PS Module Assembly Procedure

CMS Module Working Group

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Contents

1 Introduction

The following sections are a detailed step-by-step description of the PS module assembly steps. The CAD models of the baseline modules geometries can be found in [1, 2, 3]. The PS module specifications can be found in [4]

2 PSs sensor HV tail gluing

To attach the HV tail to the PSs sensor backplane the jig described in section A.1 is used and the following steps are performed:

1. Clean the jig and the magnet and weighting piece with Isopropanol.
2. Connect the vacuum pipe to the jig. The valve should be closed.
3. Get the PSs sensor and check its orientation. There is a black arrow on one of the short sides.
4. Place the PSs sensor on the jig with the backplane facing upwards. The black arrow, which is now on the strip side facing the jig, should point towards the corner with the stops.
5. Push the sensor against the stops (see figure 1).
6. Switch the vacuum on by opening the valve. The sensor is now fixed to its position.
7. Place the HV tail onto sensor and jig and push it against its stops as indicated in figure 2). The HV tail bond pad should point upwards.
8. Fix the HV tail position by placing the magnet piece in the foreseen position.
9. Properly mix Polytec EP 601 LV [5] glue and put into syringe with a yellow needle (23 gauge; 0.11 mm I.D.).
10. Connect the syringe to a semi-automatic glue dispenser in timer mode and make sure that the pressure is set to 2 bar and the device is in timer mode with 0.3 s dispensing time. Figure 4 shows the front panel of a glue dispenser that can be used for this purpose.
11. Carefully lift the HV Tail with ESD plastic tweezers. Dispense two dots of glue onto the bottom side of the HV tail Bonding pad.
12. Lower down the HV tail onto the sensor packplane. Fix the position with the weight piece.
13. When after 24 hours the glue is cured the magnet and weight pieces can be removed and the sensor released from the jig.

Electrical contact from the HV tail to the sensor backplane is provided through 20 wire bonds. For protection, the wire bond are encapsulated:

1. Place the sensor with the glued HV tail with the backplane up on a clean surface.
2. Properly mix Sylgard 186 [6] encapsulant and put into a syringe with orange (29 gauge; 0.33 mm I.D.) needle.
3. Connect the syringe to a semi-automatic glue dispenser.
4. Dispense glue enough to cover all wire bonds.
5. Let the encapsulation cure for 24 hours.

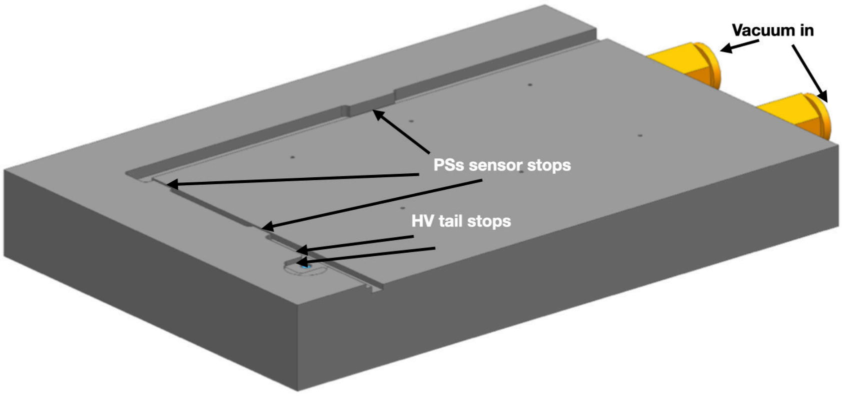


Figure 1: CAD rendering of the HV tail gluing jig showing the stops and vacuum connections.

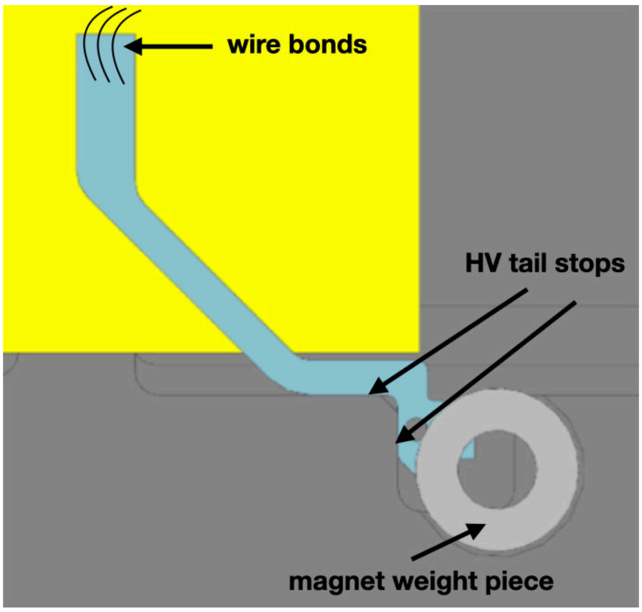


Figure 2: CAD rendering of one part of the HV tail gluing jig illustrating the HV tail positioning and the placement of the wire bonds.

3 Base plate insert gluing

To glue the positioning inserts to the base plate using the jig described in section A.2 the following steps have to be performed:

1. Clean the jig, pins and weight pieces with Isopropanol.
2. Place the base plate on the jig and push it against the stops (see figure 3).
3. Engage the toggle clamp in order to fix the position of the base plate on the jig.
4. Insert the two pins into the holes for inserts 1 and 3.
5. Place the inserts with the round hole over the pins **making sure that the side of the insert with the sleeve points towards the base plate**.
6. Place the weight pieces over the pins.
7. Put the insert with the elongated hole over the matching pin **making sure that the side of the insert with the sleeve points away from the weight**.
8. Place the weight piece with the insert into the hole for insert 2 - **make sure that the inserts touch the base plate but do not push**
9. Properly mix Polytec EP 601 LV [5] glue and put into syringe with a yellow needle (23 gauge; 0.11 mm I.D.).
10. Connect the syringe to a semi-automatic glue dispenser in timer mode and make sure that the pressure is set to 2 bar and the device is in timer mode with 0.1 s dispensing time. Figure 4 shows the front panel of a glue dispenser that can be used for this purpose.
11. The glue has to be dispensed at four locations around each insert.
    - Place the needle at an angle of about 45° wrt. to the plane of the base plate at the interface between insert and base plate.
    - When the needle is in place, dispense the glue for 0.1 s and wait for ≈ 5 s before moving to the next location around the insert or to the next insert.
12. When the glue is cured after 24 hours gently remove the weight piece for insert 2 from the gluing jig. The insert and base plate should be held down by plastic tweezers.
13. Remove the weight pieces for inserts 1 and 3. Start by slightly turning them. The inserts and base plate should be held down by plastic tweezers.
14. Remove the pins from the holes for inserts 1 and 3. Gently turn the pins while pulling them out.
15. Disengage the toggle clamp.

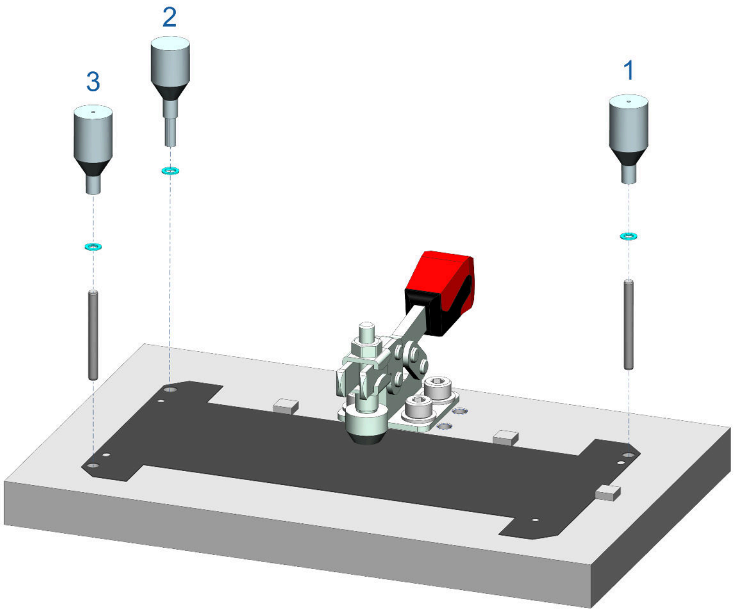


Figure 3: CAD rendering illustrating the usage of the base plate insert gluing jig.

Figure 4: Front panel of a Vieweg DC 300 semi-automatic glue dispenser used in the base plate insert gluing.

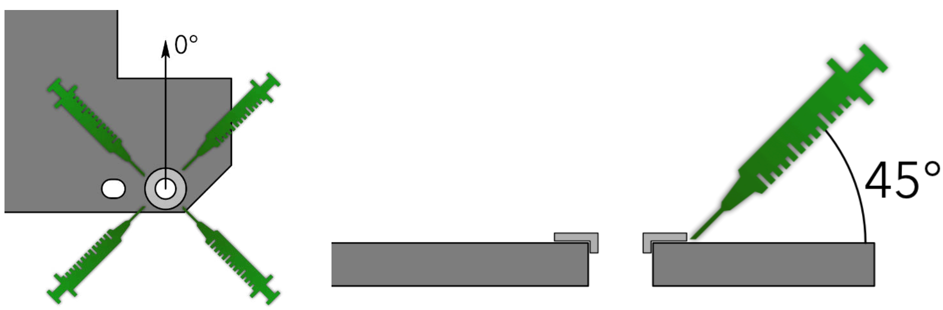


Figure 5: Sketch of where glue has to be applied during base plate insert gluing.

4 Base plate PI isolator gluing

To glue the PI isolator onto the baseplate with the jig described in section A.3, the whole operation takes place in three phases: the fixing of the Kapton on the main jig, the dispensing of the glue on the base plate and the reverse positioning of the baseplate on the Kapton sheet. The following steps are performed:

1. Clean the baseplate and the main jig with the Isopropanol with the removable pins not yet inserted
2. Insert the removable pins in their dedicated holes
3. Wearing antistatic gloves, take the Kapton sheet manipulating it with its support film and place it on the external surface of the jig in correspondence with the grid of holes through which the vacuum is dispensed
4. Try to position the Kapton against the stop removable pins
5. Turn vacuum on
6. Taking care not to damage the Kapton sheet, remove the removable pins
7. Leave the jig with the Kapton fixed with the vacuum on the working table (see figure fig 6

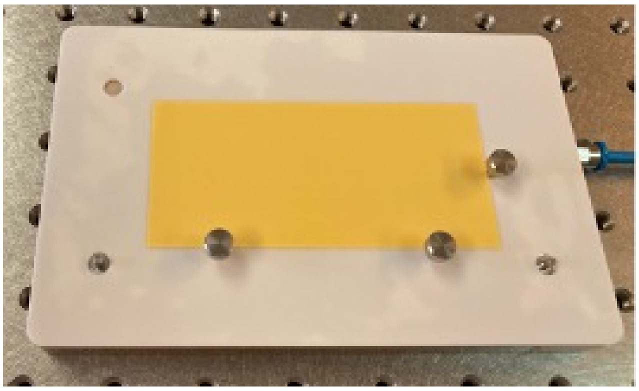


Figure 6: Kapton sheet fixed on the main jig with vacuum

Then begins the second phase of the operation which will make use of a programmable robot for glue dispensing:

1. Put the jig devoted to fix the baseplate during the glue dispensing, on the robot working plate
2. The base plate is positioned on the jig with 3 stop pins and fixed with vacuum
3. Fix the jig with the appropriate stops on the robot plate in a predetermined position, (see fig 7).

