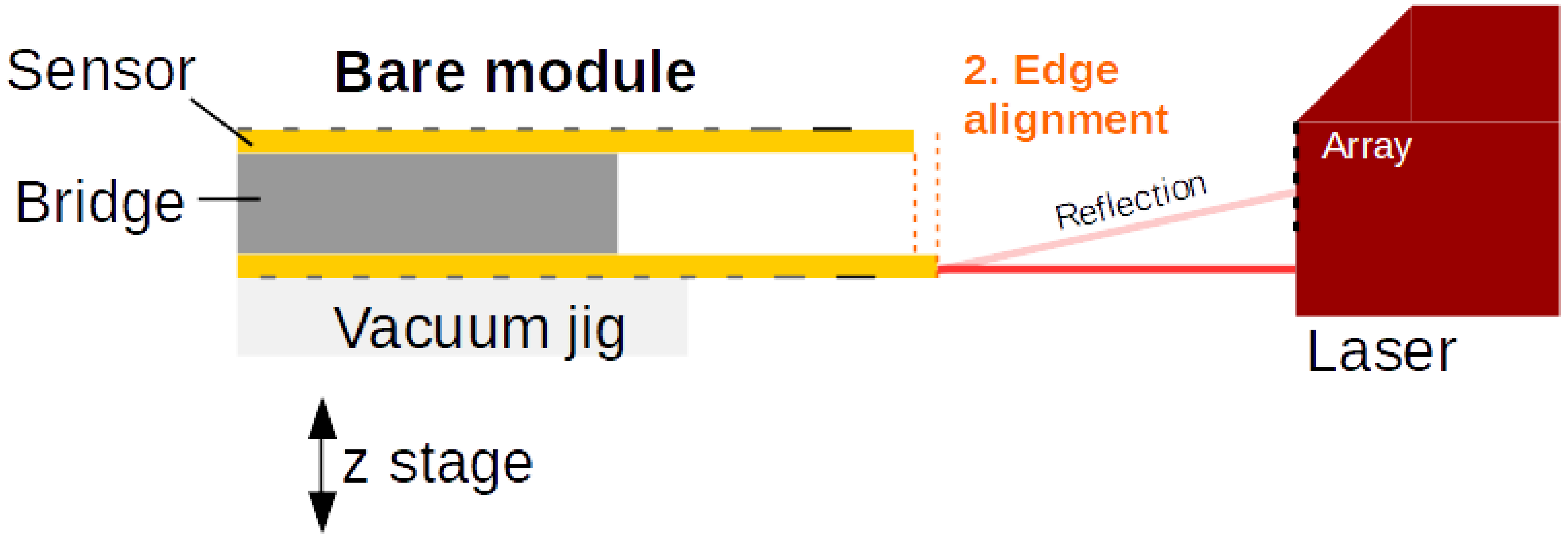


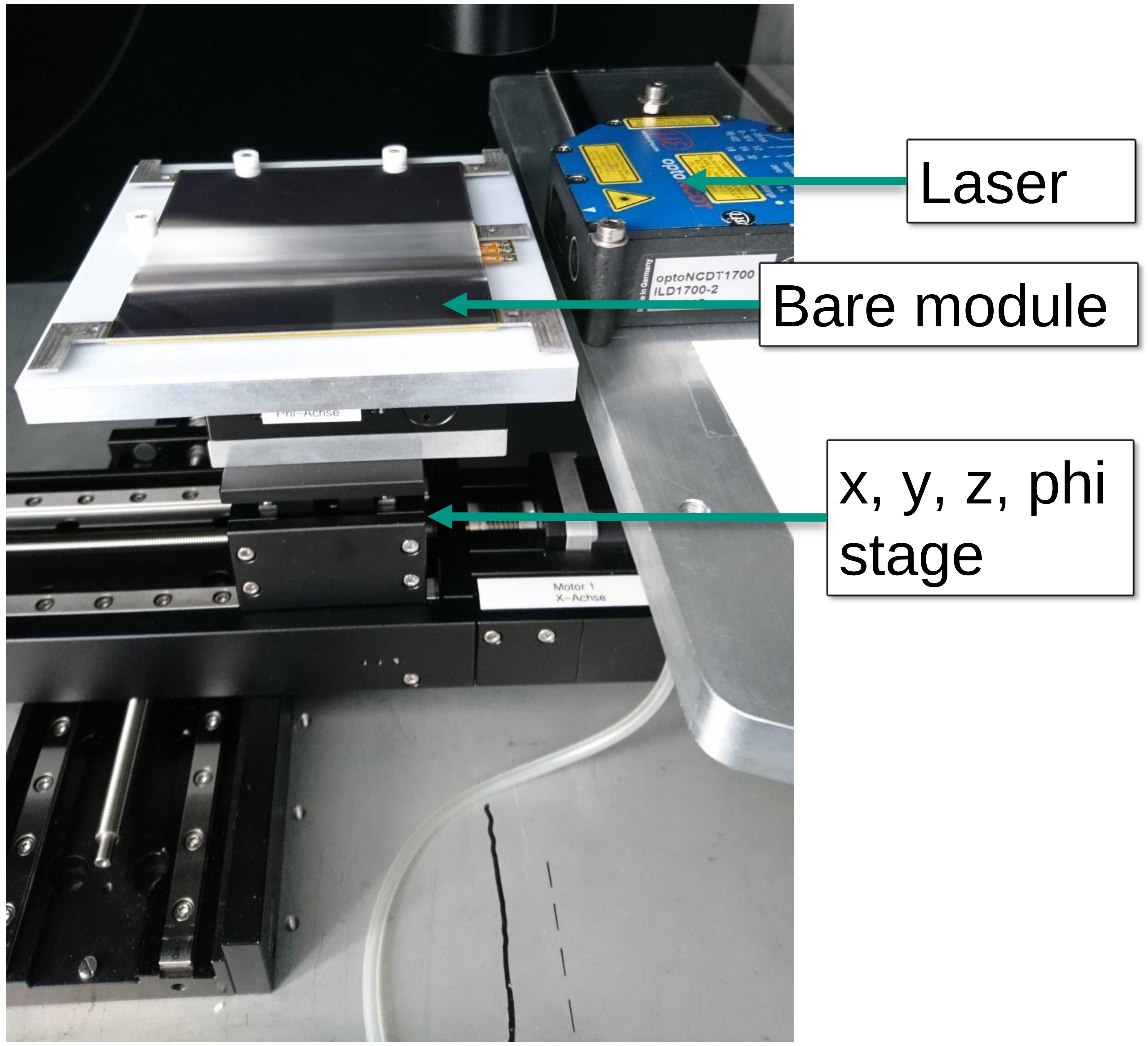




Laser Metrology – Station

- Ensure sensor alignment in bare module in laser-based metrology station
- Laser measures distance to top and bottom sensor along module side

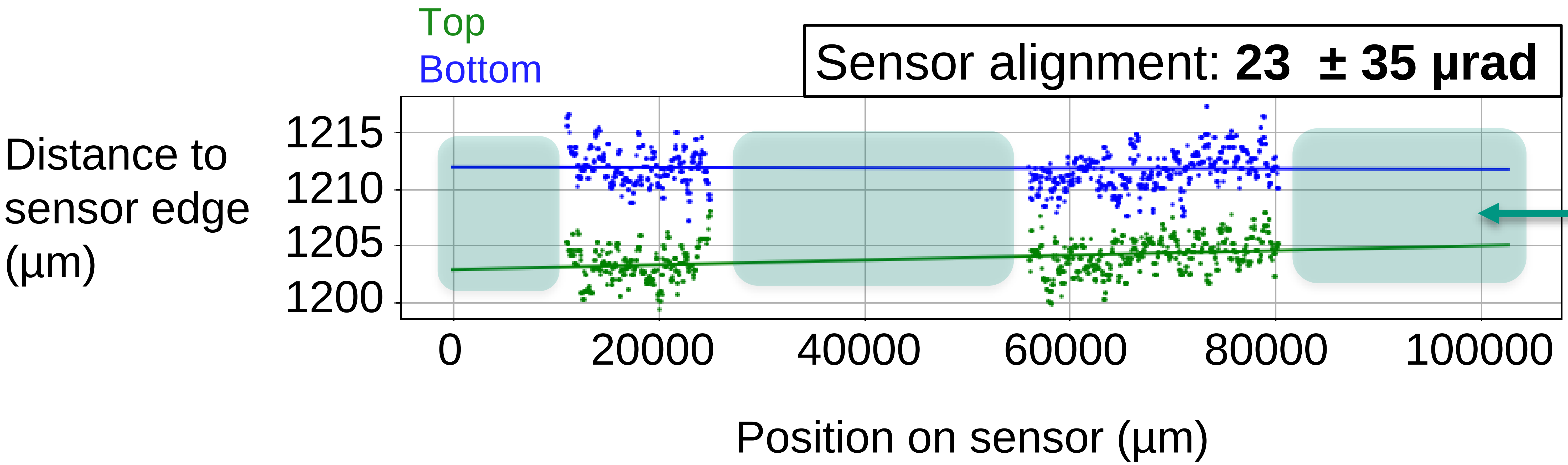




Laser Metrology – Measurement

- Top and bottom sensor distance measured at 300 Hz while sensor edges move (10mm/s) along laser
- Fit of distances vs. position on sensor gives edge orientation relative to laser
- Difference of slopes corresponds to sensor edge alignment

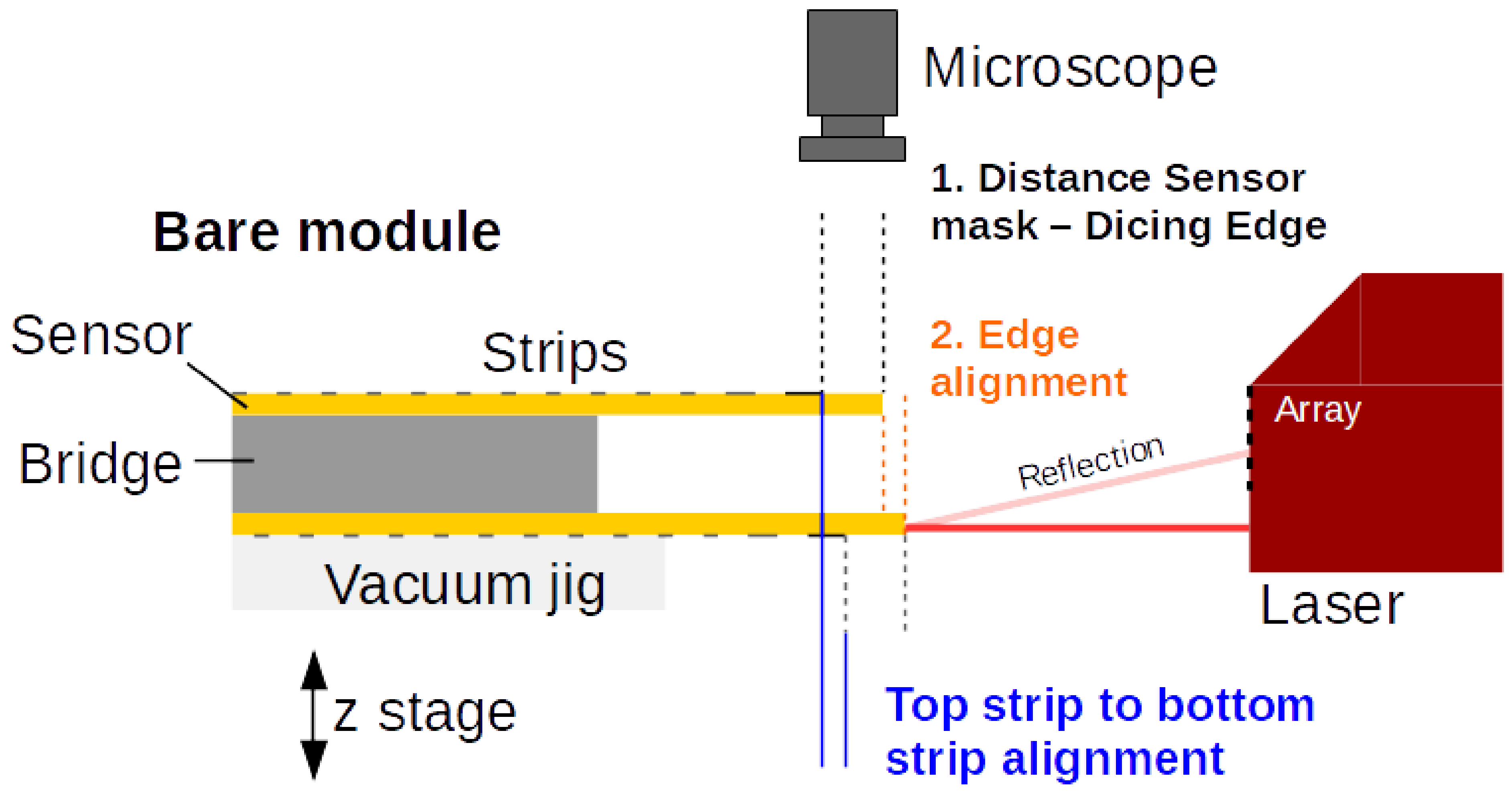

Laser spot

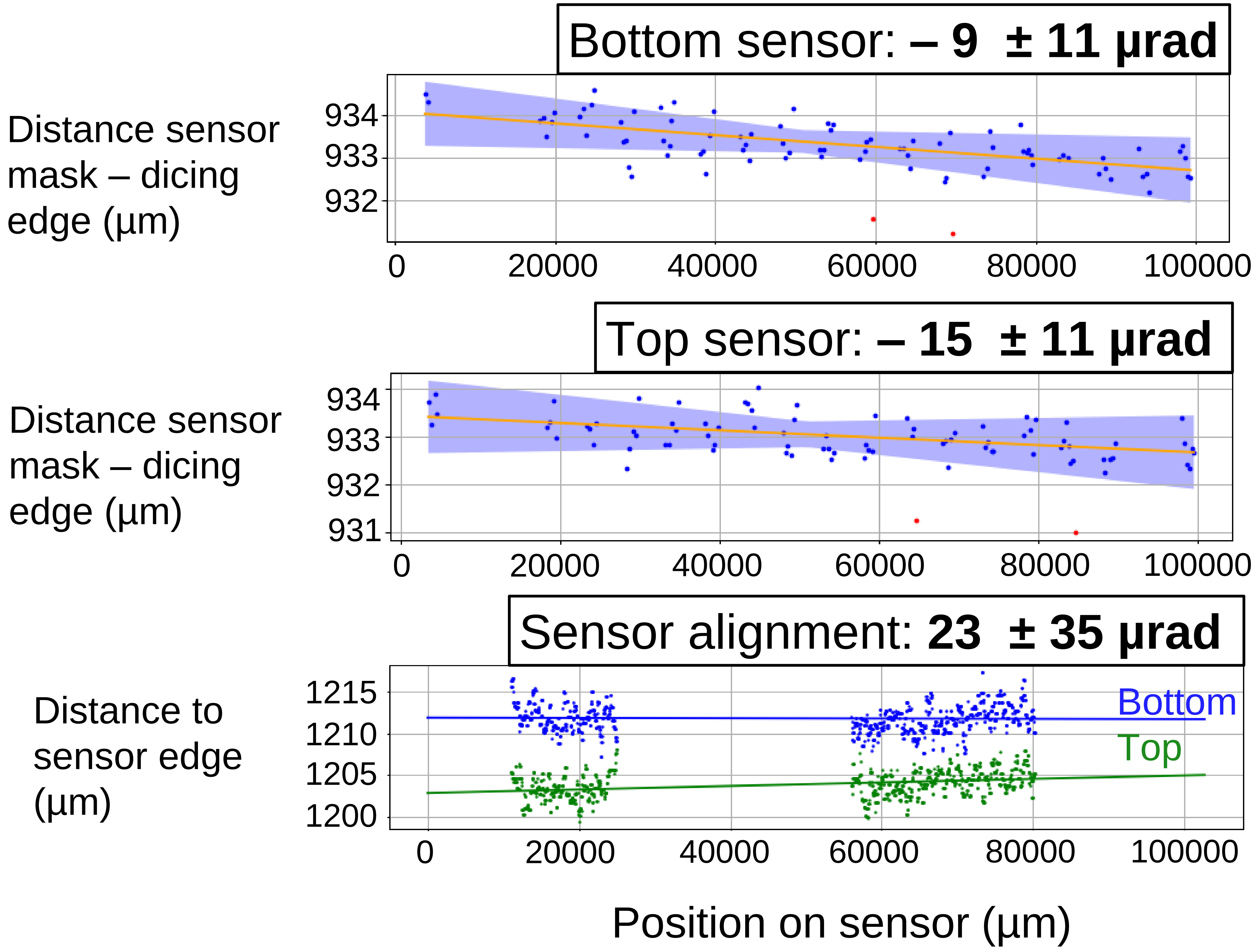

Sensor alignment: **23 ± 35 µrad**

Masked areas because bridges interfere with laser measurement

Top Strip to Bottom Strip Alignment

- Combine dicing angle measurements with edge alignment measurement for top strip to bottom strip alignment



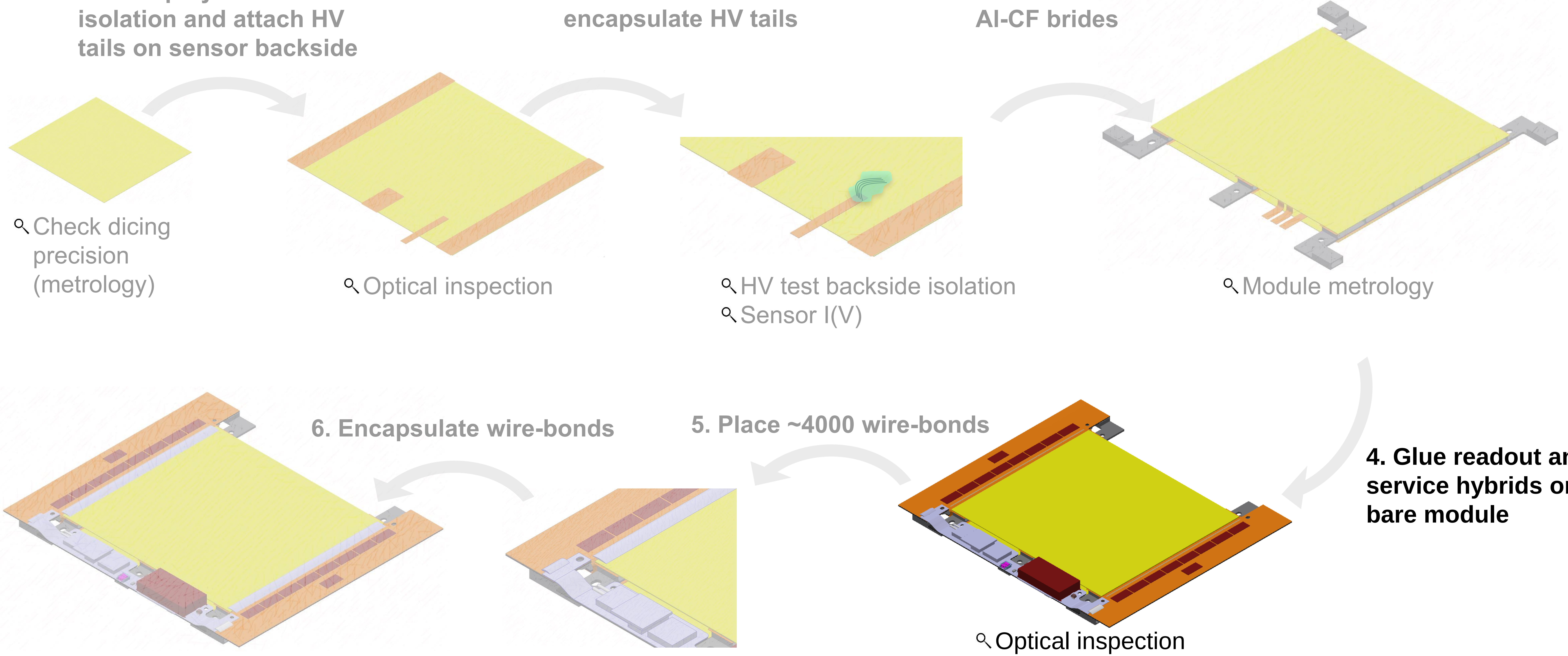

Bottom sensor: **– 9 ± 11 µrad**

Top sensor: **– 15 ± 11 µrad**

Sensor alignment: **23 ± 35 µrad**

- Top strip to bottom strip alignment: **– 1 ± 57 µrad**

Specs: |ϴ|< 400 µrad



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🔍 HV/LV test

5. Place ~4000 wire-bonds

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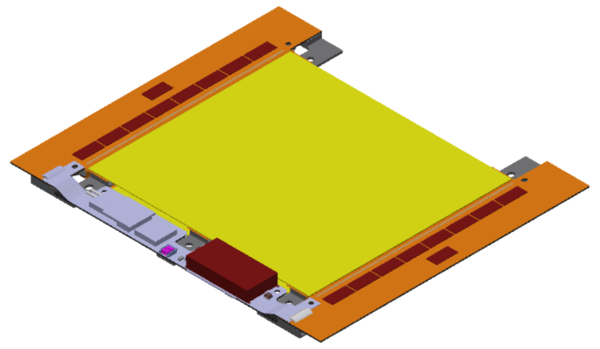
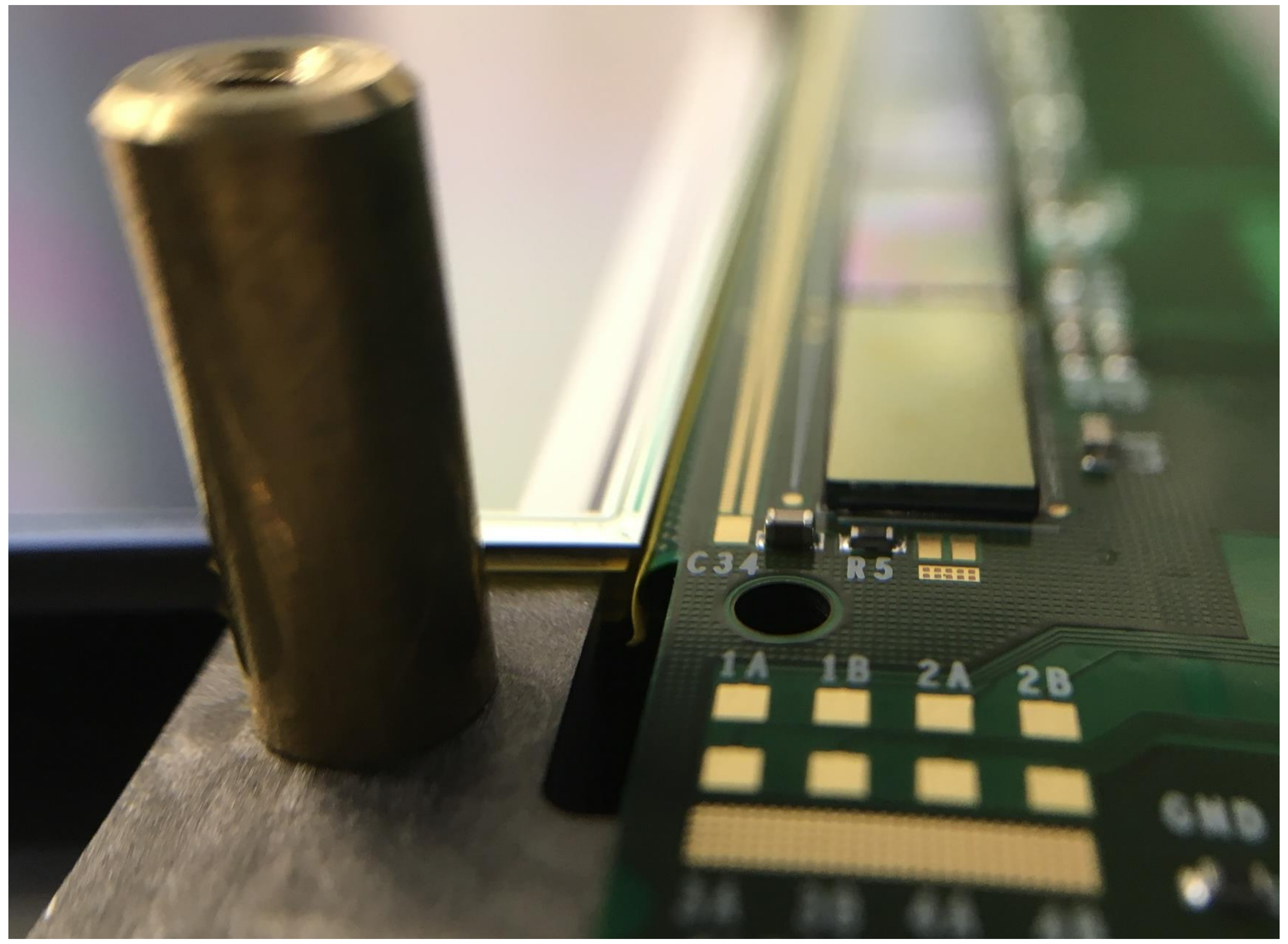
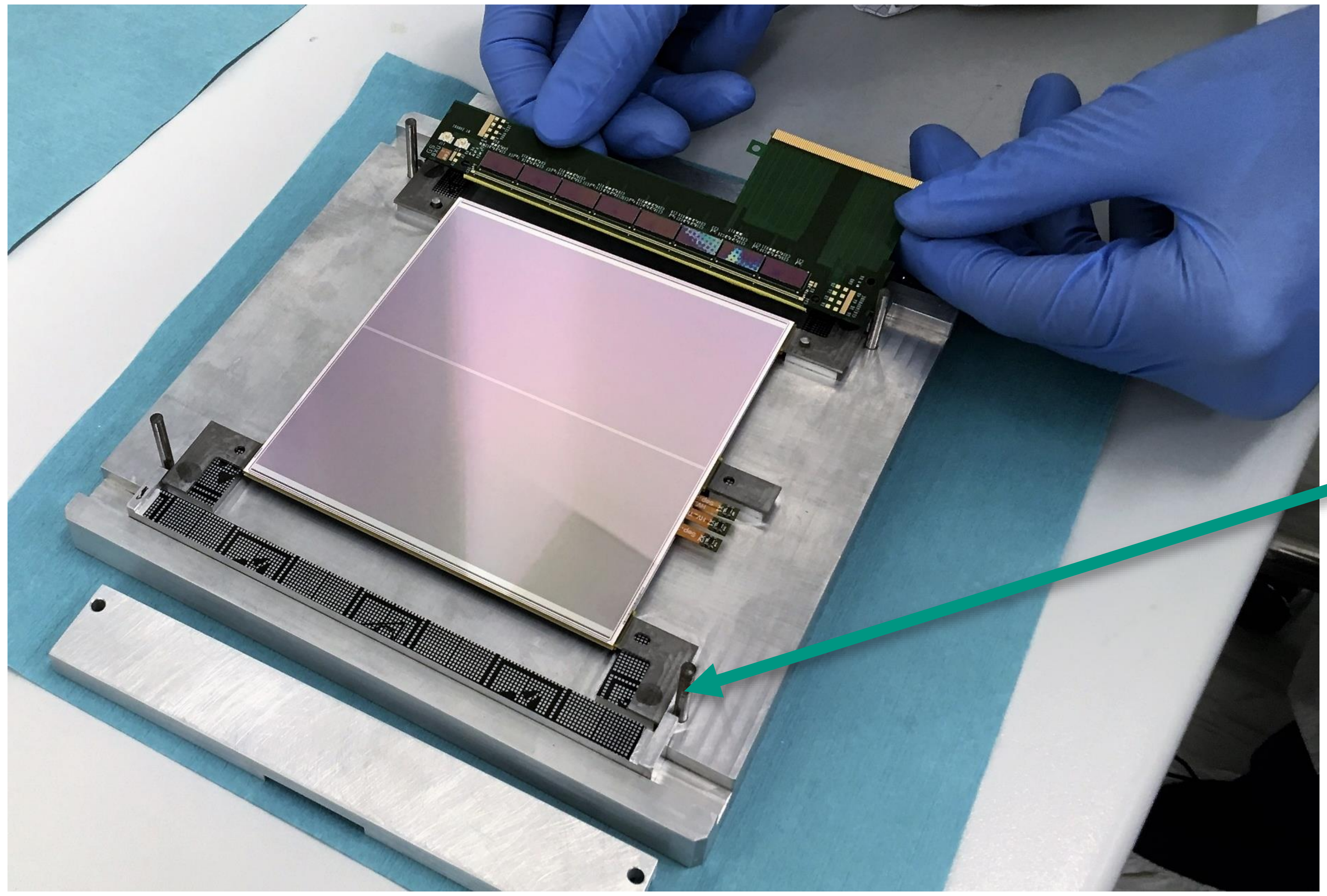
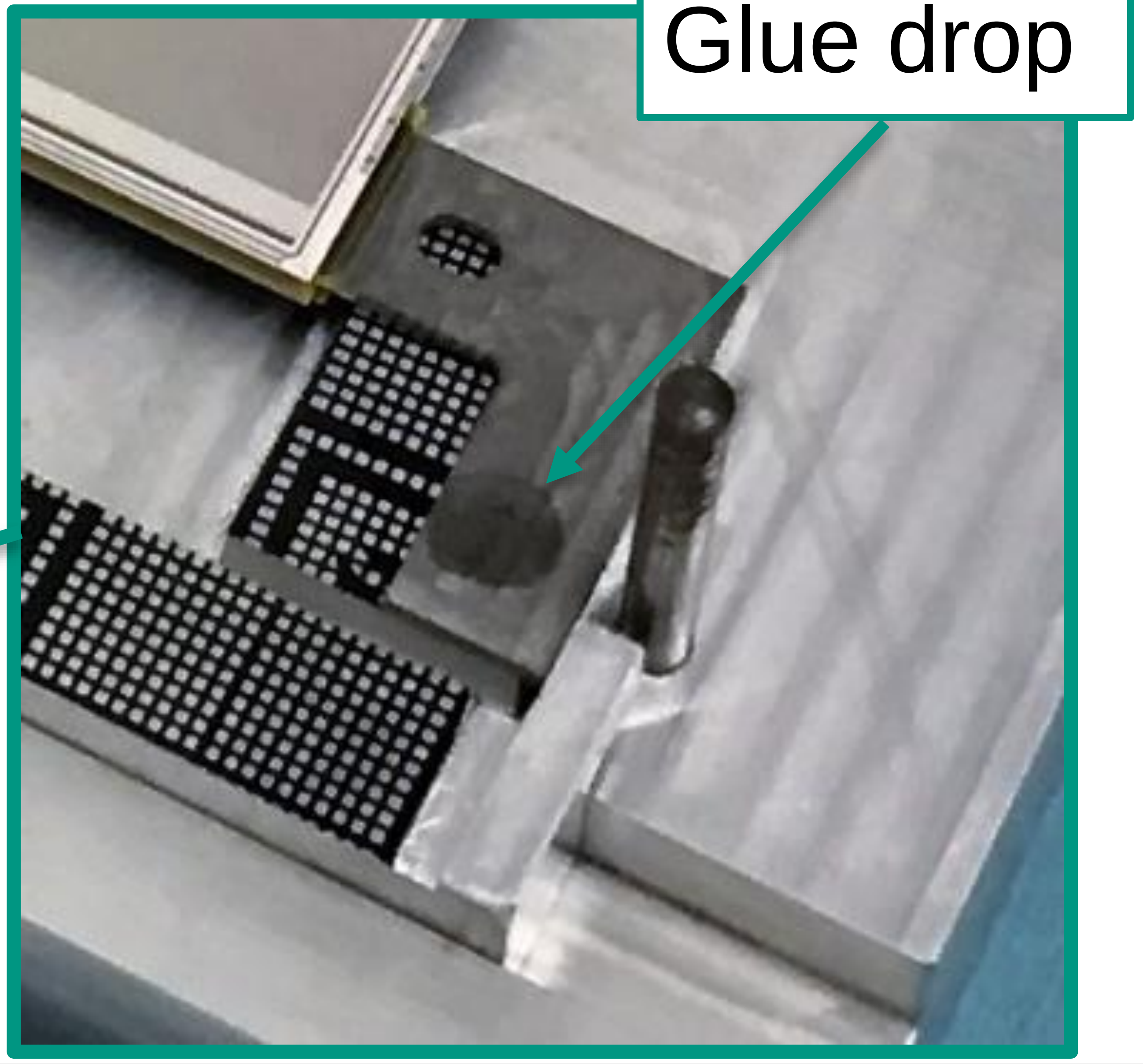
Hybrid Gluing – Jig