   The robot is programmed to recognize, by means of a special camera, as fiducial points the two corners of the baseplate as shown in the same figure, to adjust the glue pattern even if the baseplate is in a slightly displaced position
4. Properly mix Polytec EP 601 LV [5] glue and put into syringe with a green needle (18 gauge; 0.84 mm I.D.)
5. Perform all the operations to start the robot code

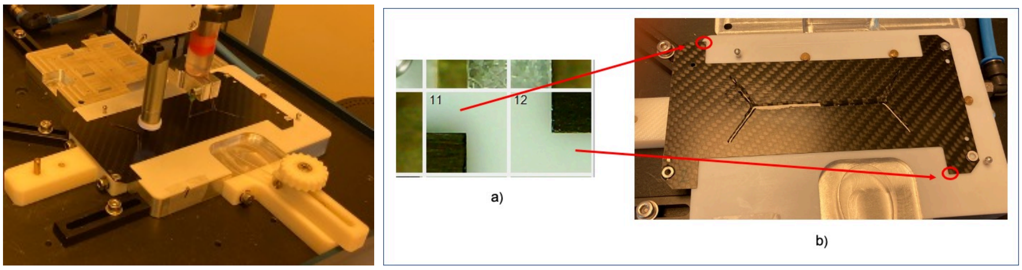


Figure 7: on the left: the baseplate under the robot, on the right: a) image of fiducial marks , b) the glue dispensed on the baseplate

6. Test the glue dispensing parameters
7. Start the robot code dispensing the glue on the baseplate. During that step the robot is synchronized with a volumetric dispenser
8. At the end of the dispensing program turn vacuum off and remove the baseplate from the jig
9. Place the baseplate on the jig containing the Kapton sheet fixed with the vacuum by inserting its inserts into the precision pins of the jig

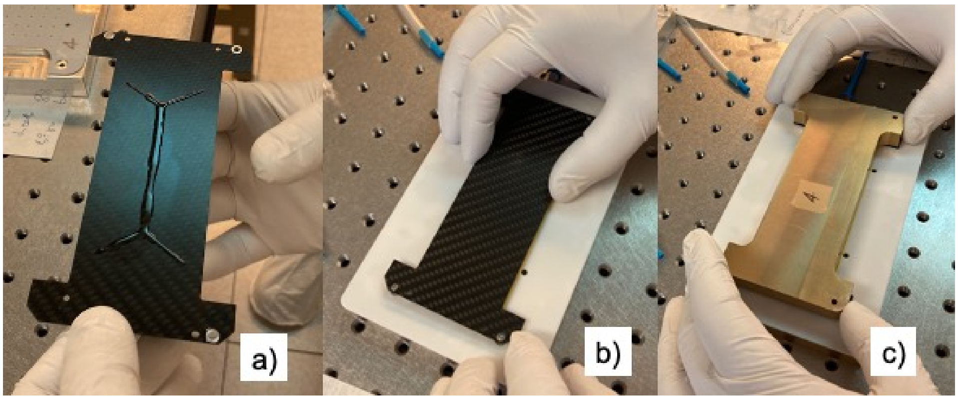


Figure 8: a) baseplate with glue b) baseplate placed on Kapton c) weight placed on baseplate

10. Place the weight on the baseplate making the contact with the its side with the extruded part, inserting its holes in the precision pins that engage the baseplate (see fig 8).
11. Leave the weight on the baseplate for the 24 hours glue curing

5 Sensor sandwich gluing

5.1 Jig-based assembly

In this section the sensor sandwich gluing based on mechanical fixture will be describes. For each step a dedicate fixture (jig) is used, the technical description of these jigs can be found in A.4.
The full procedure can be divided in the following steps:

1. Spacers gluing on top of MaPSA
2. PSs sensor gluing on top of MaPSA-spacers (sensors sandwich)
3. Sensors sandwich gluing on baseplate

5.1.1 Spacers gluing on top of MaPSA

Once the main jig with micrometer screw has been tune as described on A.4 its surface need to be cleaned with isopropyl alcohol, after this the MaPSA can be placed on the surface with the sensor backplane facing down and MPA chip facing up. Subsequently the two pusher are armed and the MaPSA is aligned with the help of three pins (which will touch the PSp sensor only), once in position it is fixed with vacuum, Fig. 9. The next operation is the placement of the spacers

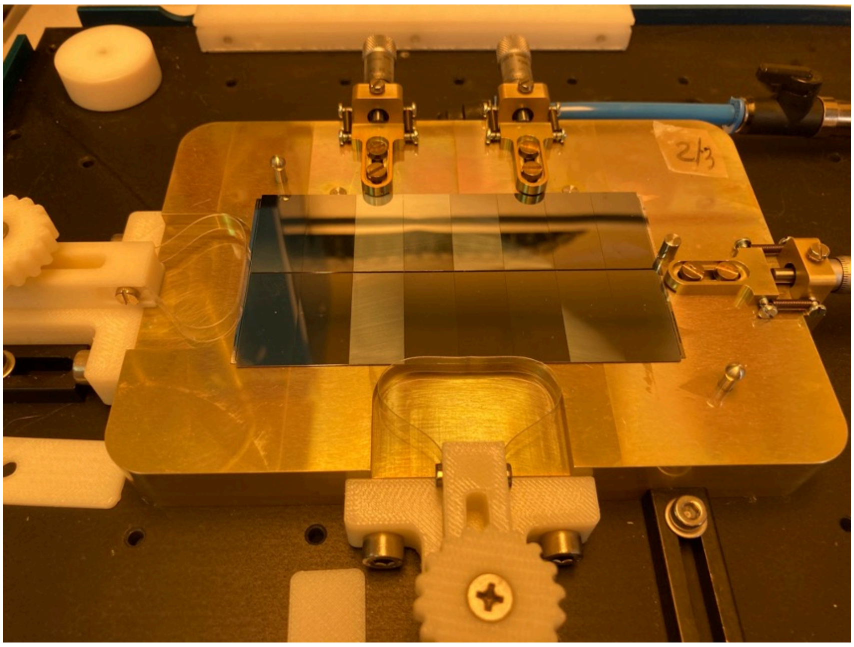
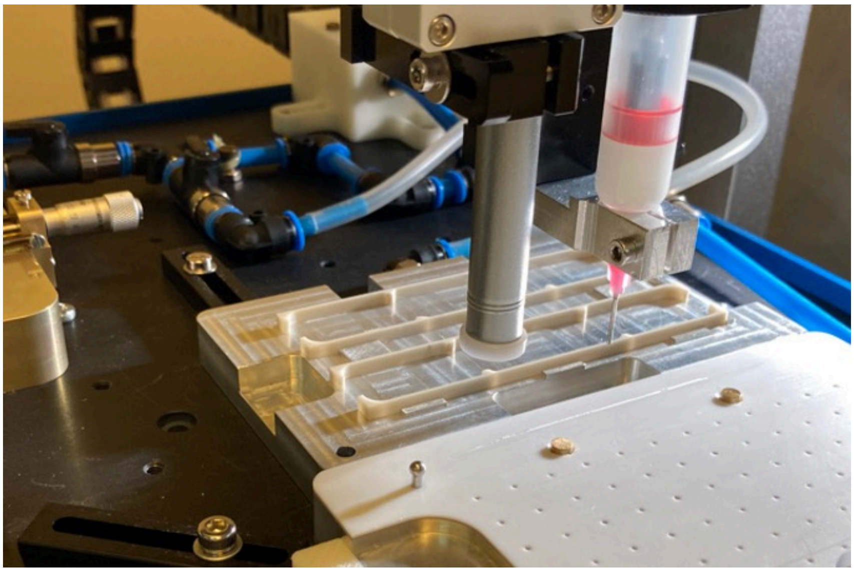
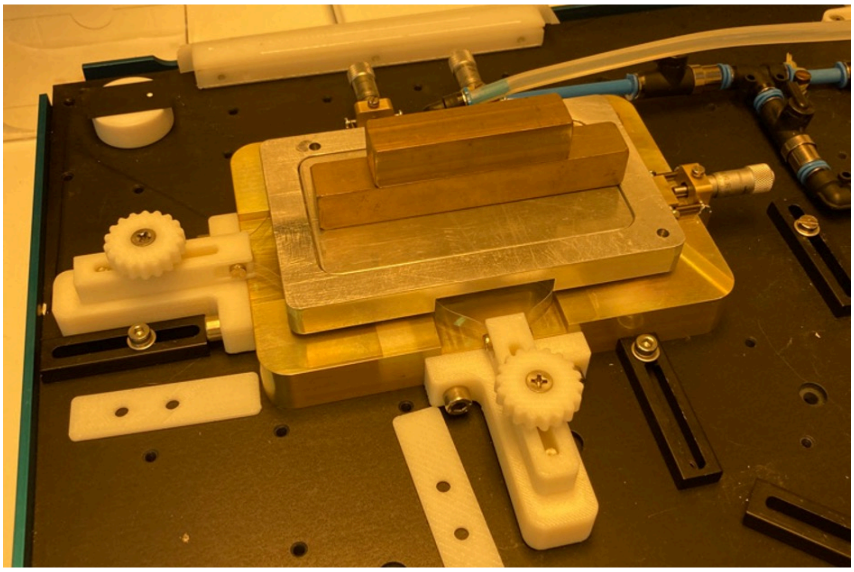


Figure 9: MaPSA placed on the main jig and pushed against alignment pins

on the spacers holding jig, the 4 spacers are manually placed, aligned by pushing them against milled steps and fixed with vacuum. Once this operation is completed the spacers holding jig is placed on the working table of the glue dispensing robot where the glue is dispensed on the spacers surface, Fig. 10a. Thanks to the pattern recognition capabilities of the robot the glue dispensing program is corrected for rotation/translation of the jig using directly the spacers corners. On this step the Polytec TC 437 [7] thermal conductive glue is used, a line of glue following the spacer



(a)



(b)

Figure 10: a) Glue dispensing via robot on top of the spacers; b) Spacers placed on MaPSA with an additional weight for glue curing.

shape is dispensed along with 2 dots on the larger profile points for each spacers. Once the glue as been dispensed and the spacers holding jig is rotated and placed on top of the main jig with MaPSA, the relative alignment between the two jigs is performed via two pins, Fig. 10b. The spacers holding jig is left in position (a small additional weight can be added on top of everything) and the vacuum which keep the spacers is disarmed during the glue curing period. After at least 24 hours the spacers holding jig is removed and MaPSA with spacers are left in position on the main jig, at this stage an optical inspection can be performed in order to check the quality of the gluing.

5.1.2 Sensor Sandwich

After the spacers gluing on MaPSA there is no need to move the MaPSA itself, it is already in position for the next step, Fig. 11. The main jig with MaPSA+Spacers is placed directly on the glue dispensing robot working area. As for the previous step the possible rotation/translation of the jig are compensated by the pattern recognition features of the robot, spacers edge are used. Polytec TC 437 glue is dispensed on top of the spacers with exactly the same parameters and pattern used in the previous step. The following action is the placement of the PSs sensor on top

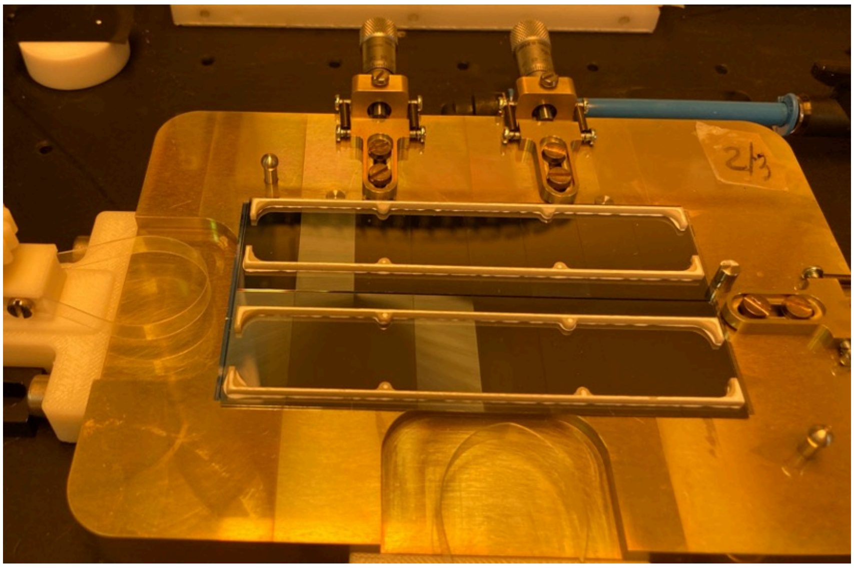
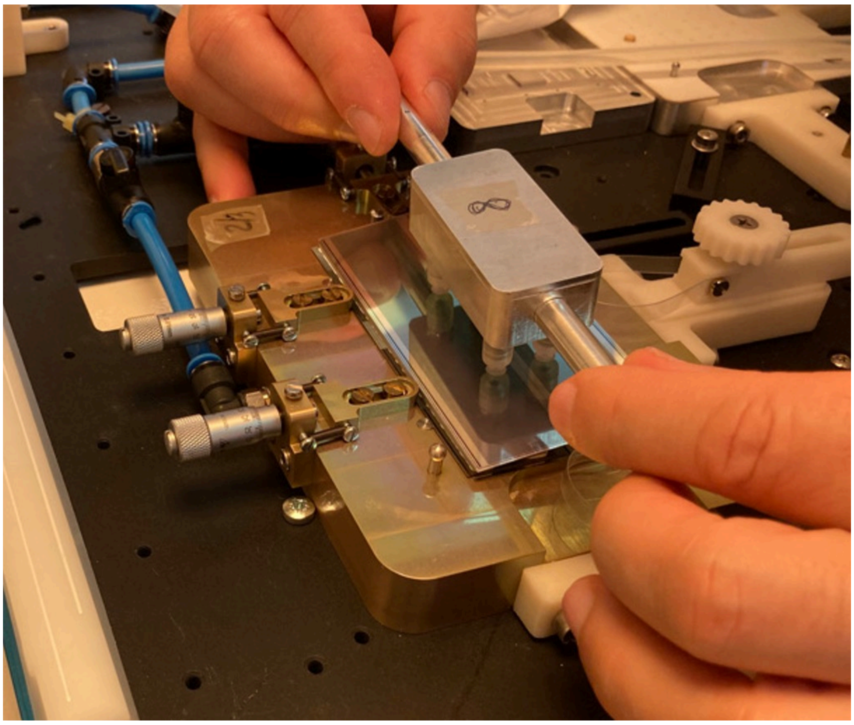


Figure 11: MaPSA+Spacers on the main jig after the glue dispensing, glue lines and points on each spacers are clearly visible.

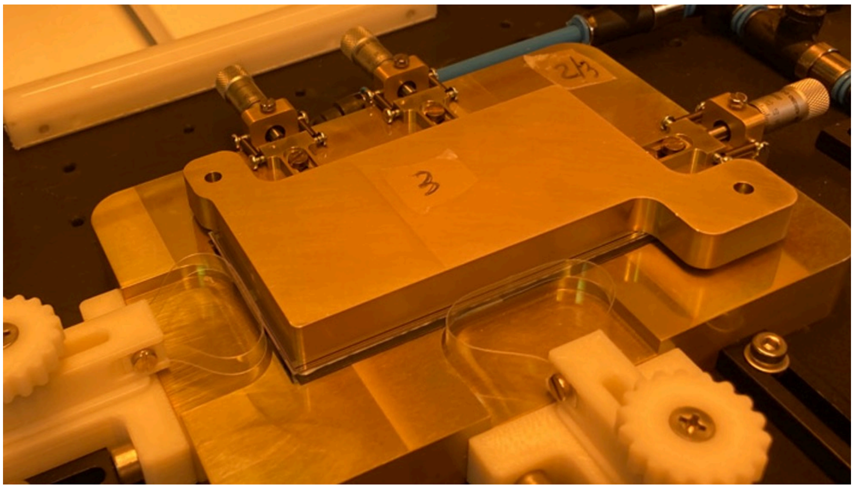
of everything in order to create the sandwich. The sensor is handling is performed via a dedicated tool, described in A.4. PSs is placed on top of spacers, Fig. 12a, pusher are mounted back to the main jig in a slightly higher position, in order to touch only the PSs, and then are armed in order to align the PSs sensors against the microcontrolled pins. A weight is added on top of the PSs sensor in order to assure the planarity and the correct glue thickness, Fig. 12b. The glue curing will last 24 hours.

5.1.3 Sensors Sandwich gluing on baseplate

After the glue curing time the main jig with the sensor sandwich on top is moved under the metrology machine. An optical measurement of the sensors relative alignment is performed, during production if a worsening of the alignment is spotted a recalibration of the main jig via tuning of the micrometer screw can be performed. The last step of the jig based assembly procedure is the gluing of the sensors sandwich on baseplate. First of all the sandwich is removed from the micrometer screw jig and placed on a dedicated jig, the baseplate gluing jig with all surfaces cleaned with isopropyl alcohol, with the PSs sensor facing down, Fig. 13a, two pusher are armed in order to put the sandwich in position, with PSs edges against pin. The baseplate, already glued to Kapton, is placed on an holding jig and placed on the glue dispensing robot working area. Low viscosity Polytec 601 LV [5] glue will be



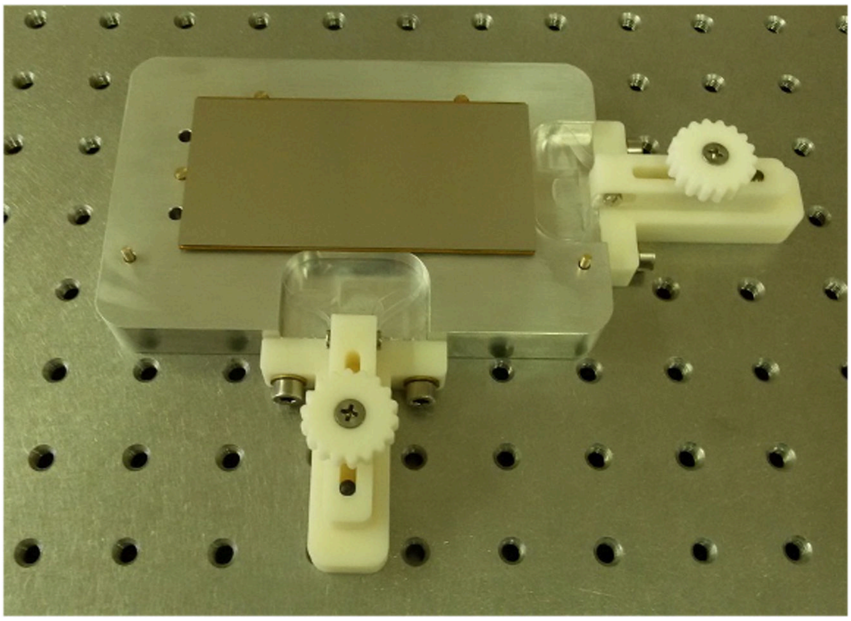
(a)



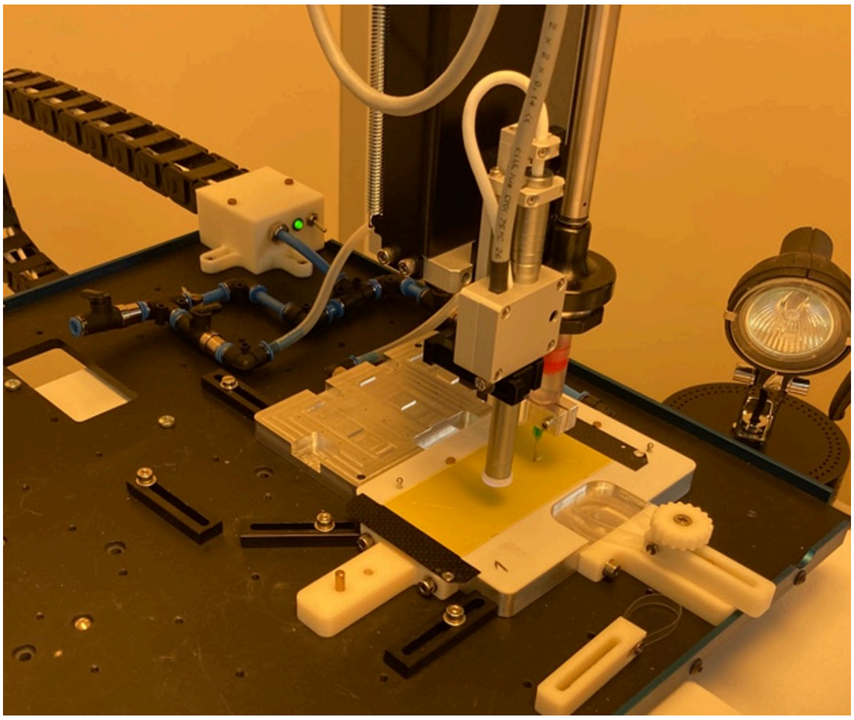
(b)

Figure 12: a) PSs is manually placed on top of the MaPSA+spacers with the help of a sensor handling tool; b) Weight on top of PSs sensor during the glue curing time.

dispensed on top of the Kapton using the same pattern and parameters as for the Kapton gluing step, Fig. 13b. Once the glue has been dispensed the baseplate is removed from the holding jig, rotated face down and placed on top of the sensors sandwich, Fig. 14a. The baseplate position is defined by two pins which will be inserted inside two baseplate insert holes. Finally a weight is placed on top of everything, Fig. 14b, to assure a good spreading of the glue and a good planarity. The glue curing will last, as usual, for 24 hours. After all the steps described the module is ready for the readout hybrids integration.



(a)



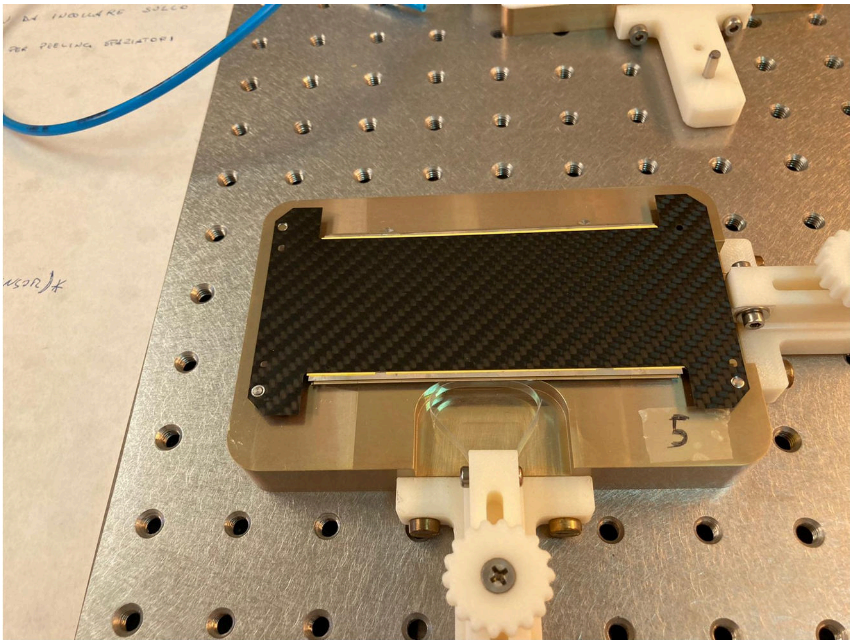
(b)

Figure 13: a) Sensors sandwich placed on top of the basplate gluing jig, the PSp backplace is fecing up; b) Glue dispensing on the baseplate+kapton.

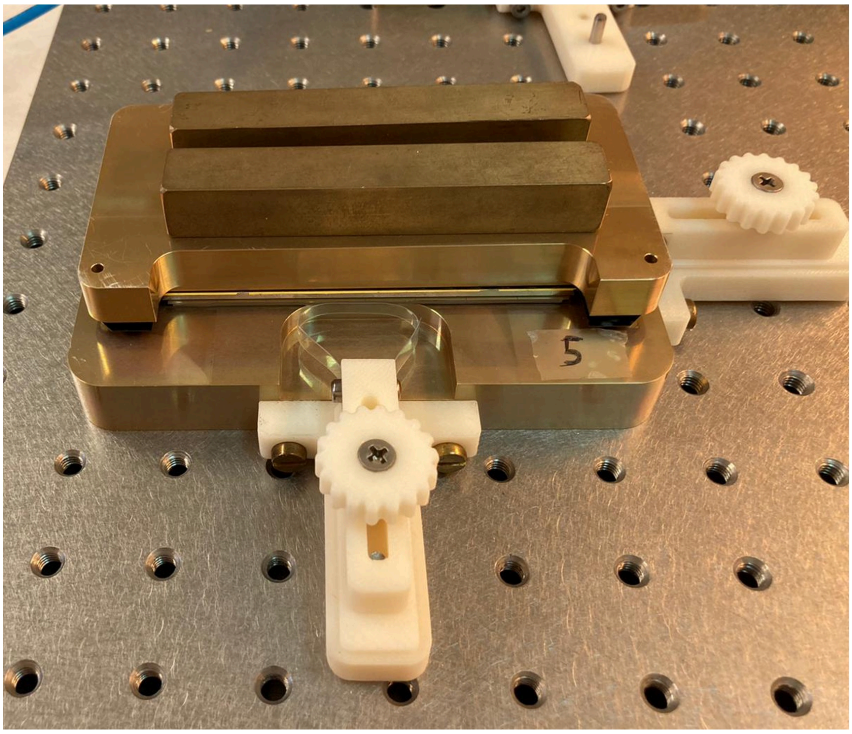
5.2 Assembly with robotic stages

5.2.1 Overview

In order to meet the high precision and throughput requirements of the sensor-spacer-baseplate-assembly (SSBA—also referred to as sensor sandwich), and to mini-



(a)



(b)

Figure 14: a) Baseplate placed face down on top of sensors sandwich; b) Weight added on top of baseplate during the glue curing period.

mize the amount of human interventions, a semi-automated module assembly system has been developed. It integrates high-precision motion stages with a microscope camera and vacuum handling tooling. Because both PS sensors face upward, and the bottom PSp sensor is slightly longer than the top PSs sensor, all eight fiducial markers engraved at the sensors' corners are visible from above. A pattern recognition algorithm is used to infer the component positions and align them with each other, without relying on the precise dicing of sensor edges, as illustrated in Fig. 15. A custom control software is used to acquire images, run the pattern recognition algorithm, and control motion stages and vacuum lines to arrange components during assembly.