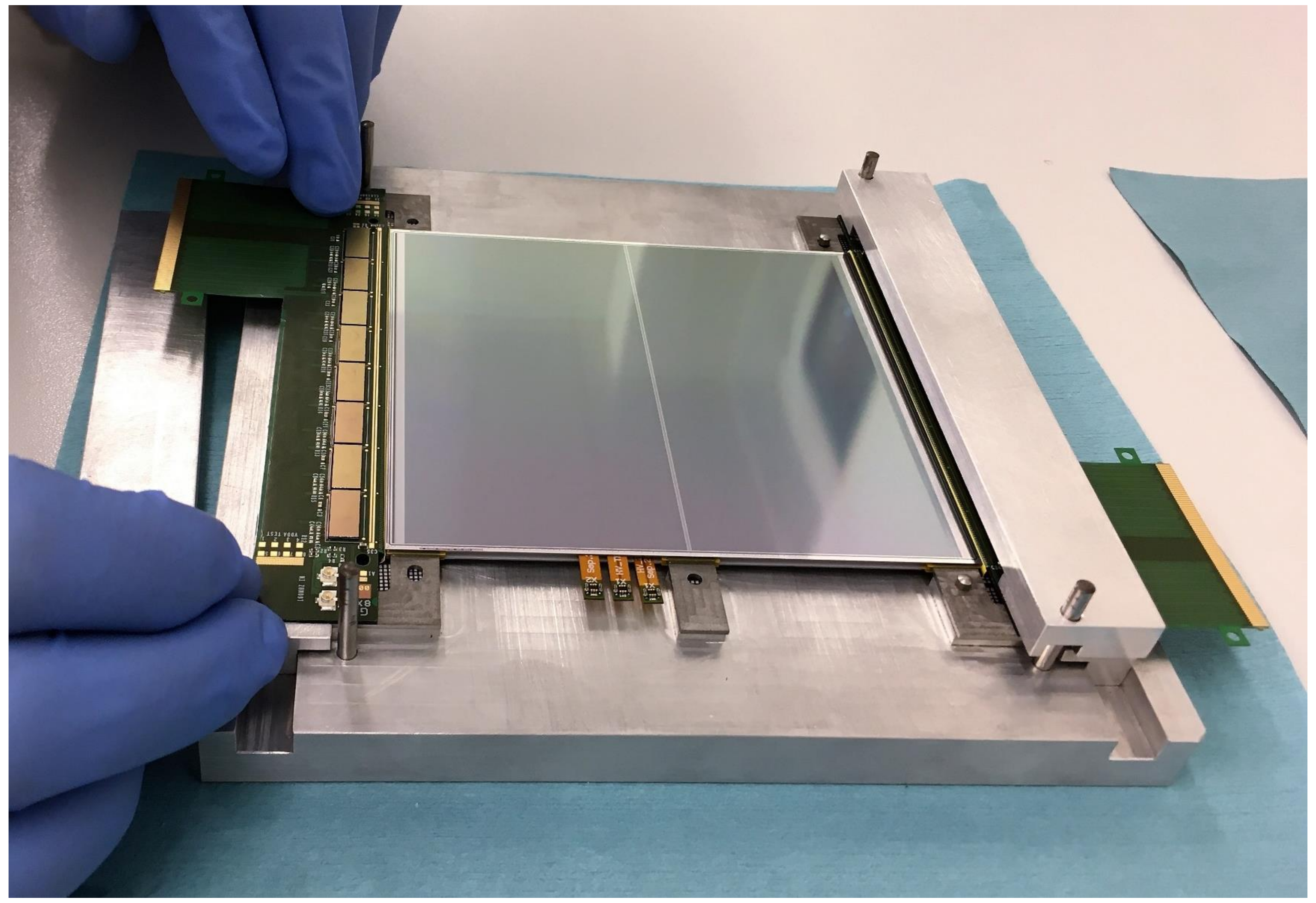


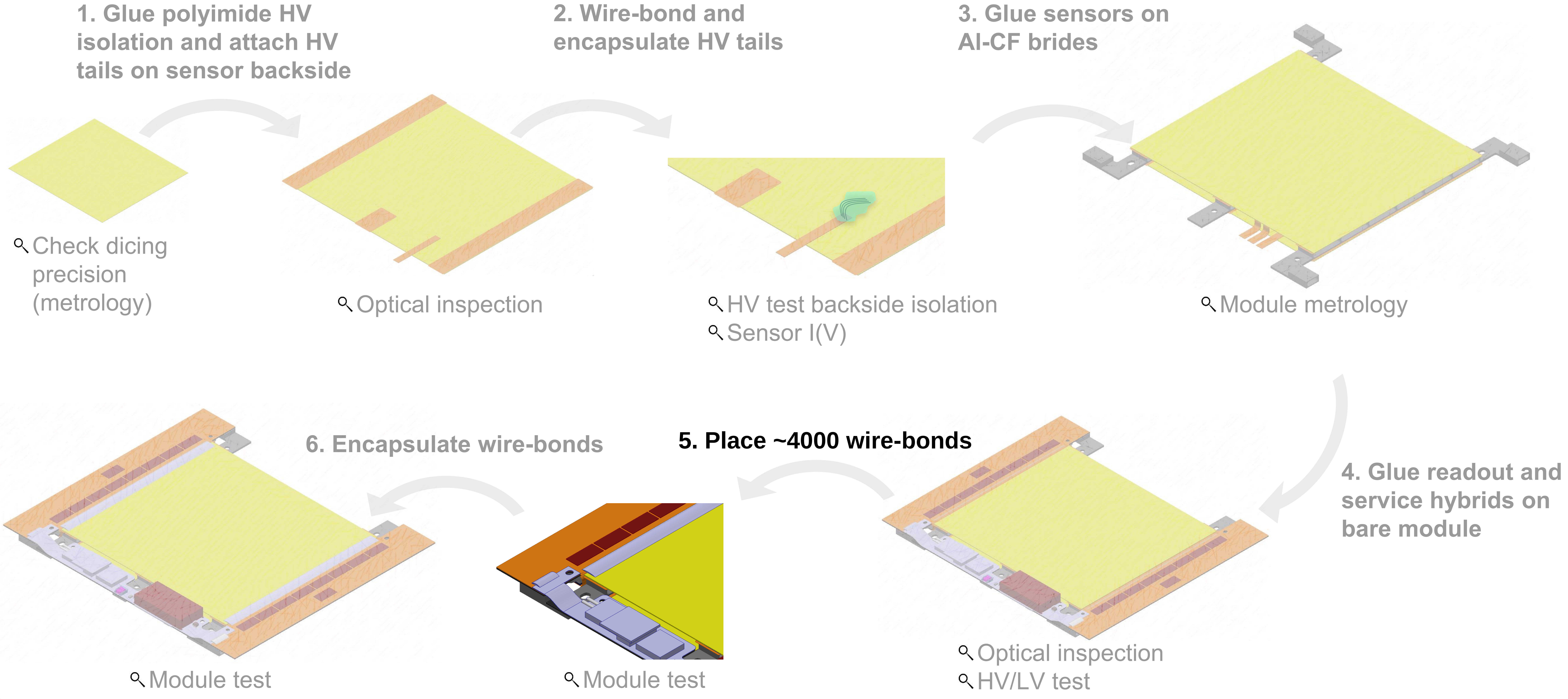
- First 2S prototypes are without a functioning service hybrid
- Front end hybrids aligned on an aluminium bar and pushed against bare module






Glue drop





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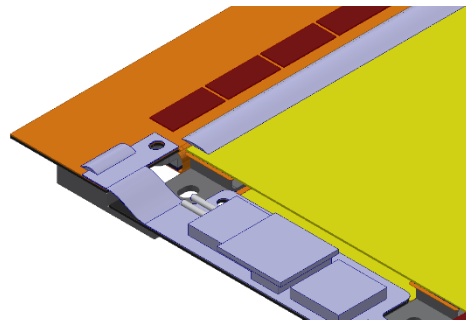
Wire-bonding