Sequential steps are carried out to glue the different SSBA components together. In addition to the standard glue satisfying all requirements for operation in the extreme tracker environment ("slow glue"), small amounts of a fast-curing medium-viscosity epoxy ("fast glue") are dispensed, which develops sufficient bonding strength between components within 20 minutes, after which the assembly can proceed. Except for dispensing glue layers, and placing or removing components from the assembly platform, most actions are fully automated and executed as a sequential list of preprogrammed buttons in the graphical user interface (GUI). Detailed descriptions of the hardware and gluing setups are provided in Appendix A.5, as well as a presentation of the software and its main capabilities.

This robot-assisted procedure allows the assembly of a sensor sandwich within two hours by a crew of two operators. Usually, one will control the hardware setup via the GUI, while the other will take care of all glue-related operations: dispensing glue layers, dip spacers into the dispensed glue layers, position spacers onto the assembly platform, etc. This organization of tasks has the advantage that one operator focuses on the actual assembly using the GUI and does not touch glues. While waiting for the fast glue to develop bonding strength, both operators will usually clean all tools from glue residues promptly and prepare for the next assembly step or a new assembly.

5.2.2 Assembly sequence

This section describes the sequence for the semi-automated SSBA. It consists of the following three main stages:

1. Gluing the MaPSA (bottom sensor) to the baseplate
2. Gluing the spacers to the PSs (top sensor)
3. Gluing the PSs-spacer sub-assembly to the MaPSA-baseplate sub-assembly.

Each step can be completed in about 30 minutes, owing to the use of fast glue.

To begin with, the operators inspect the assembly setup for readiness (software parameters, calibrations, etc.), fetch module components and the relevant tooling, and mix the slow glue. The insulating Kapton foil and positioning inserts must have been glued to the baseplate beforehand. A few manual interventions are required during the assembly to place or remove components on the assembly platform, and dispense glue layers. Sensors, spacers, and baseplate are handled using a vacuum pen, tweezers, and by hand, respectively. Individual steps of the automated assembly sequence are executed via the GUI and are listed below. The reader is referred to Appendix A.5 for more details regarding the different software routines that are used.

- *Gluing the MaPSA to the baseplate:*

  1. The MaPSA is placed onto the assembly platform and held in place by vacuum. The alignment and pickup routines are run.

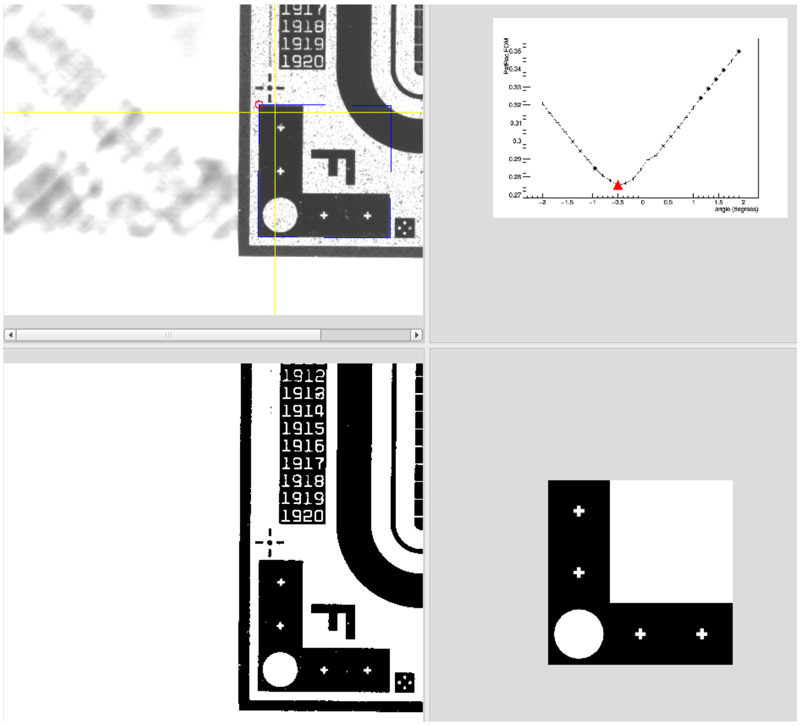


Figure 15: Illustrative view of a part of the GUI when running the pattern recognition routine. Bottom-left: the camera image after black-and-white conversion. Bottom-right: the template image that must be recognized in the camera image. Top-left: the template image has been found in the camera image (blue square), and the coordinates of its reference point (red circle) are inferred. Top-right: figure of merit of the image matching as a function of the template's angle. The minimum corresponds to the best-match angle for the template.

2. As illustrated in Fig. 16 (left), a central line of slow glue is dispensed on the baseplate's surface, plus four dots close to the corners, using a 3-axes automatic dispensing robot [8]. A syringe's needle is employed to manually dispense 4 smaller dots of fast glue close to the corners. The resulting glue pattern is visible in Fig. 16 (right).
3. The baseplate is placed onto the assembly platform with the glue layer facing up, and its position is fixed using pins.
4. The MaPSA is lowered down onto the baseplate (at its design position), and the system stays idle for about 20 minutes until the fast glue develops sufficient bonding strength.
5. The setdown routine is completed, the pins are removed, and this subassembly is released from the setup and put aside.

- *Gluing the spacers to the PSs:*

6. The PSs is placed onto the assembly platform and held in place by vacuum. The alignment and pickup routines are run.
7. Layers of slow and fast glues are dispensed on the glue pickup blocks (see Appendix A.5). The four spacers are dipped in glue on one side. They

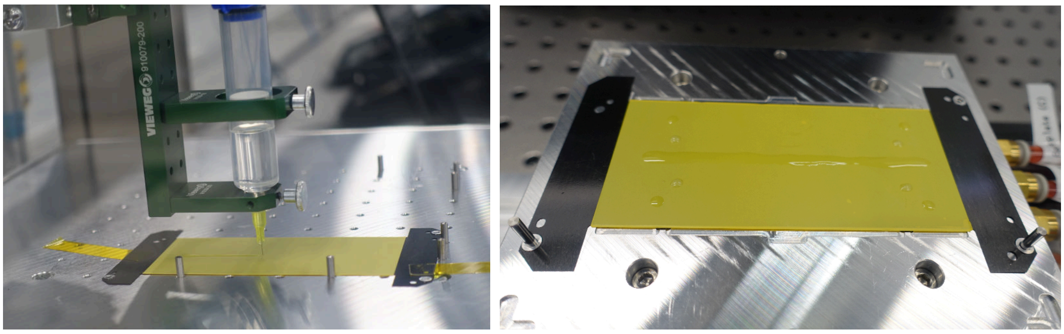


Figure 16: Left: slow glue is dispensed on the baseplate using an automatic dispensing robot. Right: the slow glue (line plus four dots) and fast glue (four smaller dots) patterns are visible on the baseplate, which is fixed to the assembly platform with pins.

are then placed onto dedicated slots machined into the assembly platform with the glue facing up, and held in place by vacuum.

8. The PSs is lowered down onto the spacers, and the system stays idle for about 20 minutes until the fast glue develops sufficient bonding strength.
9. The vacuum suction is turned off below the spacers, and this sub-assembly is picked up by the robot arm.

- *Gluing together the PSs-spacers and MaPSA-baseplate sub-assemblies:*

10. The first sub-assembly is again positioned on the assembly platform with pins, and held in place by vacuum. The alignment routine is run.
11. Layers of slow and fast glues are dispensed on the glue pickup blocks (see Appendix A.5). The latter are placed onto the dedicated gluing stage.
12. The arm is moved at a predefined position above the gluing stage, and lowered such that the bottom surface of the spacers is dipped into slow and fast glues following a specific pattern.
13. The arm is lifted up and returns to its previous position above the assembly platform.
14. The arm is lowered down onto the assembly platform, and the system stays idle for about 20 minutes until the fast glue develops sufficient bonding strength.
15. The setdown routine is completed, the pins are removed, and the SSBA is released from the setup.

At the end of the assembly sequence, the SSBA is transferred onto a plate and stored in a cabinet for at least 24 hours. Once the slow glue is cured, the various hybrids are attached to the SSBA to finalize the mechanical assembly of the module. In total, the SSBA assembly procedure may be completed within two hours. While the three curing periods of 20 minutes each cannot be sped up, the durations of other steps (glue dispensing, cleaning, positioning of components, etc.) may be considerably reduced with training.

6 Hybrid gluing

To glue the hybrids onto the bare module using the jig described in section A.6 the following steps need to be performed:

1. Clean the jig and pins with Isopropanol.
2. Inspect the PS module and hybrid using a microscope.
    - Check for evidence of damage to the silicon and pay close attention to the bonding pads.
    - Check the connectors on the hybrids for damage to the contacts, ensure the alignment pin holes are clear of any blockages, and check the bonding pads.
3. Place the three module alignment pins in the correseponding holes in the base jig (see figure 17).
4. Lock each pin in place with a 2mm allen wrench using the corresponding pair of set screws in the sides of the jig
5. Carefully place the module against the module alignment pins on the base jig using a vacuum pen (see figure 18).
    - The CF baseplate will contact the single module alignment pin. This is the POH side of the module.
    - The MPA chips will contact the pair of module alignment pins. This is the FEH-R side of the module.
    - Pull vacuum on the module when it is flush against all three module alignment pins.
6. Remove the single module alignment pin that contacts the CF baseplate (see figure 19).
7. Mount the pushers to be used for the POH attachment (see figure 20).
    - Note - these pushers may be attached earlier depending on the preference of the operator gluing the module.
8. Insert the 1.2mm/1.3mm hybrid alignment pins for guidance of the POH (see figure 21).
    - Check for pin clearance in the POH prior to applying epoxy.
9. Mix Polytec TC 437 epoxy using a mass ratio of 100:10 for part A: part B.
    - Be sure to follow all health and safety procedures for epoxy mixing, including the use of safety goggles and fume hoods.
10. Apply two layers of 25um kapton tape to the hybrid gluing jig epoxy block to form the reservoir for the epoxy(see figure 22).
    - The specific hybrid being glued will determine the required size of the reservoir.
    - If using a syringe to dispense epoxy directly onto the hybrid no reservoir is needed.

- Dispense epoxy between the layers of kapton tape and smooth the epoxy with a squeegee or razor blade.
- Clean excess epoxy as needed.

11. Apply epoxy to the POH.
    - Make sure to avoid the alignment pin holes with either the epoxy reservoir or manual dispensing.
12. Align the POH to the module using the 1.2mm/1.3mm hybrid alignment pins.
    - The single module alignment pin hole and round insert can be used as guides for the location of the POH.
    - Ensure that the HV tail coming off the PS-s clears the POH and sits above the POH.
    - Engage the two pushers on the power shield of the POH(see figure 23).
13. Let the epoxy cure.
14. Disengage the two pushers from the POH.
    - Remove the two pushers from the base jig.
15. Carefully loosen the set screws that hold the module alignment pins in place and then remove the pins. Also remove the 1.2mm/1.3mm pins used for aligning the POH.
16. Insert the hybrid alignment pins for guidance of the FEHs(see figure 24).
    - The 0.9mm pin is located near the POH on the FEH-R side.
    - The five 1mm pins are located on the left side nearest the POH and in the four 1mm holes near the ROH.
    - Check for pin clearance through the alignment holes in both FEHs prior to applying epoxy to the hybrids.
17. Mount the pushers to be used for FEH attachment(see figure 25).
18. Mix a new batch of Polytec TC 437 epoxy.
19. Apply epoxy to the FEHs.
    - Only the spacers at the edges of the FEH receive epoxy.
20. Align the FEHs to the module using the 0.9mm/1mm hybrid alignment pins.
    - The FEHs should sit on top of the POH tails.
    - The HV tail connected to the PS-s should sit on top of the FEH-R.
    - Do not connect the POH tails or the HV tail at this step.
    - Engage the four pushers on the FEHs(see figure 26).
      - These pushers should contact the POH/ROH connectors on the FEHs as this is the area directly above the epoxy and spacers.
21. Let the epoxy cure.
22. Disengage the four pushers from the FEHs.
    - Remove the four pushers from the base jig.

23. Remove the 0.9mm/1mm hybrid alignment pins from the FEHs.
24. Mount the pushers to be used for ROH attachment (see figure 27).
25. Apply a slight bend to the tails of the ROH.
    - Currently this step is done by hand, but a jig for this purpose is in development.
    - Perform a dry run of ROH placement to check for the alignment of the ROH tails to the FEH connectors and also for the fit of the ROH between the FEHs.
    - Do not connect the ROH to the FEHs for this step.
26. Mix a new batch of Polytec TC 437 epoxy.
27. Apply epoxy to the ROH.
28. Align the ROH such that you can connect the tails to the FEHs (see figure 28).
    - In the future this step will utilize 1mm/2mm pins but the current version of the ROH does not support this.
    - Mate the ROH tails to the FEH connectors.
    - Engage the pushers on the ROH.
29. Let the epoxy cure.
30. Disengage the two ROH pushers.
    - Remove the two pushers from the base jig.
31. Connect the HV tail from the PS-s to the FEH-R (see figure 29).
32. Connect the POH tails to the FEHs (see figure 30).
33. Turn off the vacuum supply to the jig.
    - Once the module is no longer held by vacuum transfer it to a module carrier using a vacuum pen (see figure 31).

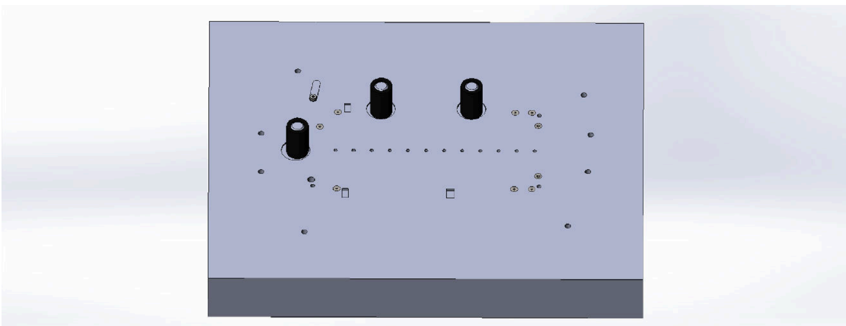


Figure 17: Hybrid gluing jig with module alignment pins engaged.

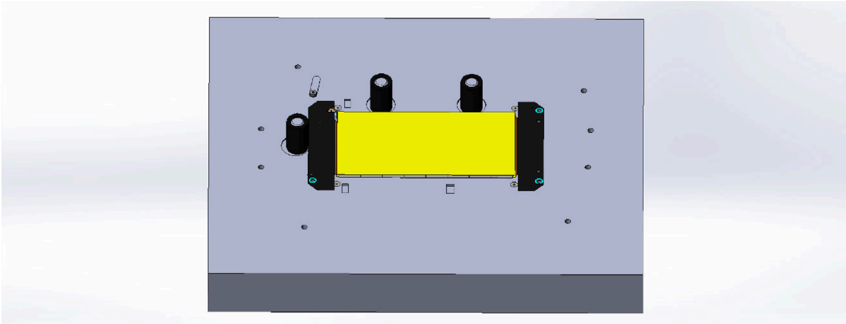


Figure 18: Bare module aligned against module alignment pins.

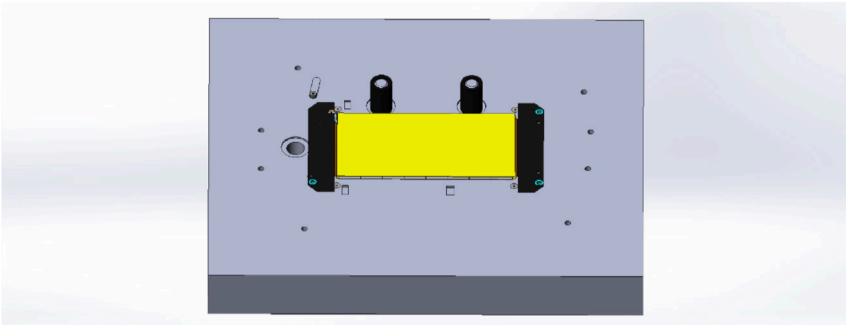


Figure 19: Single module alignment pin removed.

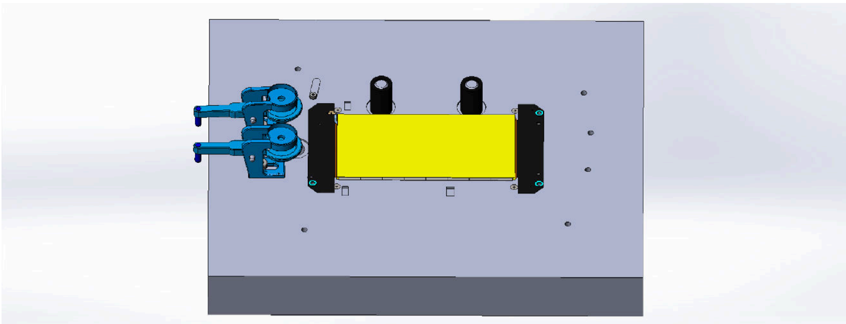


Figure 20: POH pushers mounted to the base jig.

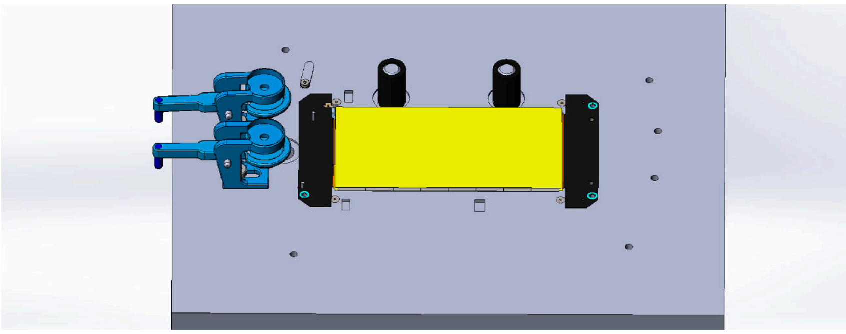


Figure 21: POH pins in place in the base jig.

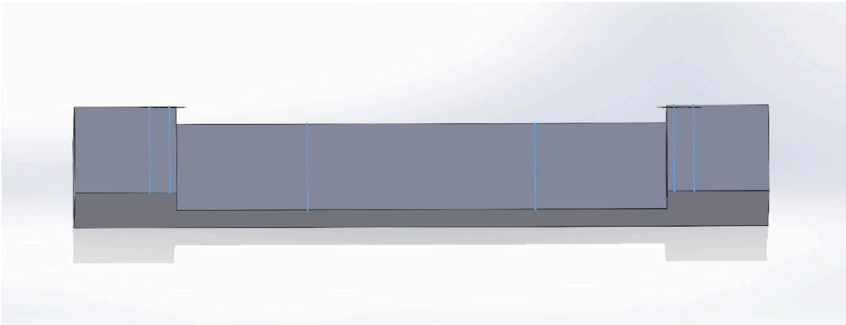


Figure 22: Epoxy reservoir for hybrid dipping.

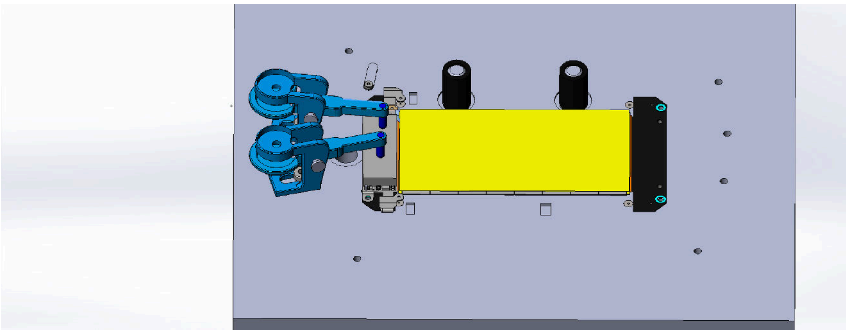


Figure 23: POH attached to module.

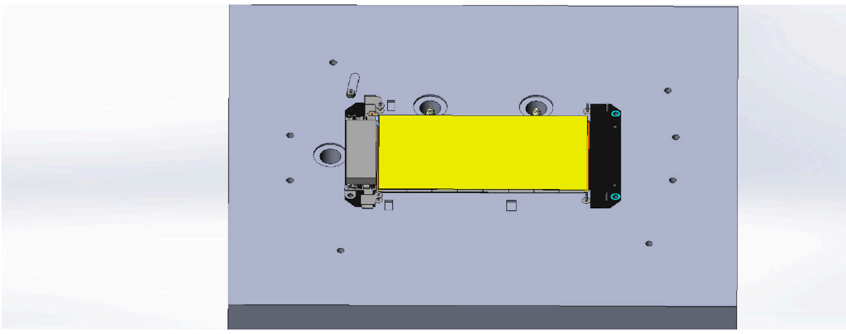


Figure 24: FEH alignment pins in place.

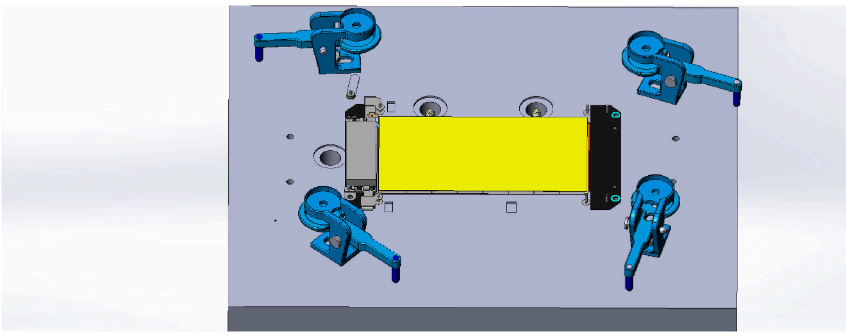


Figure 25: FEH pushers in place.

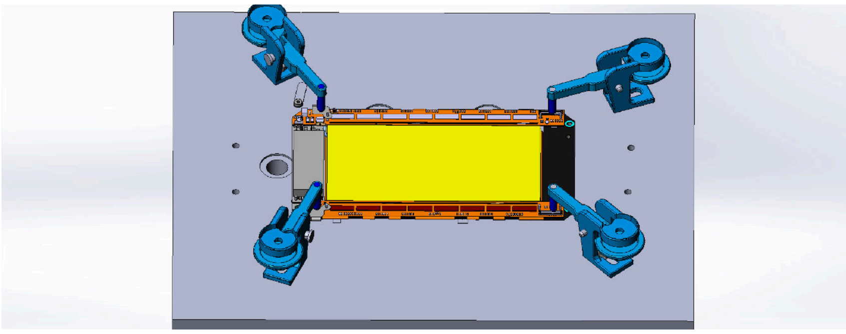


Figure 26: FEHs attached to module.

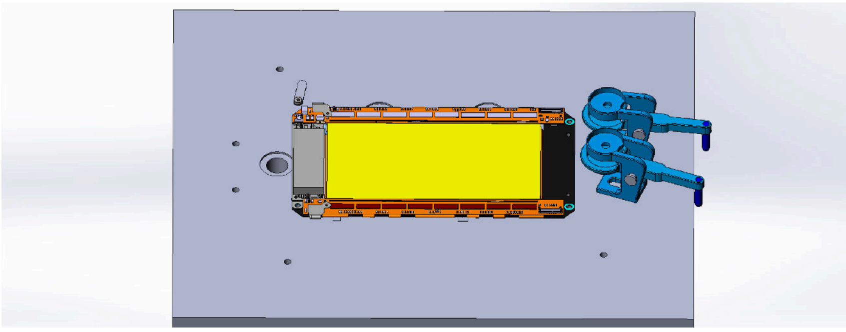


Figure 27: ROH pushers in place.