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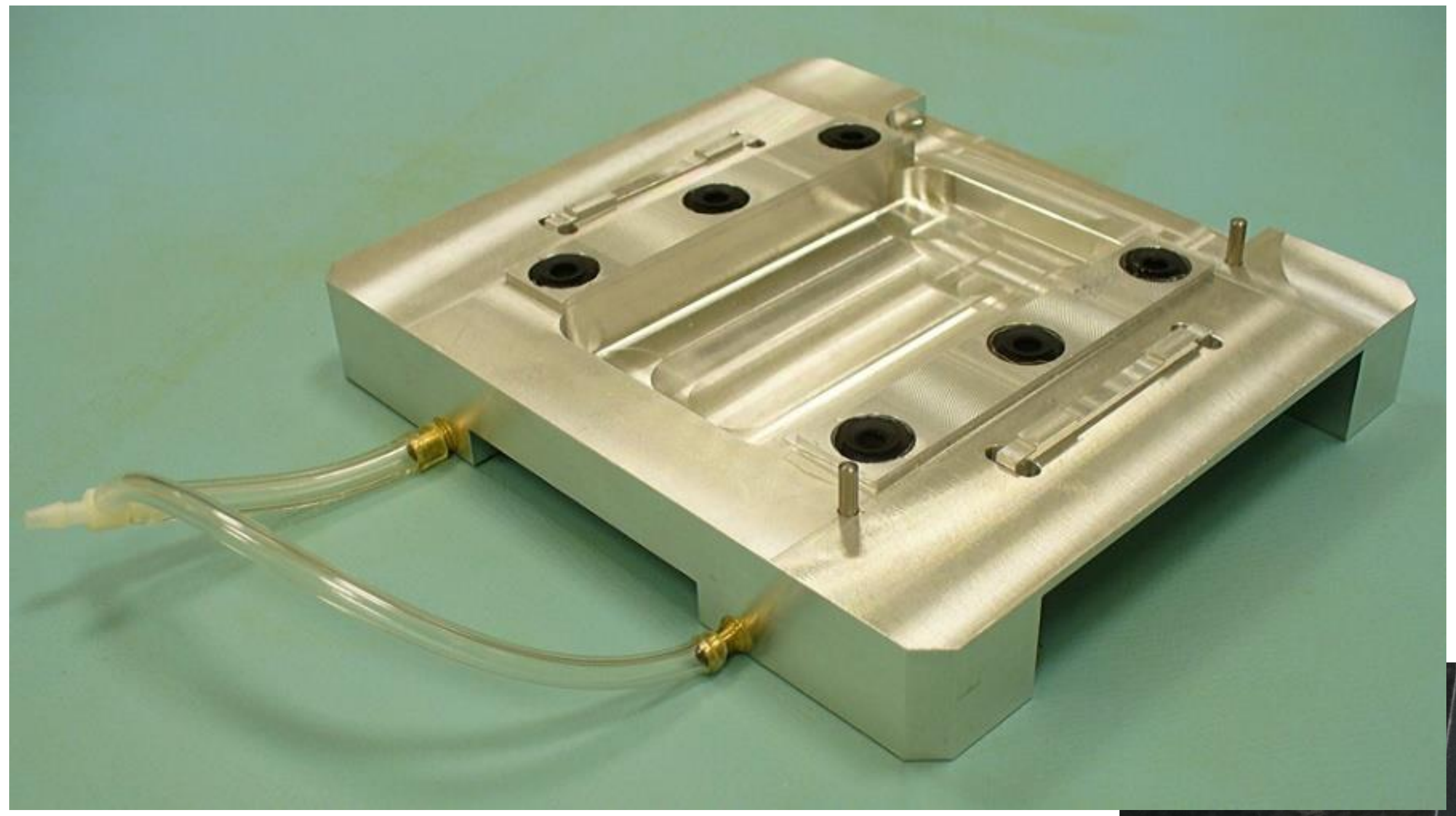
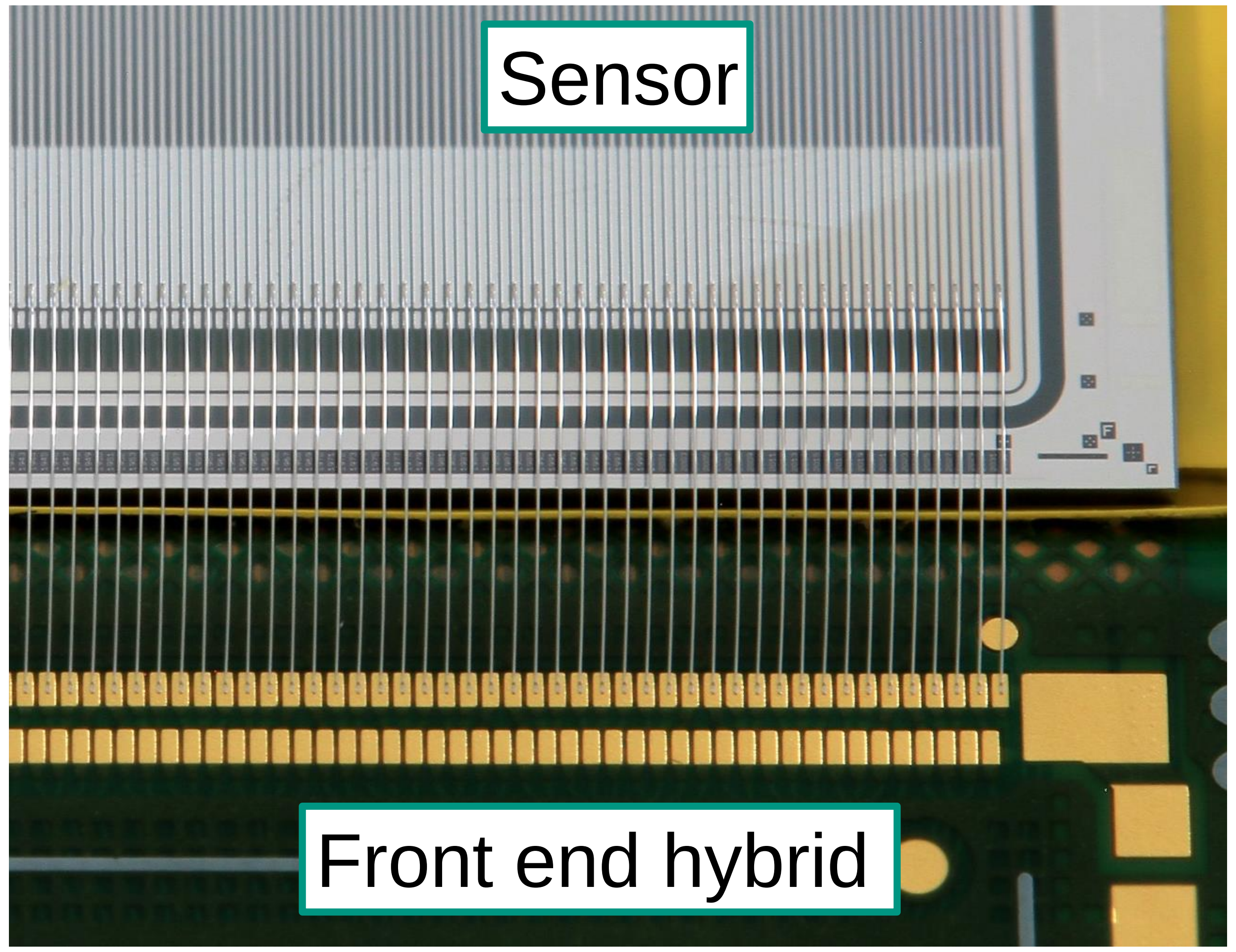
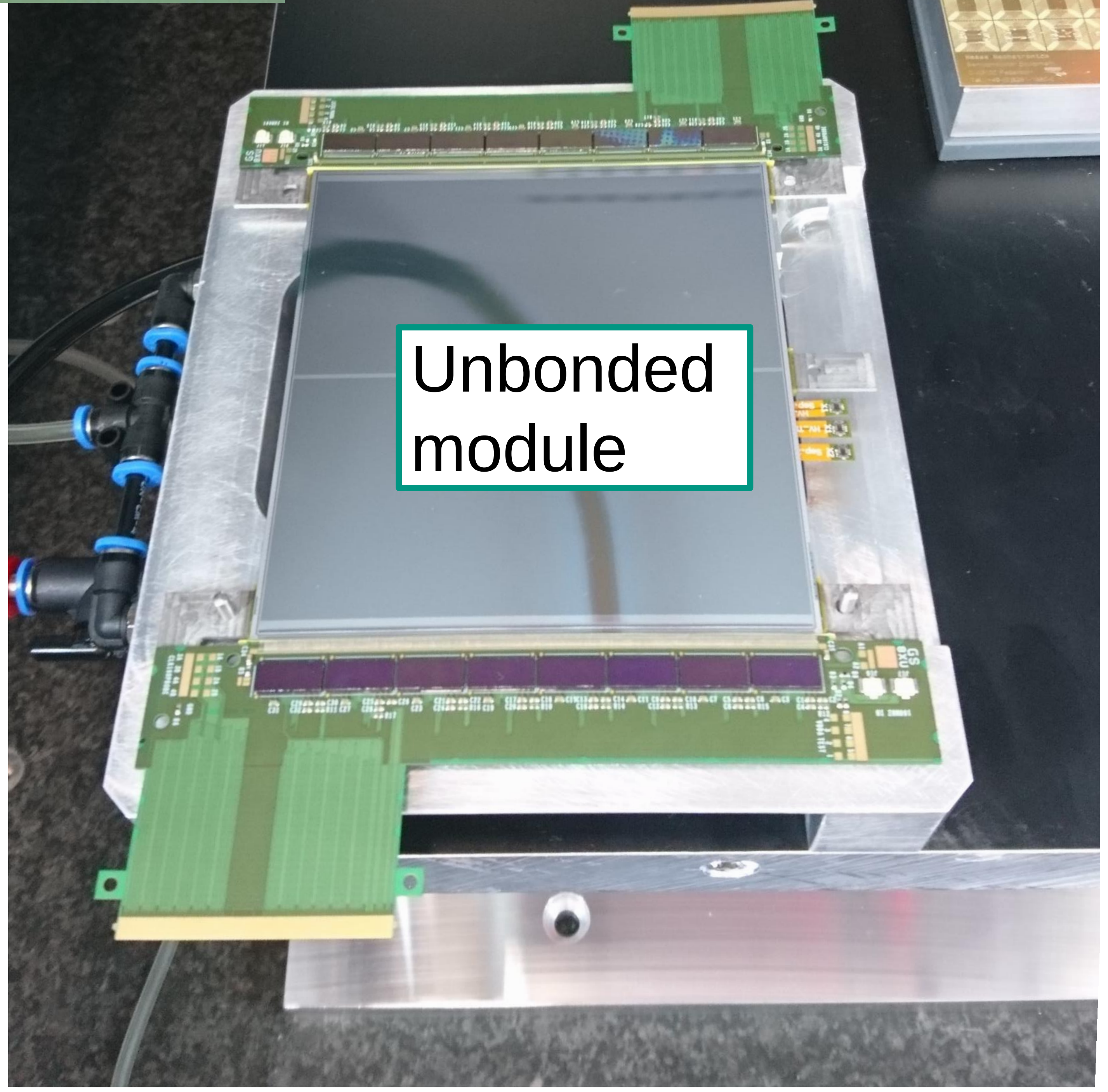
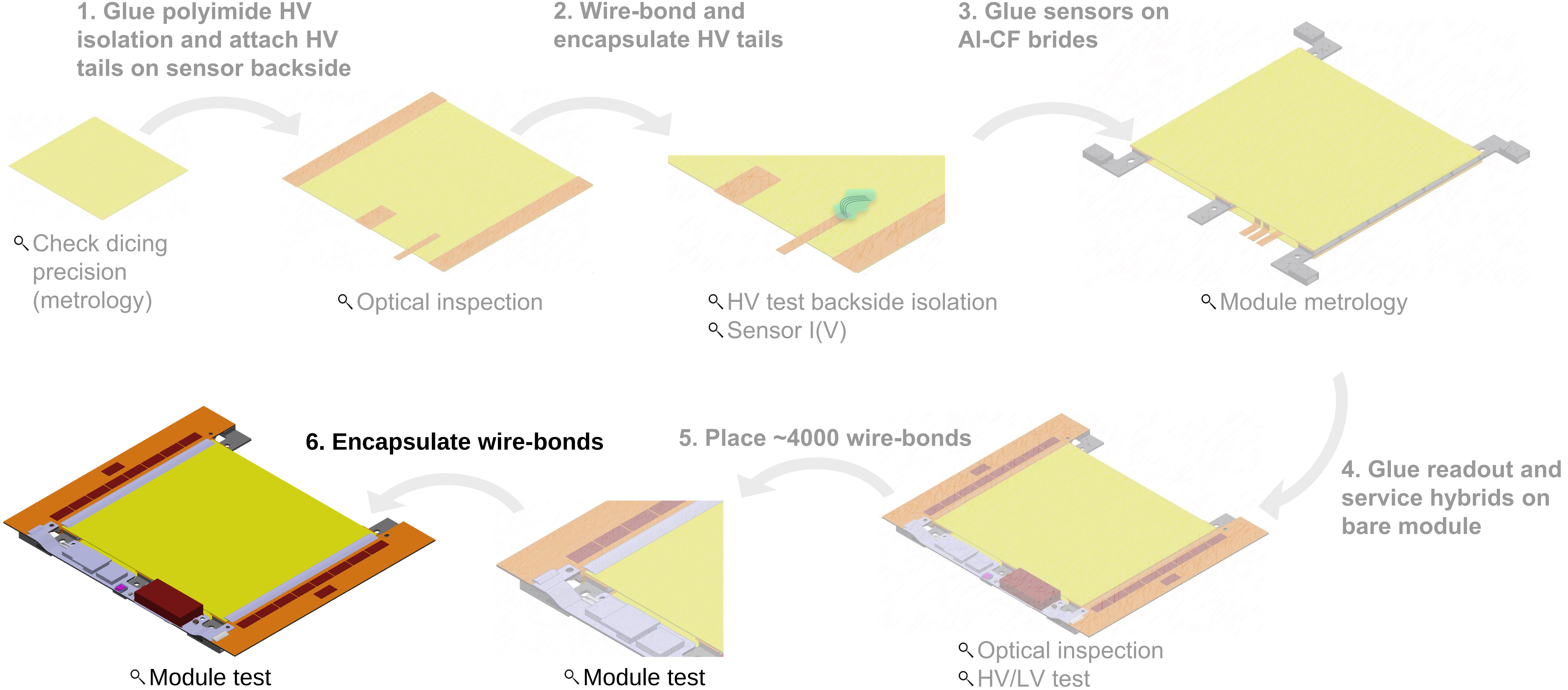
- Vacuum jig can fix module on both sides
- Adjustable support rods to stabilize front end hybrids
- Each 2S Module
  - Bond length: ~4 mm
  - Bond height: 500-700 µm
  - 4064 readout bonds
    - 4 rows of 1016
    - 90 µm pitch
    - staggered pads
    - 2x 12 sensor bias bonds
    - +Pull-test bonds









1. Glue polyimide HV isolation and attach HV tails on sensor backside

🔍Check dicing precision (metrology)

🔍Optical inspection

2. Wire-bond and encapsulate HV tails

🔍HV test backside isolation
🔍Sensor I(V)

3. Glue sensors on Al-CF brides

🔍Module metrology

4. Glue readout and service hybrids on bare module

🔍Optical inspection
🔍HV/LV test

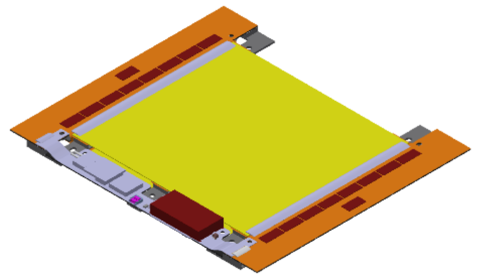
5. Place ~4000 wire-bonds

🔍Module test

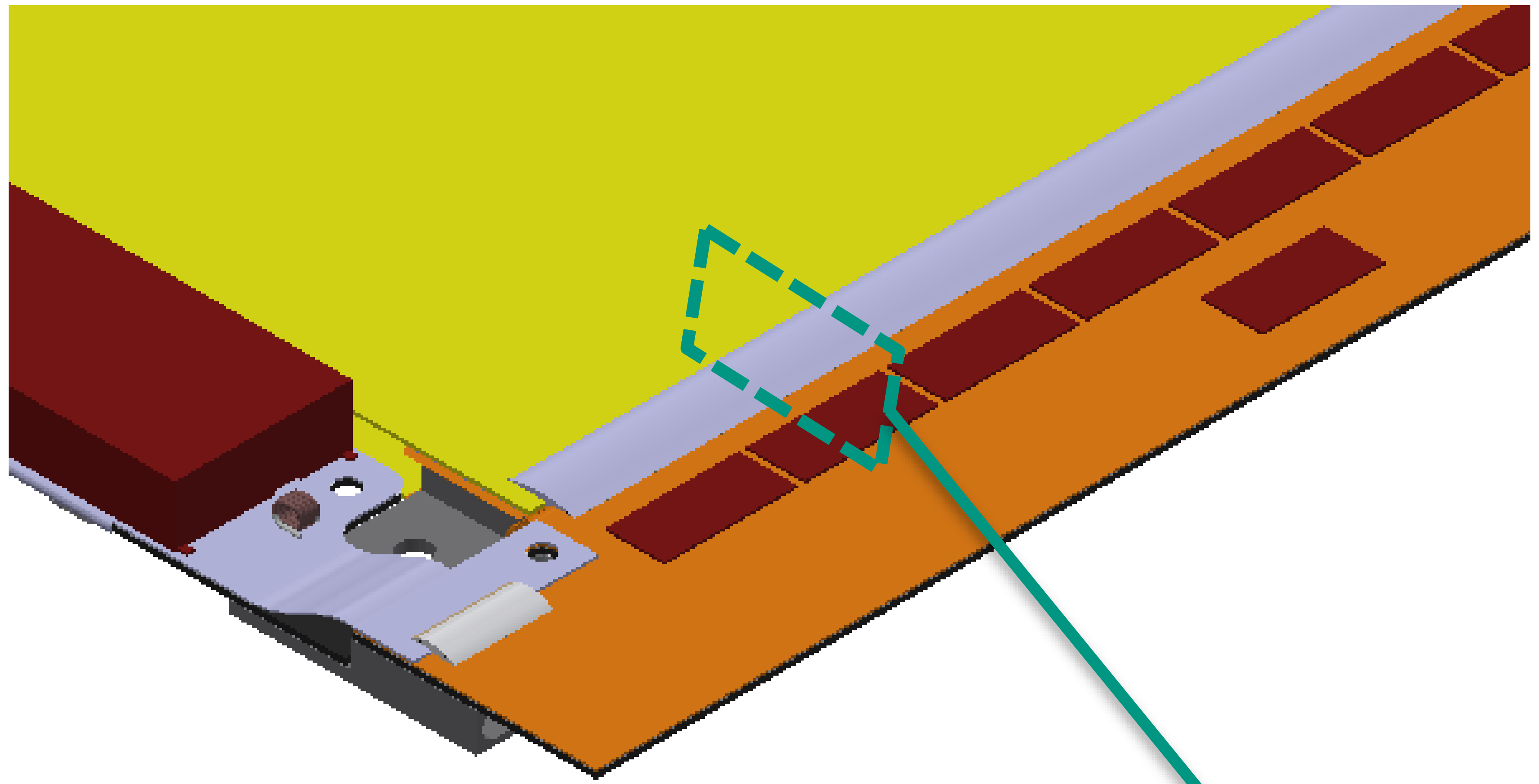
6. Encapsulate wire-bonds

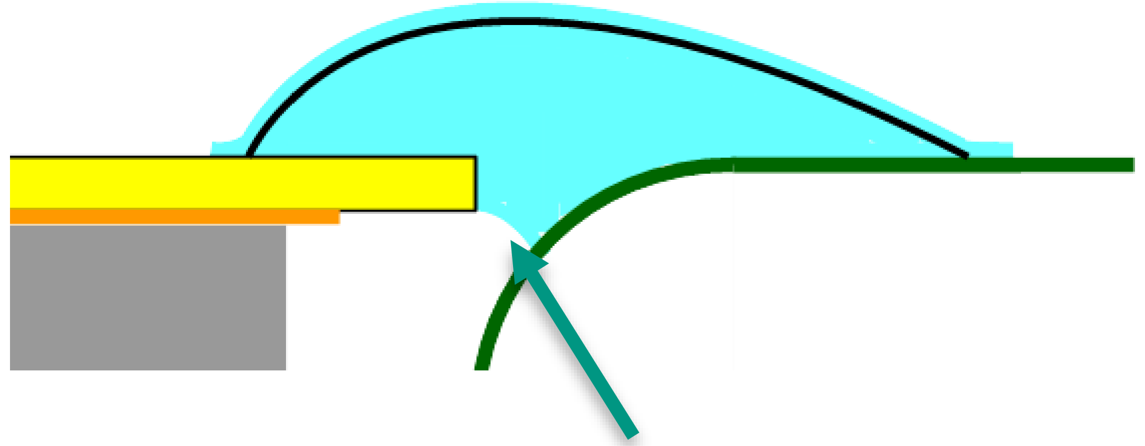
🔍Module test

Wire-Bond Encapsulation (WBE)