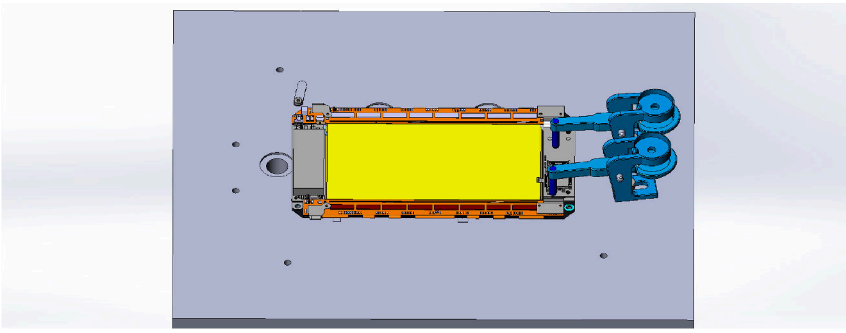


Figure 28: ROH attached to module.

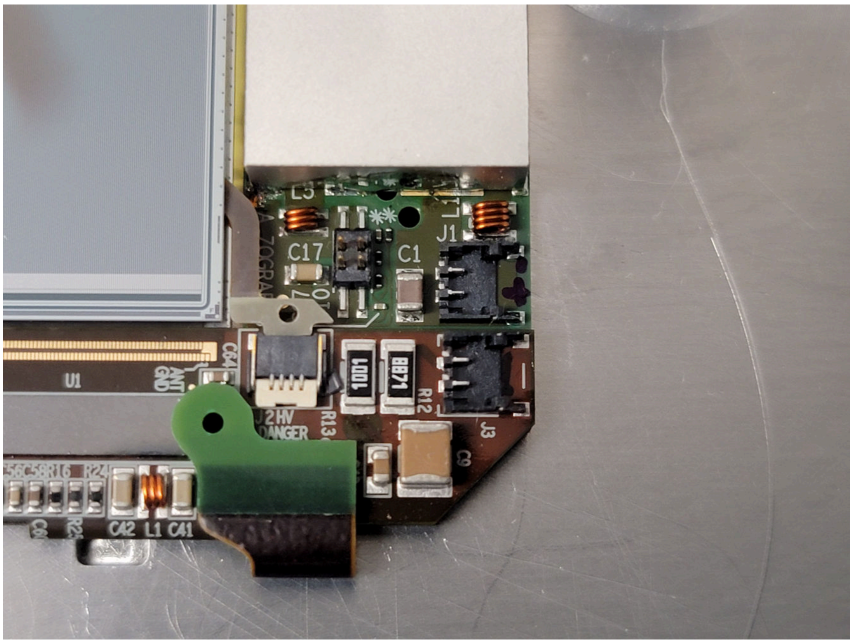


Figure 29: HV tail attached to FEH-R.

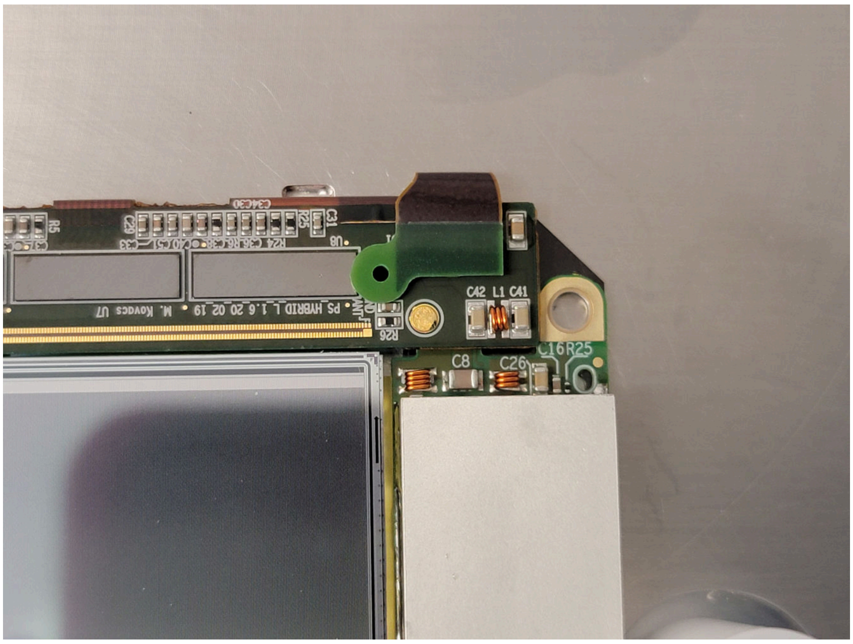


Figure 30: POH tail attached to FEH-L.

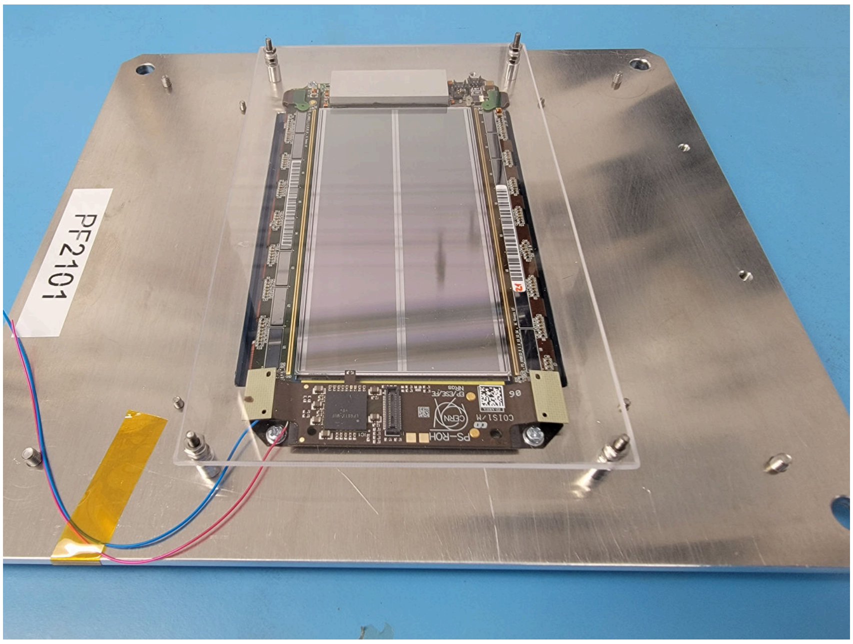


Figure 31: Module mounted onto carrier.

7 Wire bonding

8 Wire bond encapsulation

To encapsulate the wire-bonds of a PS module, the module has to be placed on a carrier and be mounted on the dispensing robot stage. An adapting plate was designed for mounting purpose and is described in section A.8.

Mixing and preparation of SYLGARD 186 Silicone Elastomer:

1. Mix the glue with portion of 100:10
2. 5 minutes of mixing with 900 rpm
3. 4 minutes of deforming with 1200 rpm
4. Fill the syringe with SYLGARD with an angle to avoid bubble formation

Two dispensing programs developed at DESY are dedicated for encapsulating wire-bonds on PS-p and PS-s sides:

For PS-p side, a blue needle tip (inner diameter 0.41 mm) is used and the three-line method is implemented in the program to nicely cover the wire-bonds and prevent the glue from leaking through the gap between hybrid and sensor. Program of line 1 and line 2 dispense the glue 1 mm above and 0.5 mm away from the bond feet with the speed of 1.4mm/sec and the pressure of 4 bar along the hybrid and sensor respectively. Program of line 3 dispenses the glue 1.65 mm above the bond feet with the speed of 1.6mm/sec along the mid gap of the first two lines. The dispensing pattern is shown in fig 32.

For PS-s side, an orange needle tip (inner diameter 0.33 mm) is used and only two dispensing lines are needed since the wire-bonds are shorter. A mid-point dispensing technique is needed to avoid glue tail due to a narrower needle. Program of both lines dispense the glue 1 mm above the bond foot with the speed of 0.8mm/sec and the pressure of 5 bar.

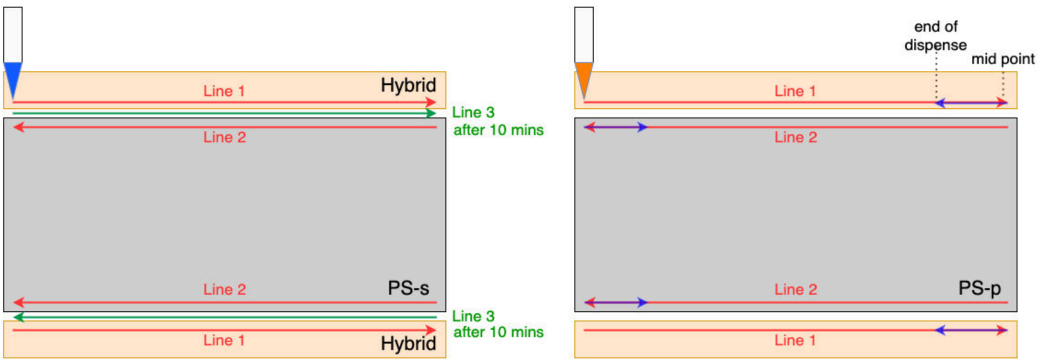


Figure 32

To start the encapsulation program, the following steps are performed:

1. Place the syringe on the dispensing robot.
2. Mount the carrier to the robot stage.
3. Start the dispensing program for line 1 and 2.

4. For PS-s side, let stand for 10 minutes and start the dispensing program for line 3.
5. Handle the module after 24 hours of glue curing.

A Tooling

A.1 HV tail gluing jig

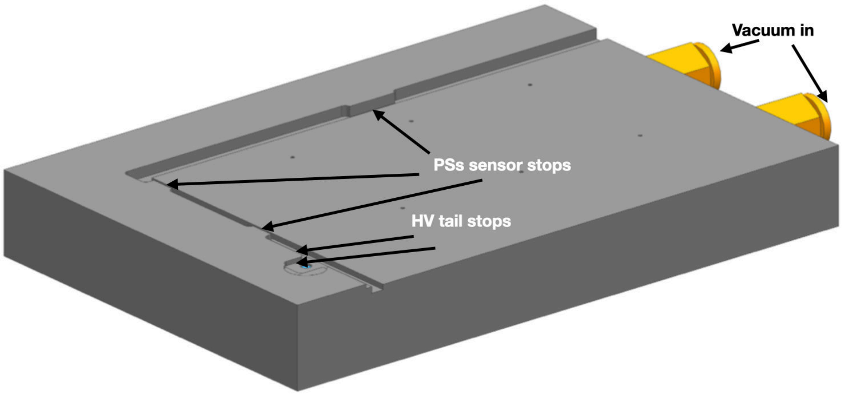


Figure 33: CAD rendering of the jig used to glue the Hv Tail.

Figure 33 shows the CAD rendering of the jig used to glue the HV tails to the PSs sensor backplane. The jig is made of ESD plastic. For positioning the PSs sensor the jig has three stops. Once the sensor is positioned it is fixed by turning on the vacuum. Six vacuum holes hold down the sensor. The HV tail is positioned by stops and held down by a magnet.

A.2 Base plate insert gluing jig

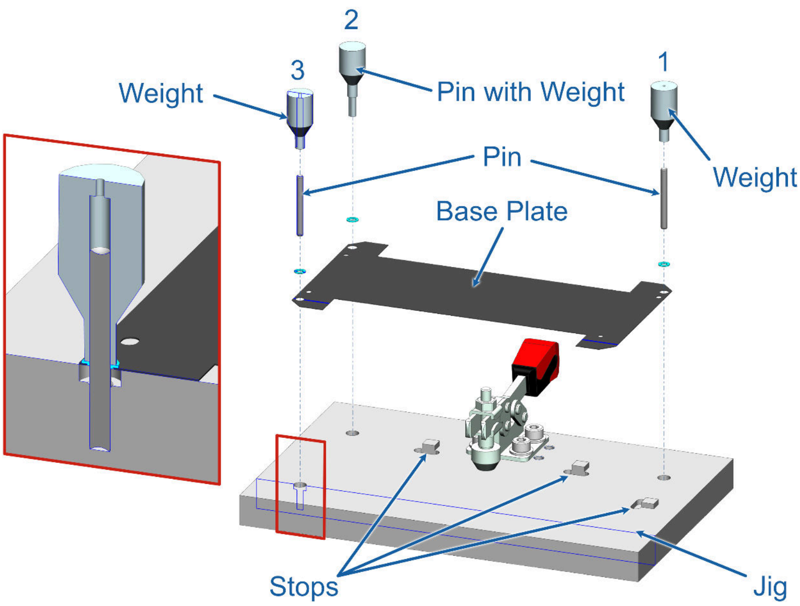


Figure 34: Exploded CAD rendering of the jig used to glue the positioning inserts to the PS base plate.