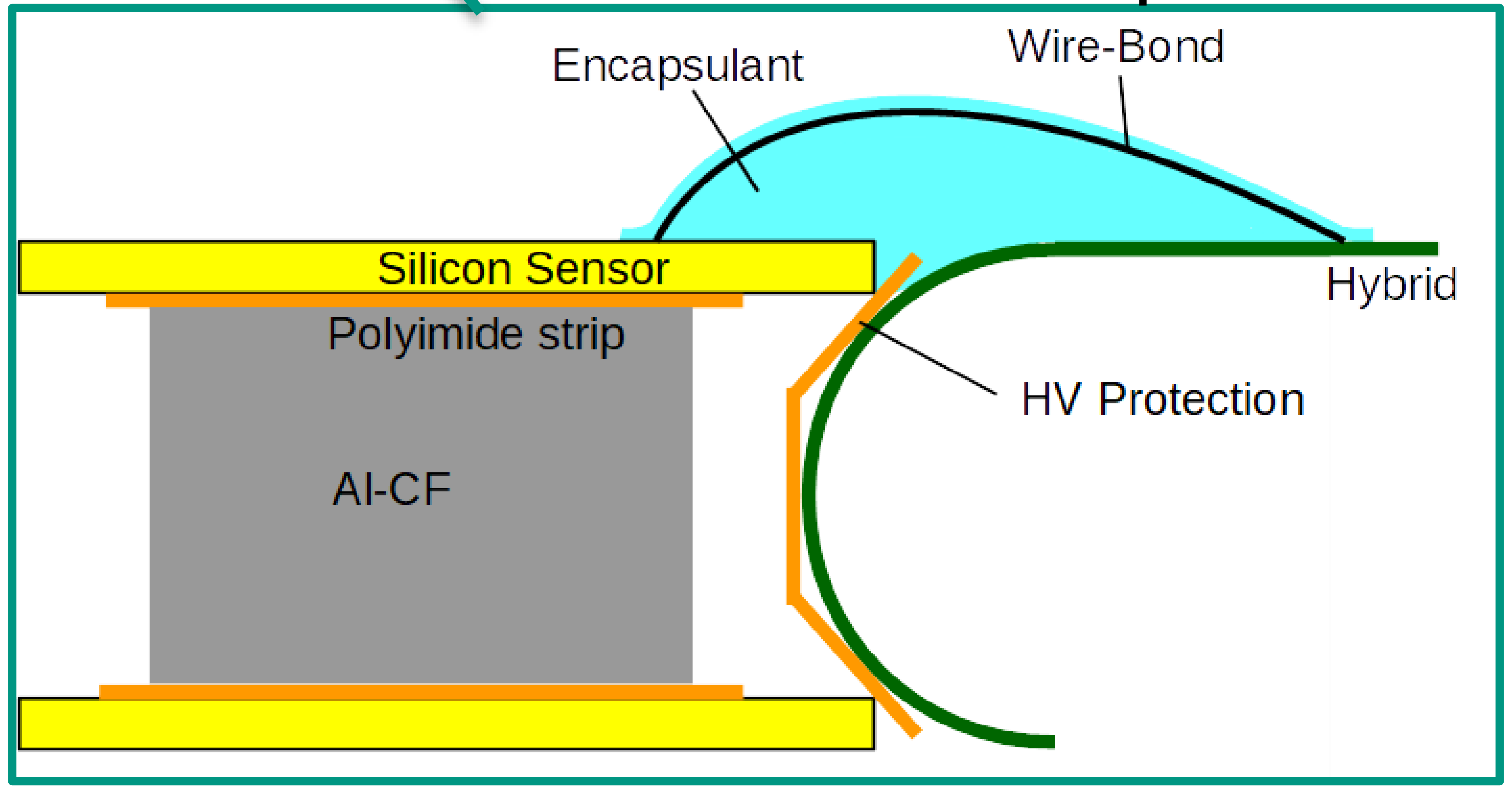
- See yesterdays talk by Kirk Arndt
- WBE prevents
  - Mechanical damage
  - Electrochemical corrosion
  - Lift-up of bond feet
- Test WBE for
  - Stable and reliable application process
  - Irradiation hardness
  - Coefficient of thermal expansion (CTE) mismatch to covered parts, test behavior during thermal cycling: ~10 cm of encapsulated wire-bonds!





Baseline design with small gap

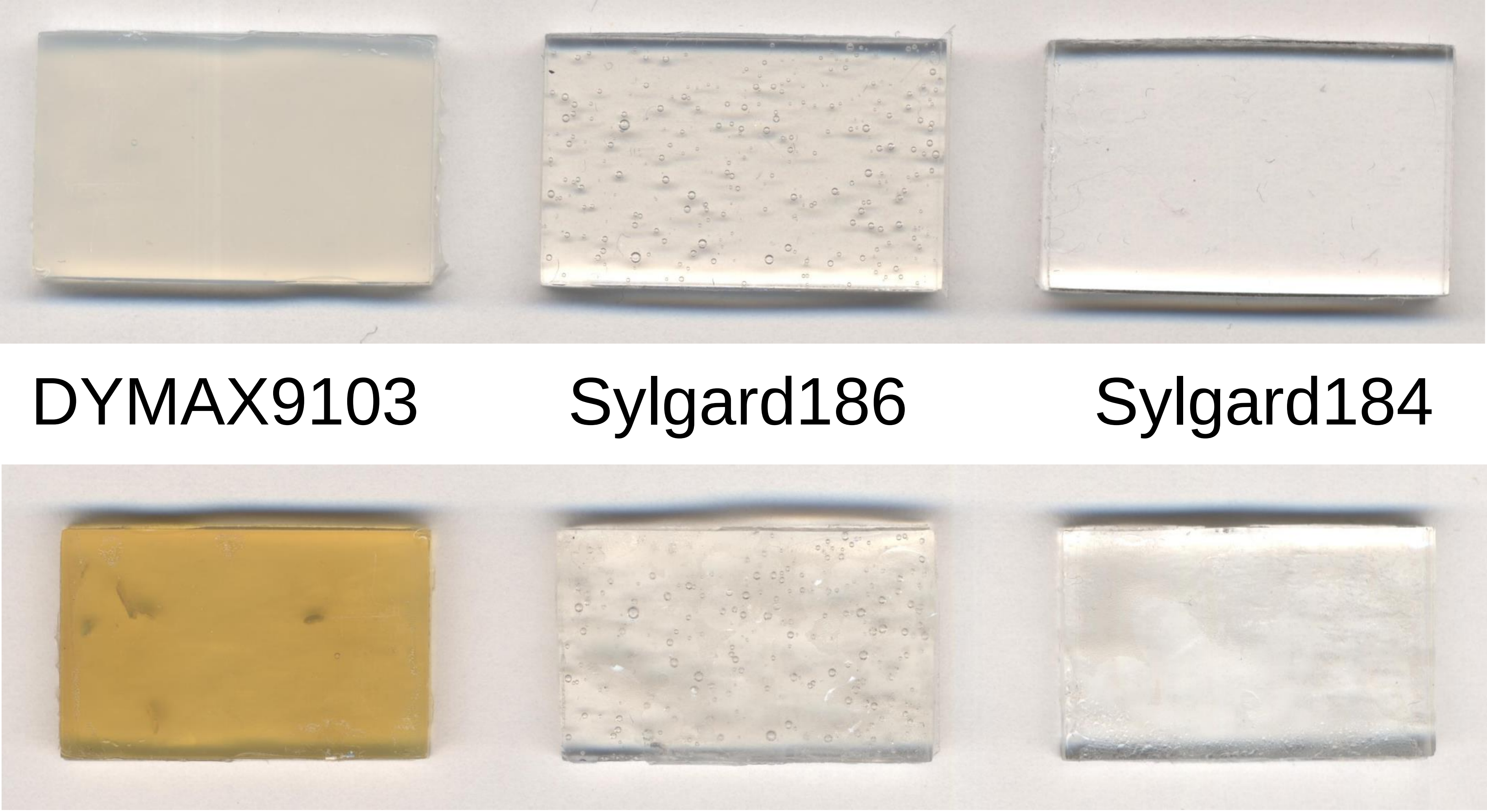
Ideal encapsulation



WBE – Materials

- First try: irradiate blocks of different WBE with 3.5 MGy (10^{15} protons/cm²)
  - No shrinkage observed
  - Reduction of flexibility of silicon-based Sylgard materials
  - The urethane-based Dymax material not flexible after application, turns brownish after irradiation but keeps its stiffness → Flexibility preferred, dismissed
- Suitable flow property achieved with mix of Sylgard 184 and 186 (part A: 20% 184 | 80% 186, part B: 184)
  - No excess material across sensors
  - Smooth coverage of bond feet and loop
- Developed 3-step application technique as reliable process…

Before irradiation

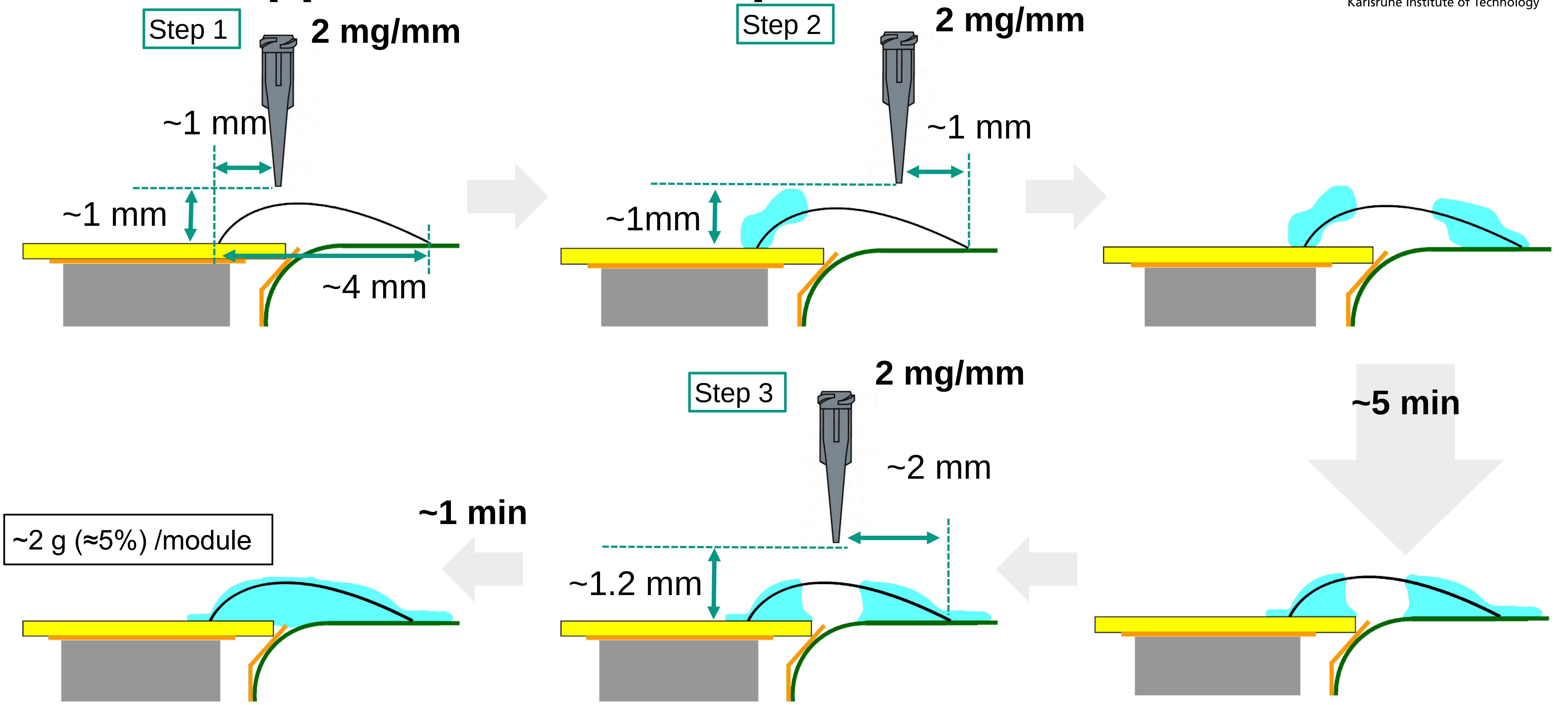


DYMAX9103 Sylgard186 Sylgard184

After irradiation

25000 cP 65000 cP 3500 cP

WBE – Application Technique



Step 1

2 mg/mm

~1 mm

~1 mm

~4 mm

Step 2

2 mg/mm

~1 mm

~1mm

~5 min

Step 3

2 mg/mm

~2 mm

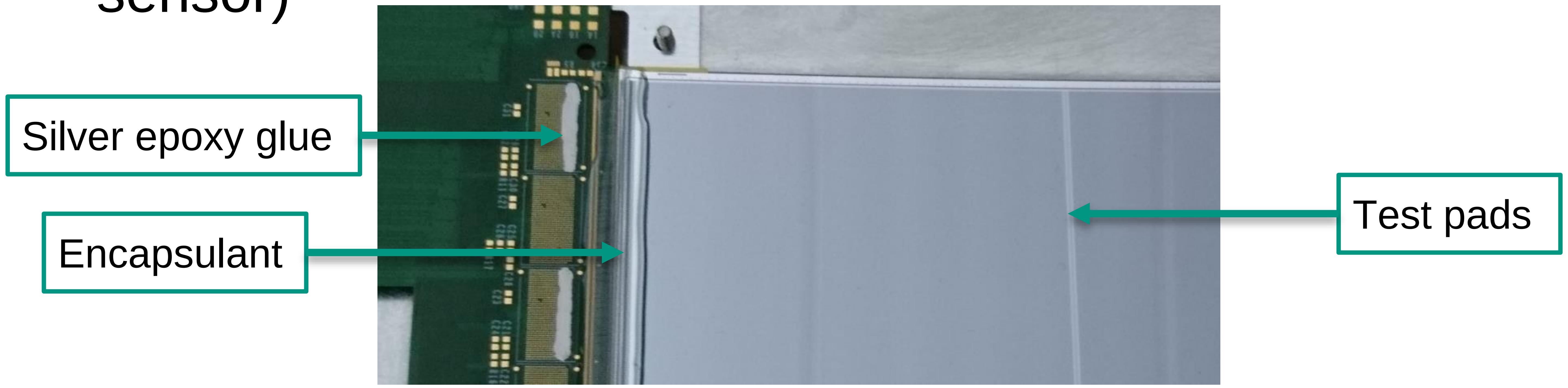
~1.2 mm

~1 min

~2 g (≈5%) /module

WBE – Stress Measurements on Sylgard

- Use dummy module to test bond connections under thermal cycles, encapsulation and irradiation
- Use silver epoxy glue to ground all strip channels of one readout chip at once and check wire-bond connectivity from test pad to this ground strip by strip (segmented sensor)



- No wire-bond connection lost due to thermal cycling, encapsulation or irradiation
- Mixture of Sylgard is usable for 2S and PS Module region

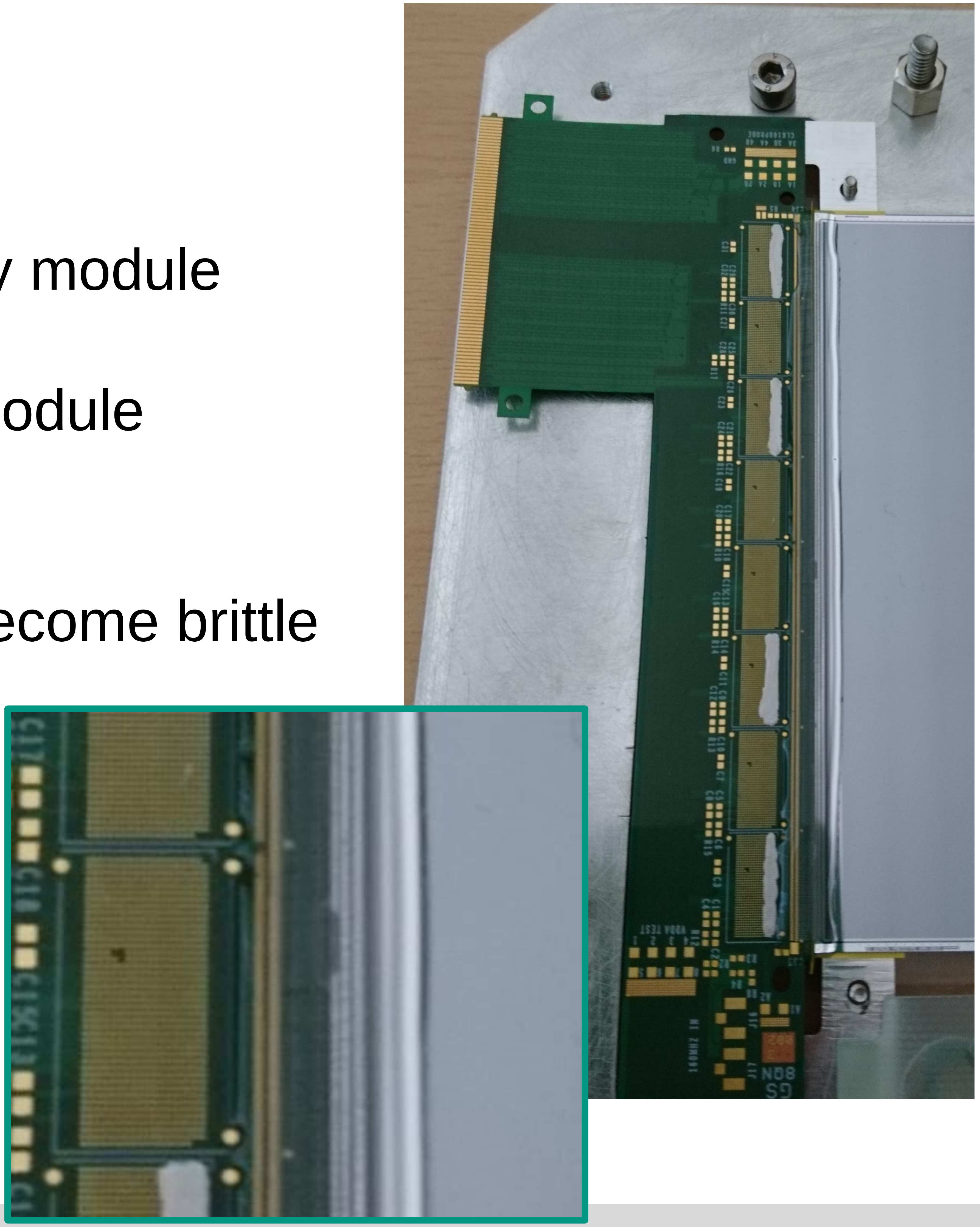
Test procedure

- Check wire-bond connection
- 20 thermal cycles -35°C/20°C
- Check wire-bond connection
- Encapsulate wire-bonds
- Check wire-bond connection
- 20 thermal cycles -35°C/20°C
- Check wire-bond connection
- Irradiate WBE
- Check wire-bond connection
- 20 thermal cycles -35°C/20°C
- Check wire-bond connection

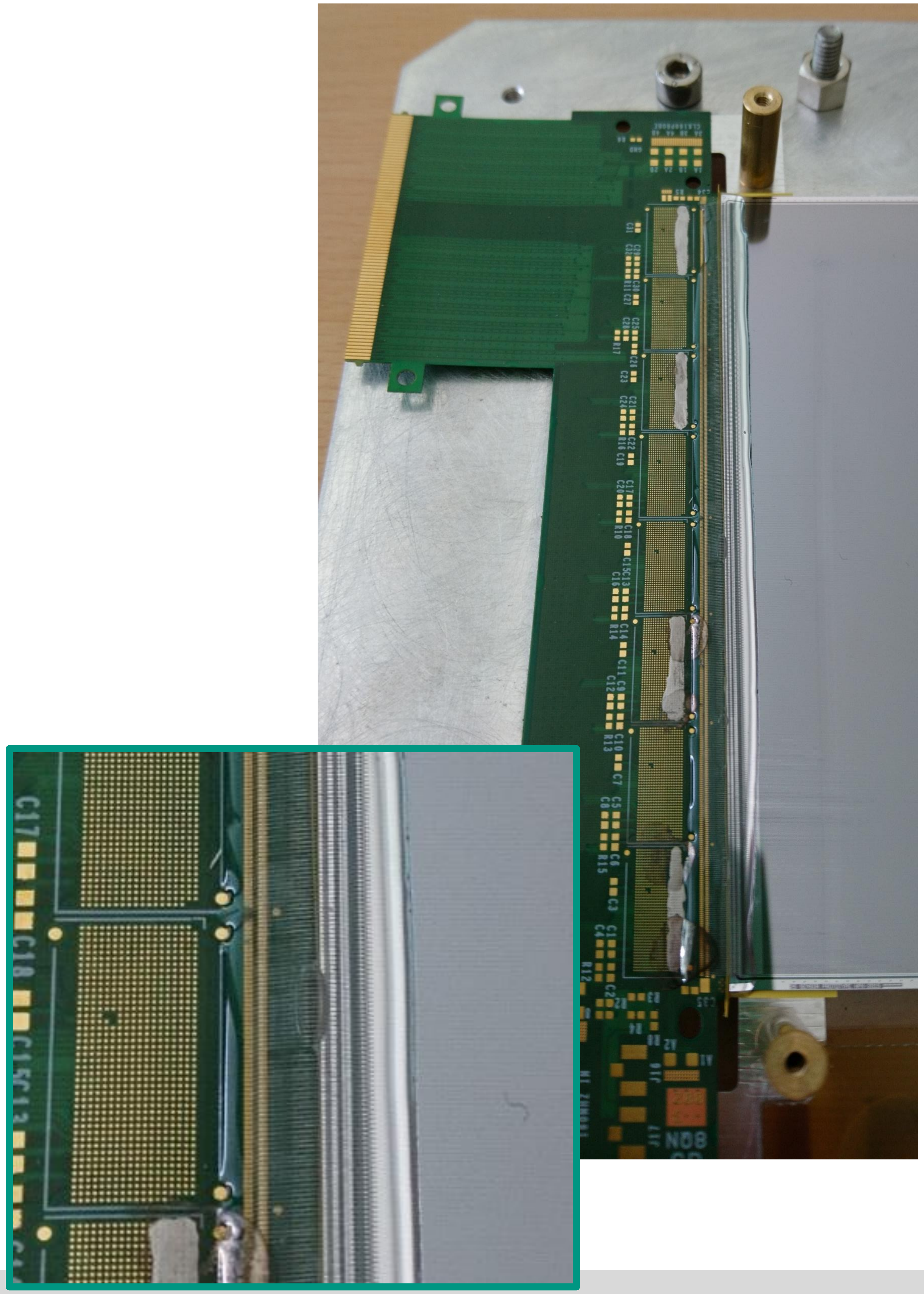
WBE – Irradiation

- Encapsulation of dummy module irradiated with 3.5 MGy (10^{15} protons/cm², PS Module region)
- Encapsulant does not become brittle
- No change of color

Before

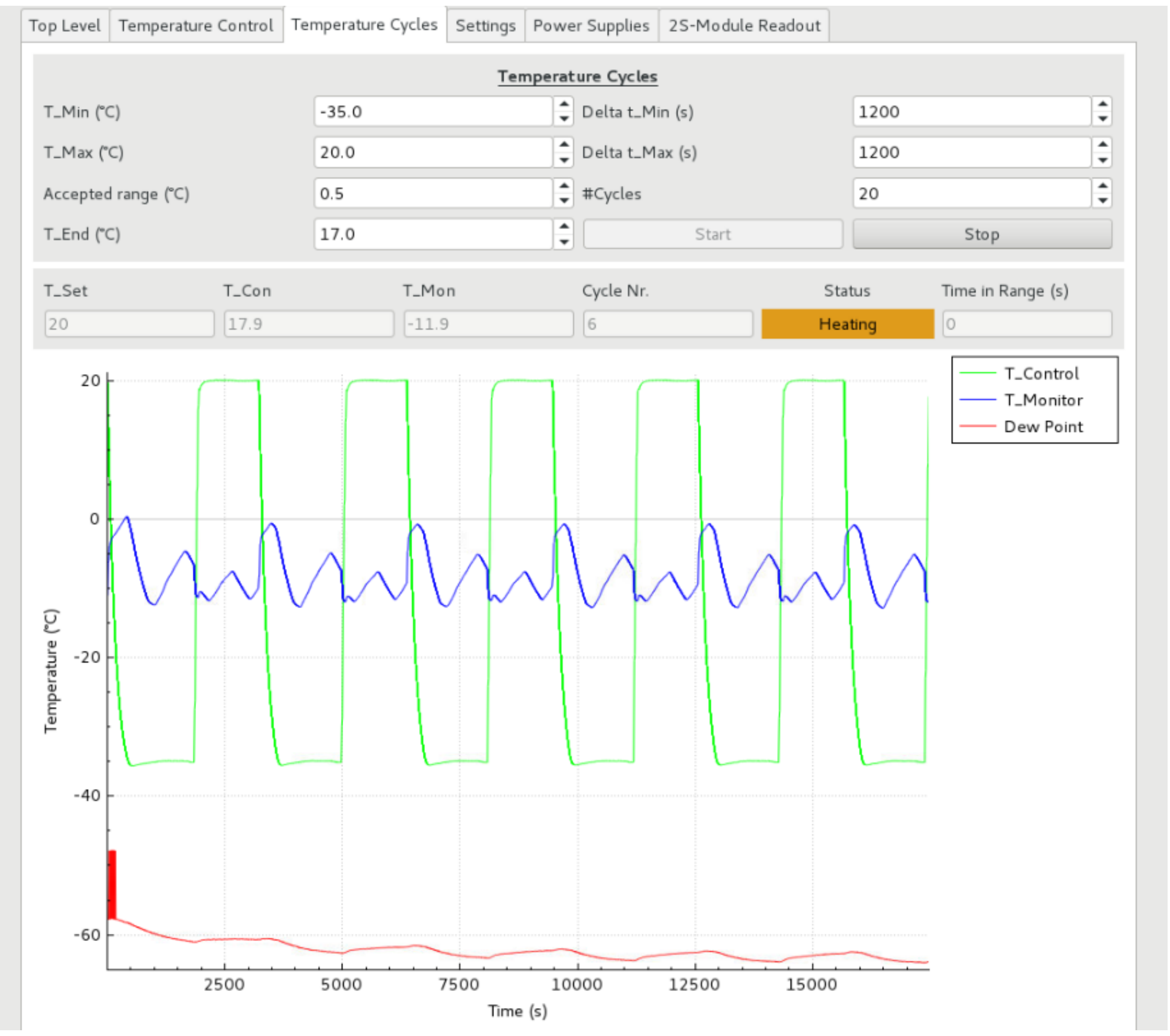


After



Module Functional Tests (Roland Koppenhöfer)

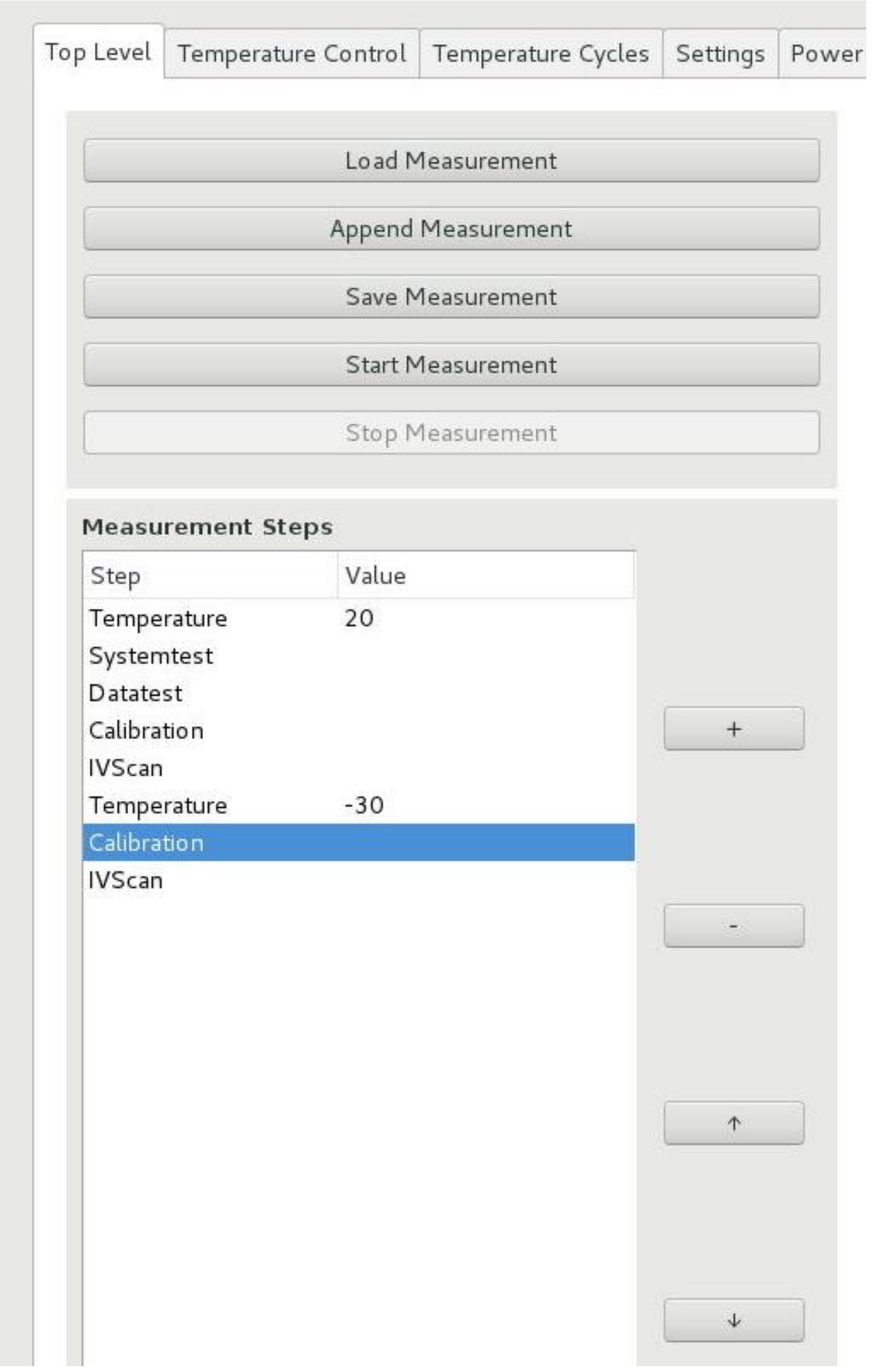
- Dedicated temperature-stabilized setup to test 2S Modules during prototyping and production phase:
  - Quick and safe mounting
  - Temperature control
    - Precooling with additional Peltier elements (– 35 °C on cooling jig)
    - Monitor humidity
  - Scintillator below setup for signal studies
  - GUI (Top level measurements)