Figure 34 shows the exploded CAD rendering of the jig used to glue the positioning inserts to the PS module base plate. The jig plate is made of Aluminum EN AW-5083 and has a size of 100 mm × 160 mm × 12 mm. For positioning the base plate the jig has three stops. Once positioned against the stops the base plate is fixed by toggle clamps. In the current design holes are foreseen for either AMF series 6830 size 0 horizontal or AMF series 6800 size 0 vertical toggle clamps. Inserts 1 and 3 are positioned on the jig with standard 2.5h7 pins and held down by weight pieces. Since insert 2 has an elongated hole a dedicated matching pin with weight is used. The following is a list of parts including links to the drawings where applicable:

- 1× jig plate
- 1× AMF toggle clamp 93005 (horizontal) or 90001 (vertical)
- 4× cylinder screw ISO 4762 M4 × 10 A2
- 4× washer ISO 7089 4 A2
- 2× 2.5h7 × 24 pin
- 2× weight piece for pins
- 1× pin with weight

A.3 Base plate PI isolator gluing jig

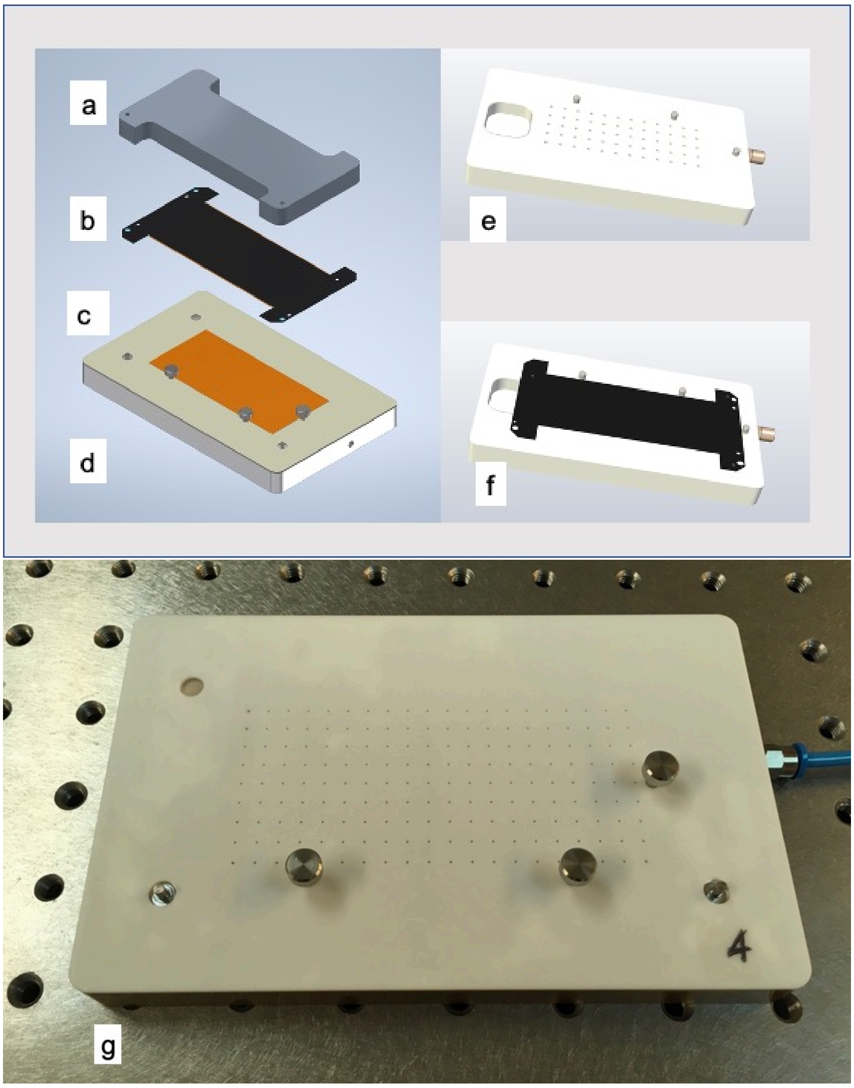


Figure 35: Exploded CAD rendering of the jigs devoted to glue the PI isolator to the PS base plate. a) weight, b) base plate, c) kapton sheet, d) jig to glue PI isolator, e) jig for glue dispensing on base plate, f) same as e) with the base plate fixed on it, g) picture of the main jig

Figure 35 shows an exploded view of the jigs for gluing the Kapton sheet onto the baseplate. In the left part of the figure the tools used for gluing the Kapton sheet on the baseplate are represented. At the bottom the jig made from an aluminum plate 15 mm thick, 160 mm long and 100 mm wide is shown. The inner part of the plate is dug to make a vacuum dispenser. The upper outer face, covered with a layer of Teflon, presents at this excavation, a grid of holes of 0.5 mm of diameter, 5 mm spaced. Under such a grid, the Kapton sheet is then placed, to be fixed with the vacuum; Its position is determined by the use of three stop pins that are removed after the fixing operation. Two precision pins are placed on the outer surface of the jig, at which the baseplate is inserted by means of its precision inserts after dispensing the glue on it. In this way, the position of the Kapton with respect to the precision pins, where the baseplate inserts are inserted, is determined by the jig design. The right side of the figure shows the jig specially designed to house the baseplate during the glue dispensing. Here the same grid structure of holes for vacuum dispensing and three stop pins to place the baseplate is shown. A digging on the upper face of the jig makes it possible to remove the baseplate without touching the dispensed glue. The manufacturing drawings for all parts are available in [9, 10, 11].

A.4 Sensor sandwich gluing jig

This section described the jigs and tool used in the fixture based assembly process. The manufacturing drawings for all parts are available in [12].

A.4.1 Main Jig (or Micrometer Screws Jig)

The Main Jig or Micrometer screws jig or MaPSA holding jig is composed by an alluminum plate with a vacuum chamber, 2 fixed pins, 3 flat pins, 3 mobile pins regulated by micrometer screw and 2 3D printed pushers. In Fig. 36 a 3D rendering

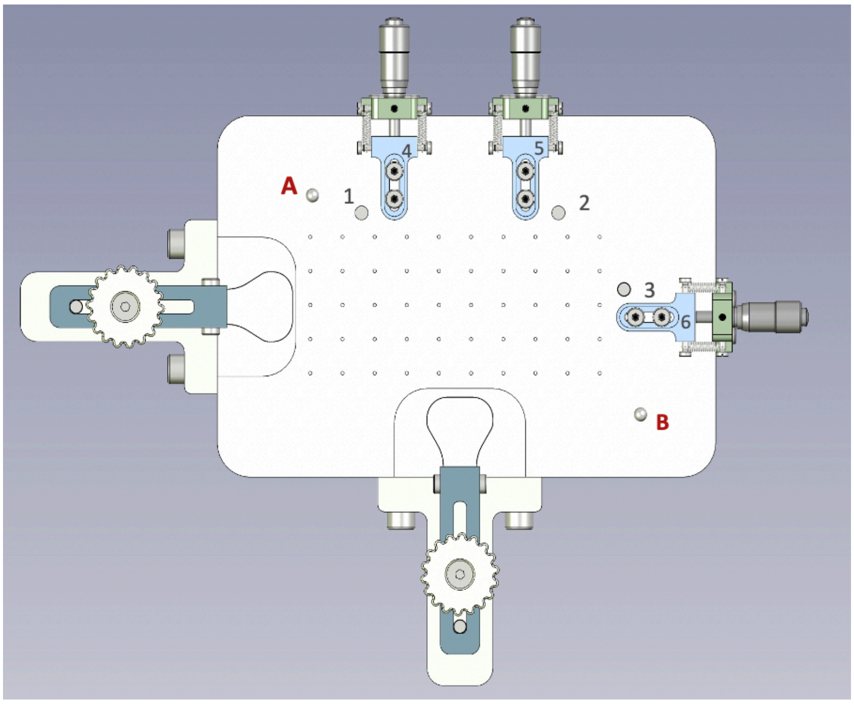


Figure 36: 3D rendering of the Main Jig: A and B are the fixed pins, (1,2,3) are the flat head pins and (4,5,6) are the mobile pin regulated via micrometer screws

of the jig is shown here a detailed description of the components:

Central small holes The vacuum chamber need to keep MaPSA in position during the operation;

A & B Fixed pins, they provide the alignment between this jig and the Spacers Holding Jig (Fig. 40)

1, 2 & 3 Flat head pins, they set the reference position for the MaPSA. They are meant to touch only the PSp sensor edges so the height of these pins can be regulated via grub screws. In particular the height of pin 1 & 2 should not exceed 320μm in order to not touch the MPA chips (Fig. 38b).

4, 5 & 6 Mobile pins, they align the PSs sensors to the MaPSA. The lower edge of the mobile pin is extruded in order to not touch the MPA chips (Fig. 38b). Their position need to be calibrate under a CMM machine, the calibration procedure will be described in the following.

Pusher The two pusher are composed of 3D printed plastic objects, 150μm Kapton strips are used as springs.

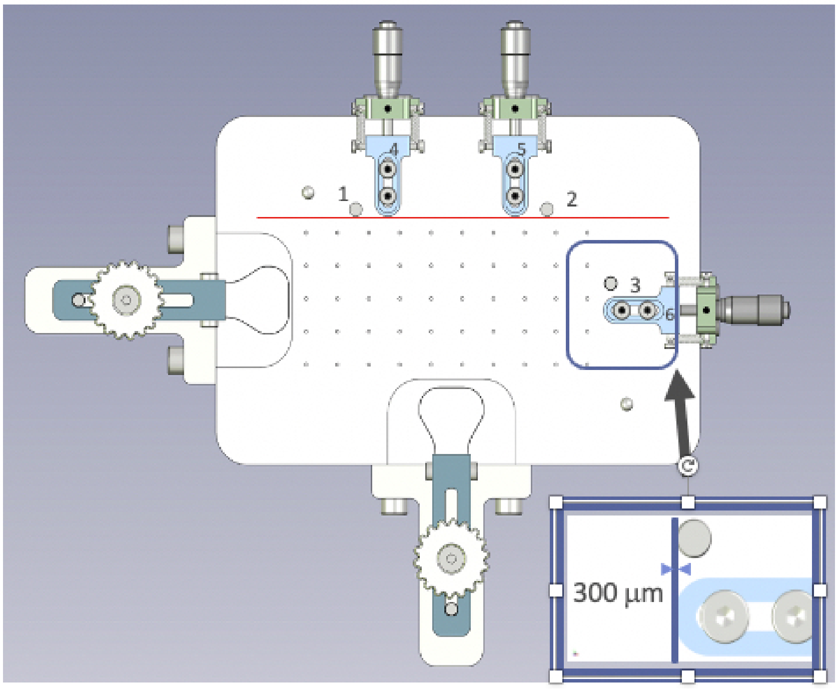
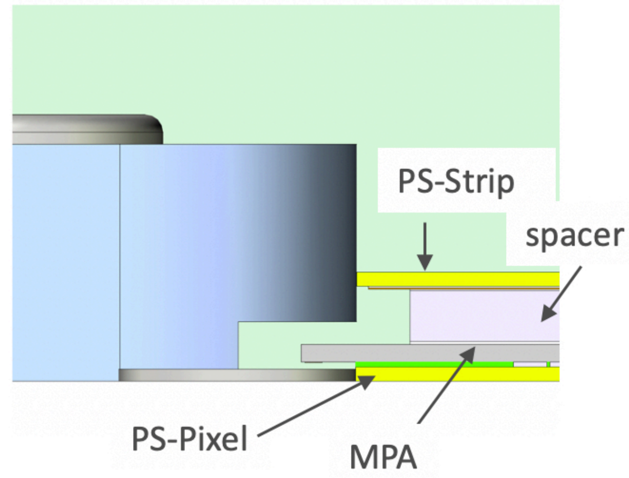


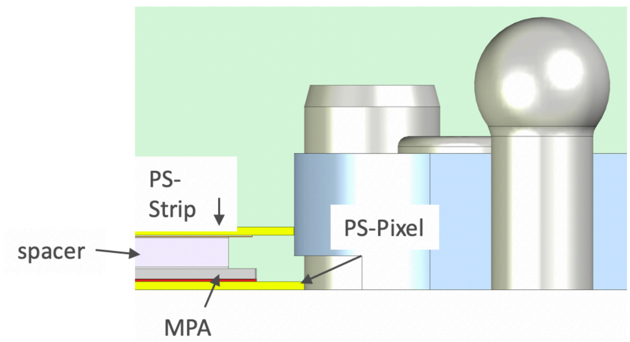
Figure 37: Schematic 3D rendering of the calibration of the Main Jig: the red line indicates that pins 1 & 2 and 4 & 5 are placed all on the same line, the zoomed region on bottom left indicates a shift of 300μm between flat head pin and mobile pin in order to account for different PSp and PSs sensors dimension.