Temperature Cycles

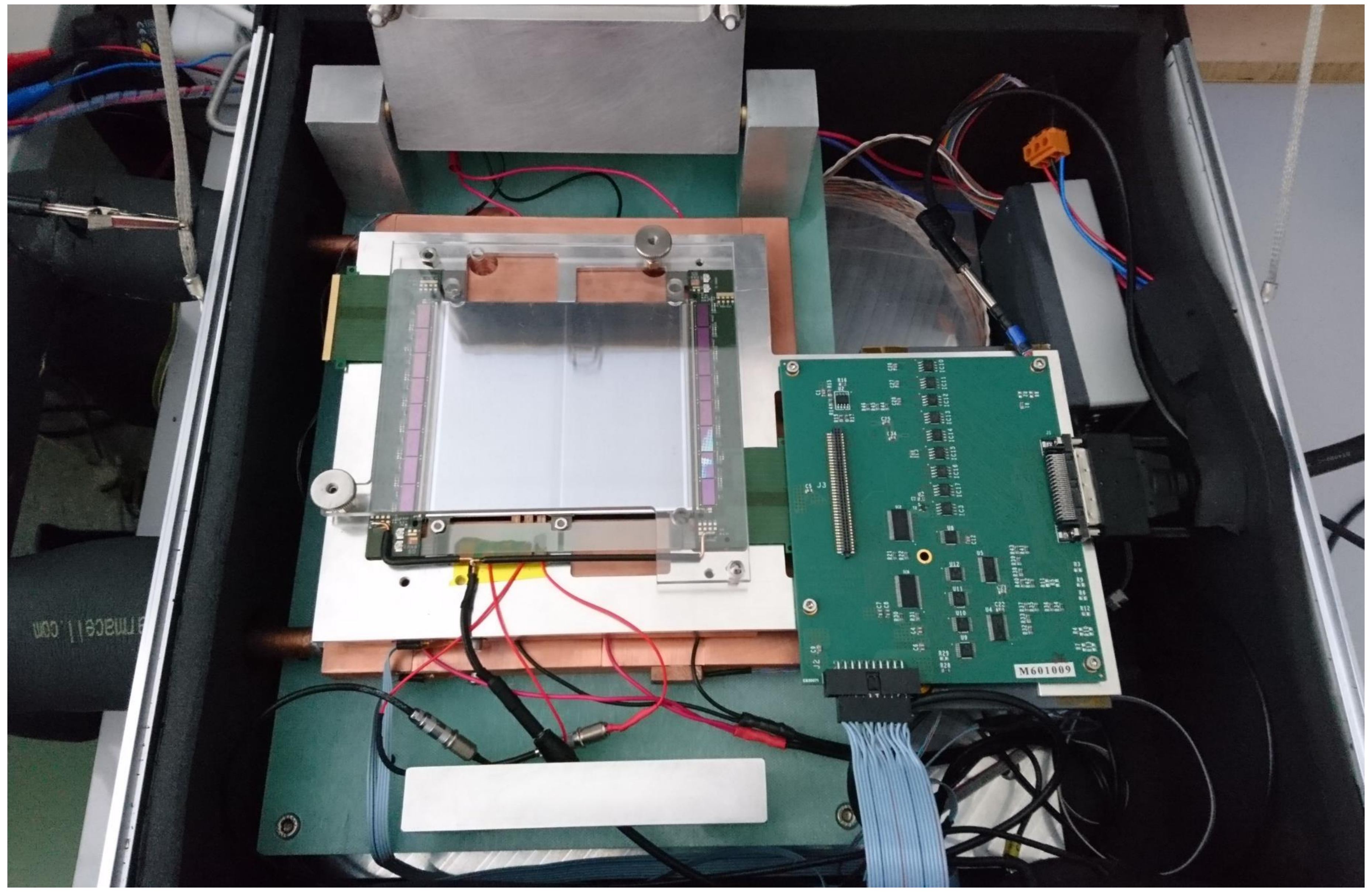
T_Min (°C): -35.0
Delta t_Min (s): 1200
T_Max (°C): 20.0
Delta t_Max (s): 1200
Accepted range (°C): 0.5
#Cycles: 20
T_End (°C): 17.0

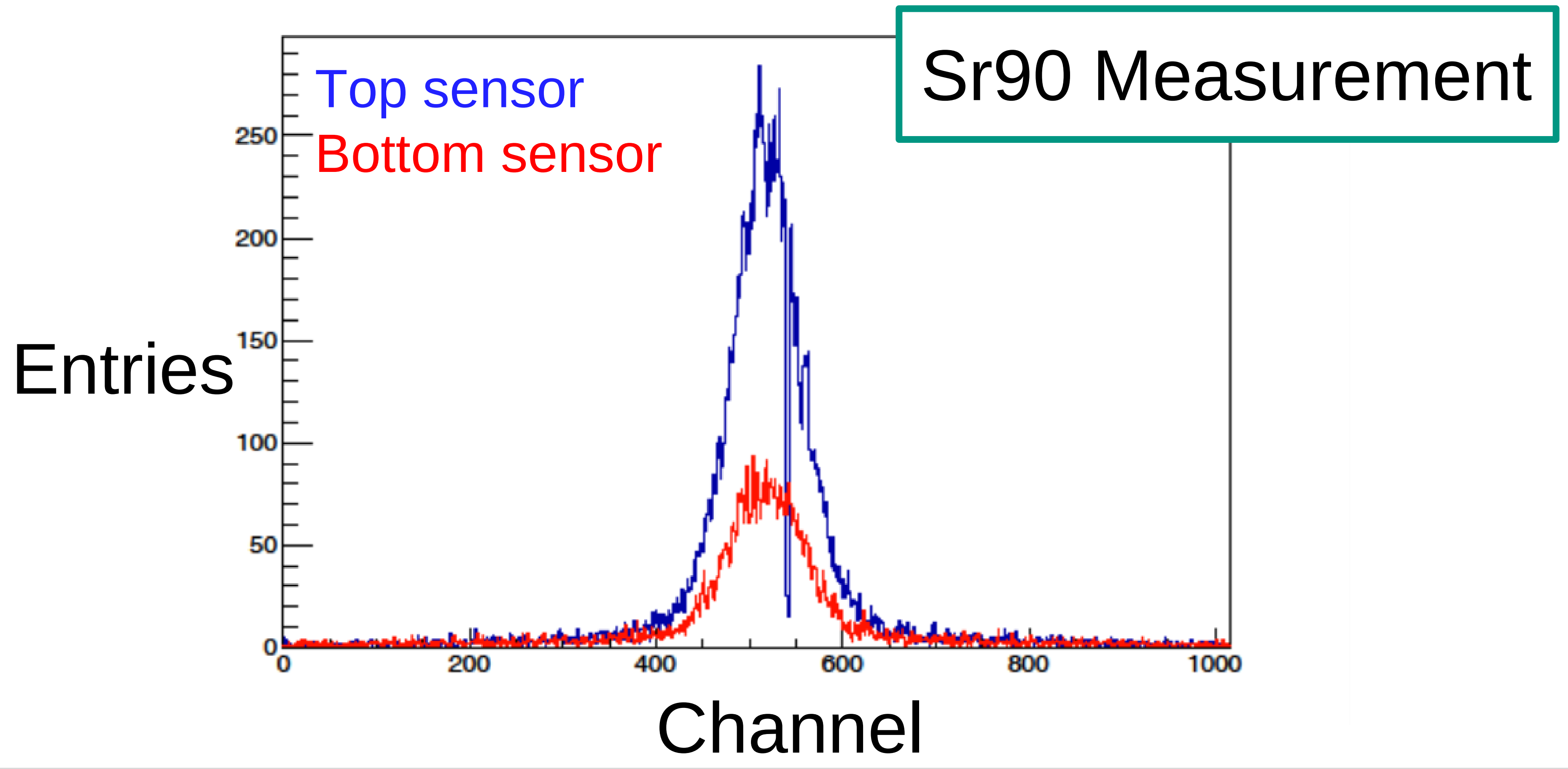
T_Set: 20
T_Con: 17.9
T_Mon: -11.9
Cycle Nr.: 6
Status: Heating
Time in Range (s): 0



Measurement Steps

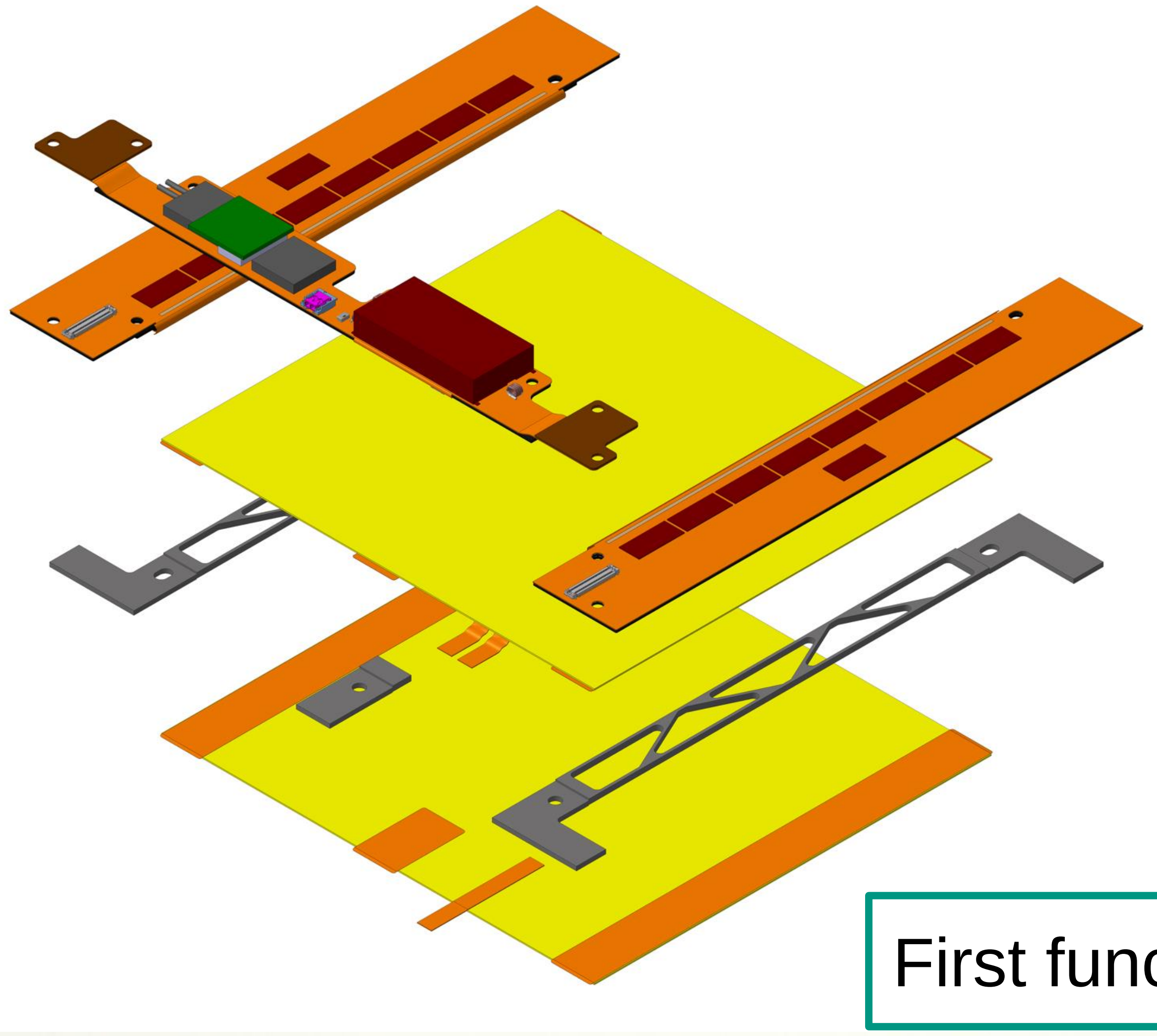
Step	Value
Temperature	20
Systemtest	
Datatest	
Calibration	
IVScan	
Temperature	-30
Calibration	
IVScan	



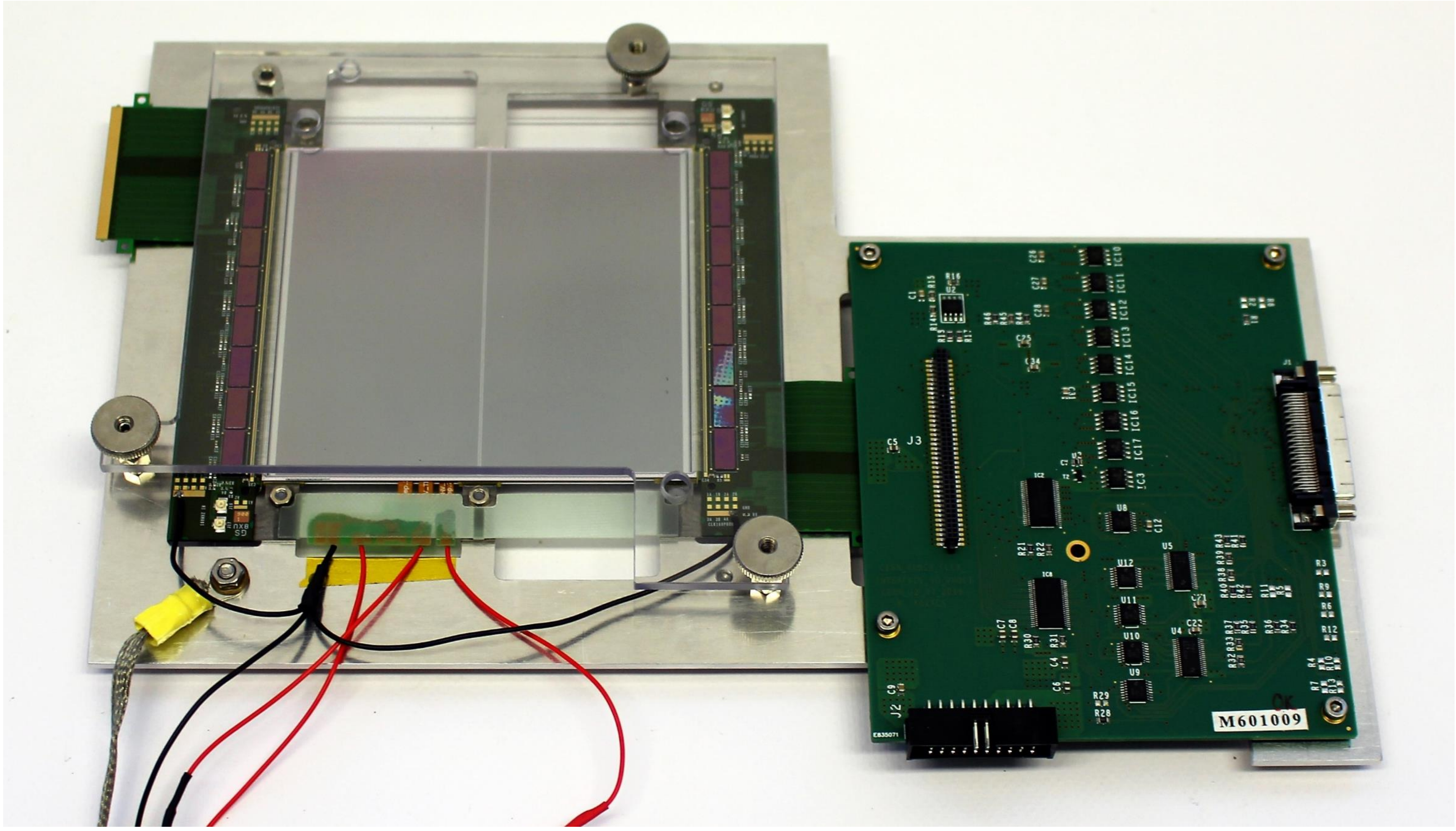


Summary

- 2S Module baseline design has been proven to work with previous functional CERN prototypes
- First working module prototypes outside of CERN are currently assembled at different production sites
- KIT built its first functional 2S Module in January
  - Assembly and test procedures proven to work
  - Mechanical precision well in specs
  - WBE proven to be usable even in PS Module region
- Outlook
  - Finalize assembly procedure (HV/IV test station, improve jig designs)
  - Estimate clean room space and time for assembly steps



First functional KIT 2S Module

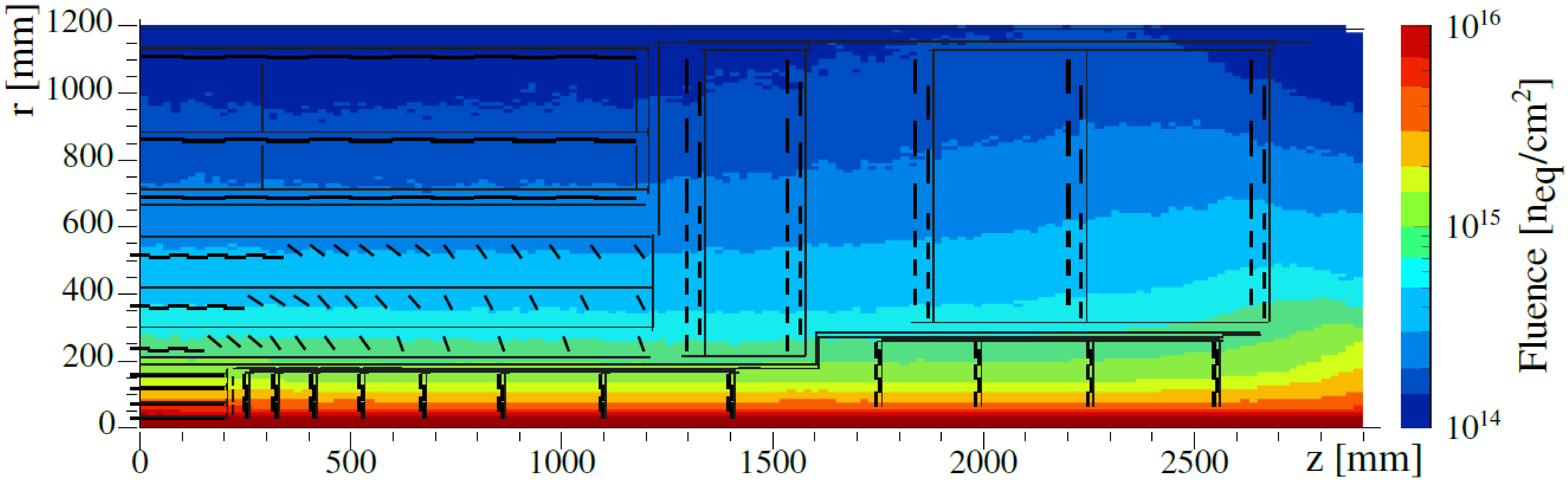


Backup

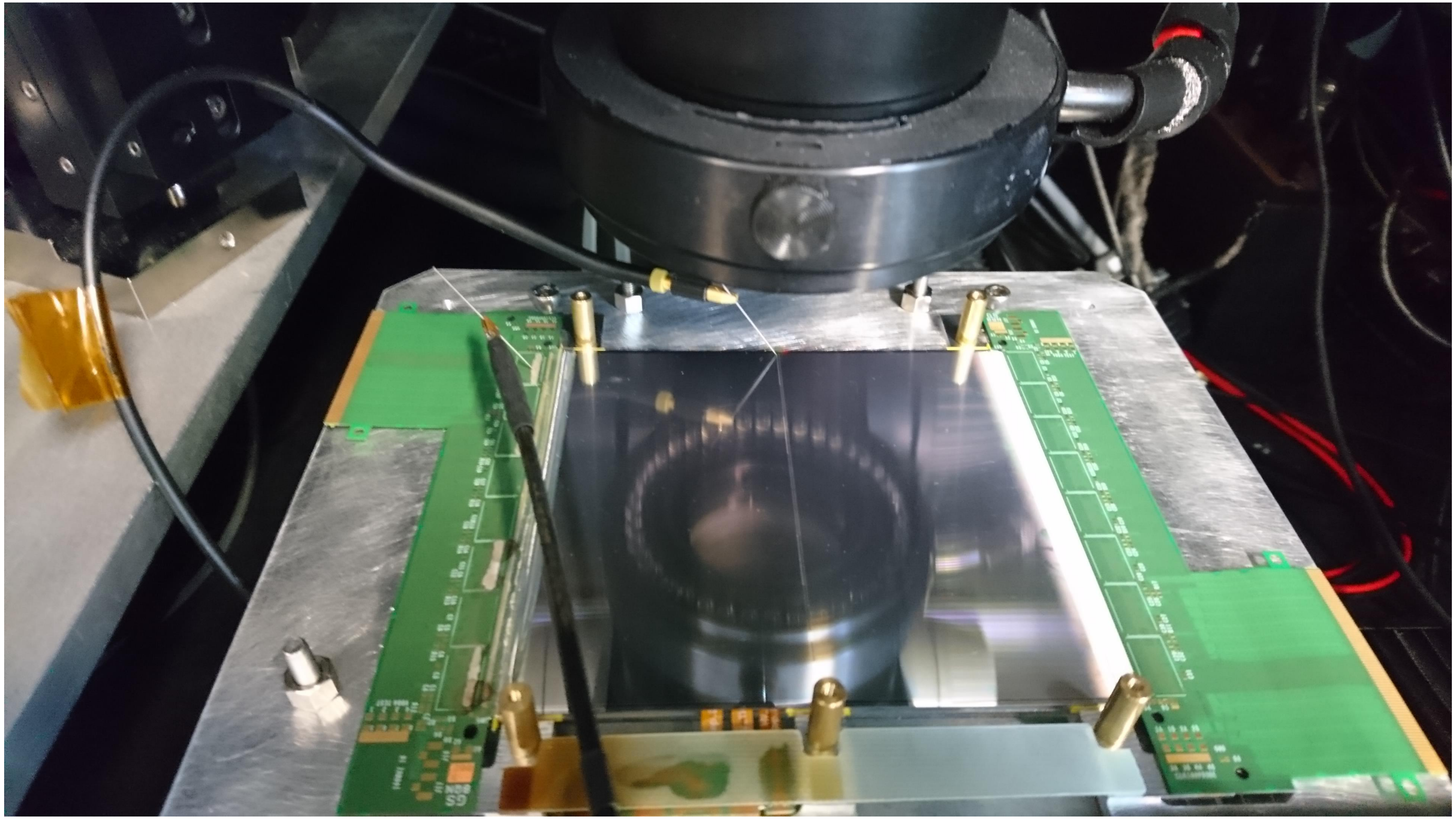
Expected Fluences in the CMS Outer Tracker

- Most of **2S modules** below $3x10^{14}n_{eq}/cm^2$ at $3000fb^{-1}$ ($4x10^{14}n_{eq}/cm^2$ at $4000fb^{-1}$)
  - only one ring in last disk up to $5.3x10^{14}n_{eq}/cm^2$ at $4000fb^{-1}$

- Max. fluence for **PS modules** around $1x10^{15}n_{eq}/cm^2$ at $3000fb^{-1}$ ($1.3x10^{15}n_{eq}/cm^2$ at $4000fb^{-1}$)
  - Expected dose in silicon ~950 kGy

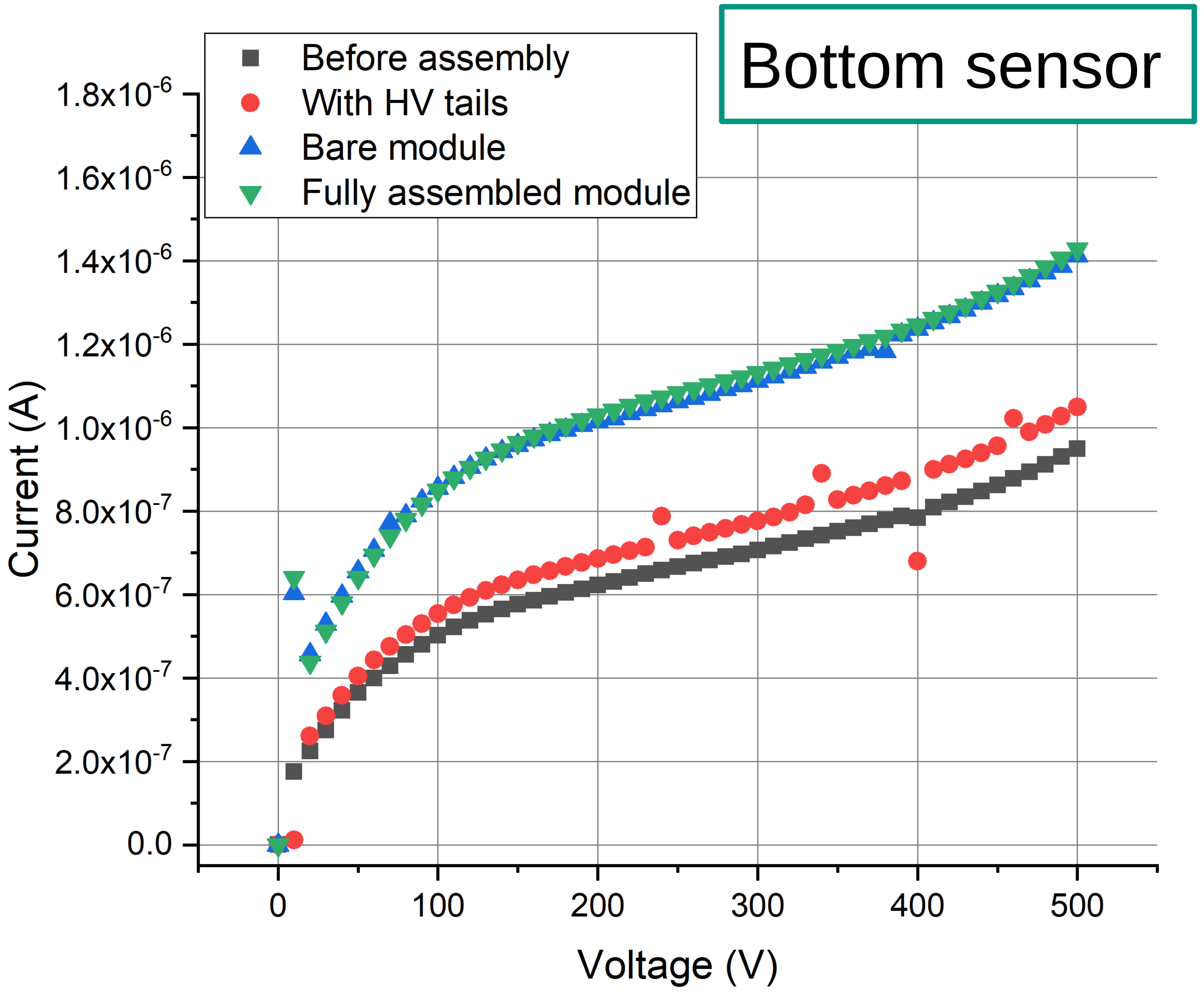


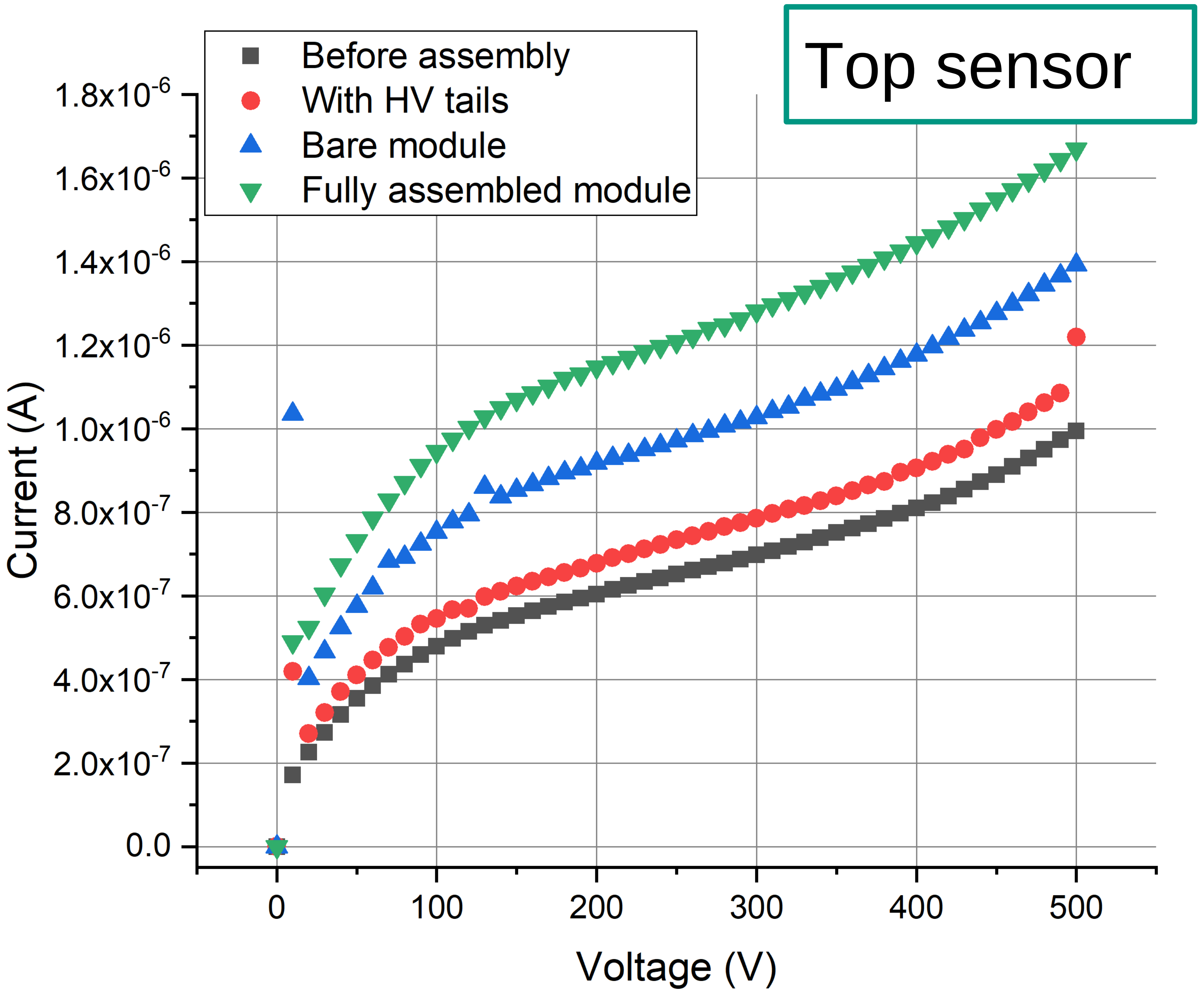
Testing of Wire-bond connectivity



I(V) Measurements

- During assembly of first functional KIT module measured I(V) curve after each step





- Assembly did not impair I(V) characteristics (shift due to temperature differences)