The main feature of this jig is presence of the mobile pins, they allow for a precise alignment between the two sensors and they can be re-tuned every time a degradation of the alignment is spot during production. On Fig. 37 a schematic representation of the calibration is shown, the procedure is performed with a CMM machine with an optical tool and it is composed by the following step:

1. The Jig is placed under the Optical CMM machine
2. A reference system is created measuring the position of the pins 1, 2 & 3. Pins 1 & 2 define the X axis while pin 3 define the Y axis direction.
3. Mobile pin 4 & 5 are placed via micrometer screws exactly on the X axis (so with a Y value of 0) previously defined, this set the long edge of the PSp and of the PSs to be aligned. On Fig. 38a a detailed CAD representation of the final position of the pins is shown along with the sensors and the MPA chips.
4. Mobile pin 6 is placed 300μm inside with respect to pin 3, this means at X=300μm. This shift is necessary to take into account the different size of PSp and PSs sensors. On Fig. 38b a detailed CAD representation of the final position of this pin is shown.
5. Once the positions of the mobile pins have been set that are fixed with 2 M3 screws each one directly on the main jig plate



(a)



(b)

Figure 38: a) 3D rendering of the calibrated position of a mobile pin on the long side of the sensors, the extruded part of the mobile pine in order to avoid the contact with MPA is clearly visible; b) 3D rendering of the calibrated position of the mobile pin on the short side of the sensors, the shift with respect to the flat head pin is clearly visible

A.4.2 Spacers Holding Jig

This jig is composed by a single Aluminum plate milled in order to have a single vacuum chamber to keep all the four spacers in position and four step for each spacer to align them. A 3D rendering of the jig is shown on Fig. 39. Two bigger holes are present on two opposite corners, their function is to match two pins in the main Jig in order to perform a relative alignment between the MaPSA and the spacers. The principle of this coupling is represented in Fig. 40.

A.4.3 Baseplate Gluing Jig

The Baseplate Gluing Jig, Fig. 41, is composed by an Aluminum plate with three flat head short pins and two long pins. The first three are used to place in position the sensors sandwich by touching the PSs sensors edges, their height should not exceed the MPA chip height and can be tuned via grub screws (one for each pin) from the backside of the plate. The other two pins will go through two inserts of

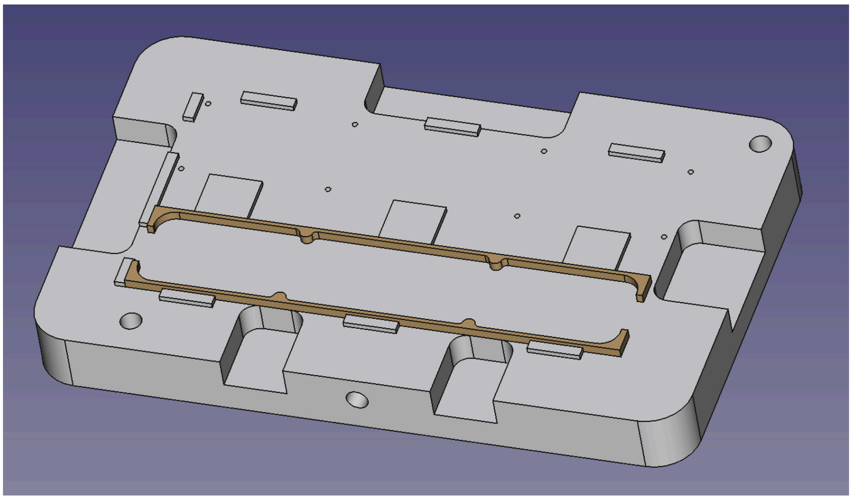


Figure 39: CAD 3D rendering of the spacers holding jig, two out of four spacers are added in order to show the way they are placed on the jig.

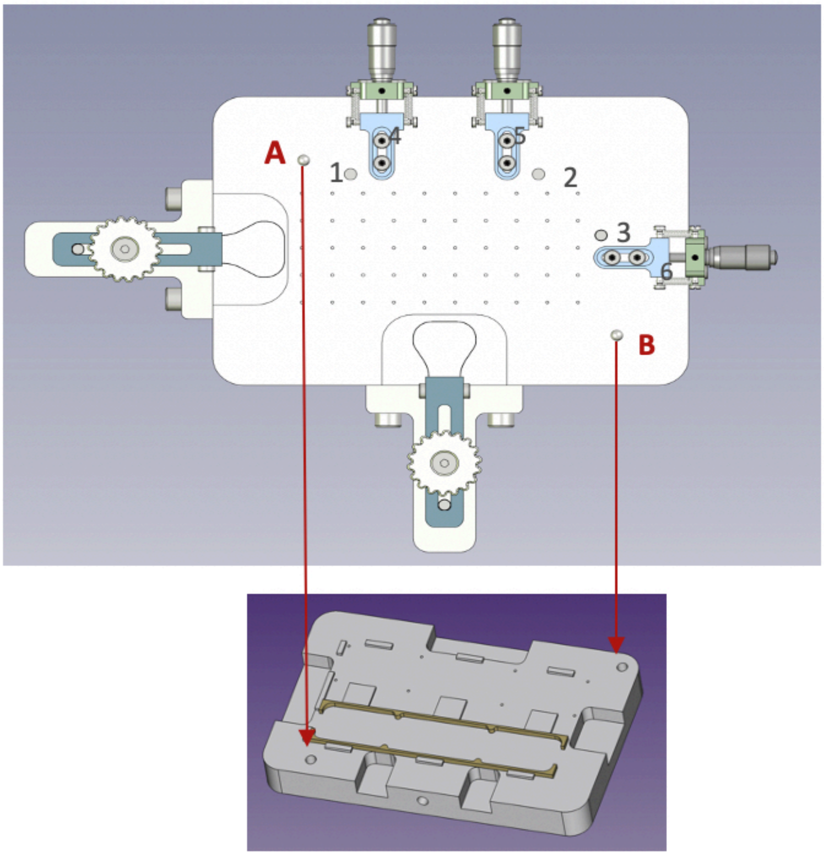


Figure 40: Schematic 3D rendering representation of the alignment principle between the MaPSA holding jig and the spacers holding jig.

the baseplate, in this way the relative alignment between the sensors sandwich and the baseplate is constraint by the relative position of this pins. Two pushers, made

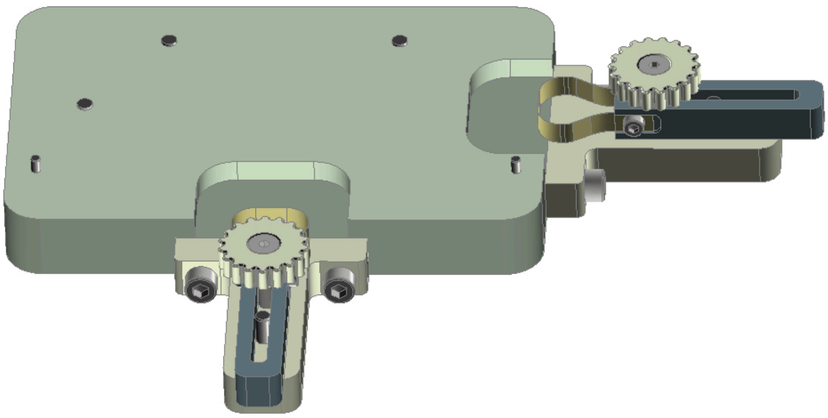


Figure 41: Schematic 3D rendering representation of the alignment principle between the MaPSA holding jig and the spacers holding jig.

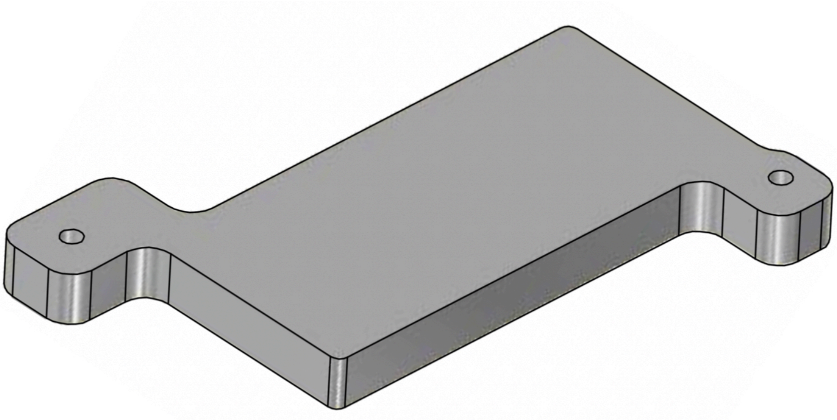
of 3D printed plastic components, are added in order to press the sensors sandwich against the alignment pins. Springs are made of $150\mu m$ Kapton strips.

A.4.4 Weights

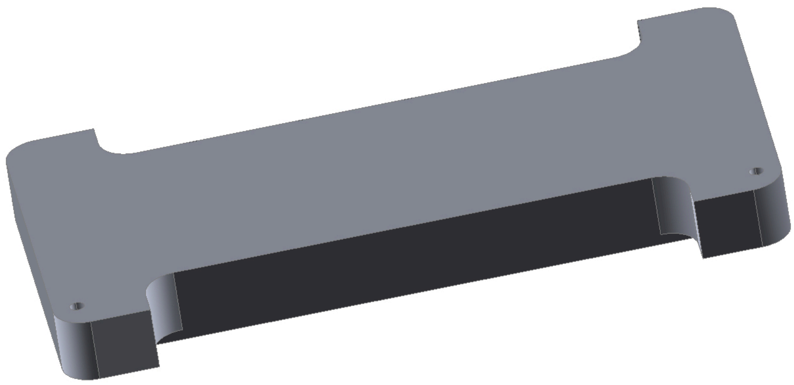
Also two weights are used in the sensors sandwich assembly. One is used to press the PSs sensor on top of MaPSA+spacers, Fig. 42a, while the other is used to press the baseplate on top of the sensors sandwich, Fig. 42b. Both weights are simple Aluminum plates with two holes on each one which will accommodate pins on the jig where they need to be placed.

A.4.5 Sensor Handling Tool

During the jig based sensors sandwich procedure all the sensor movements are performed with the help of a sensor handling tool. This tool is made by an Aluminum vacuum chamber with four suction cups, these cups are made of ESD plastic material. On Fig. 43a a 3D rendering of the tool is shown, the numbers indicate the different components of the tool itself. On Fig. 43b a picture of a real handling tool is shown.

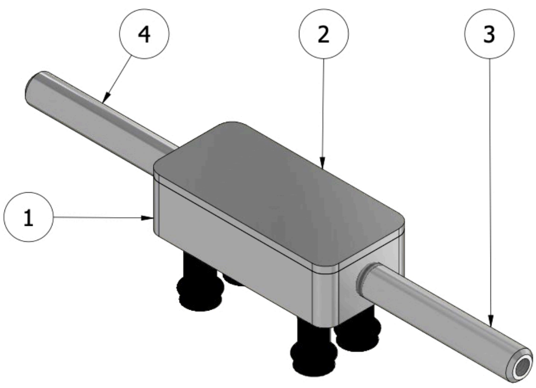


(a)



(b)

Figure 42: a) Weight used to press PSs sensor against MaPSA+spacers; b) Weight used to press baseplate against sensors sandwich



(a)

(b)

Figure 43: a) CAD 3D rendering of the sensor handling tool: 1) vacuum chamber with suction cups on bottom 2) vacuum chamber lid 3) and 4) handles; b) Picture of a produced sensor handling tool

A.5 PS automated assembly setup

This section describes the hardware and software setups of the automated assembly system, and the corresponding calibration procedures.

A.5.1 Hardware setup

The hardware setup consists of three subsystems, namely the motion, handling, and vision subsystems. It is installed on top of a vibration-damping table whose stainless-steel surface includes a grid of mounting holes. Figure 44 illustrates the hardware setup and indicates the (x, y, z, α) coordinate system of the motion system, which is henceforth referred to as the laboratory frame. This setup is flexible and easily adaptable to meet evolving requirements and integrate improvements during the R&D phase.

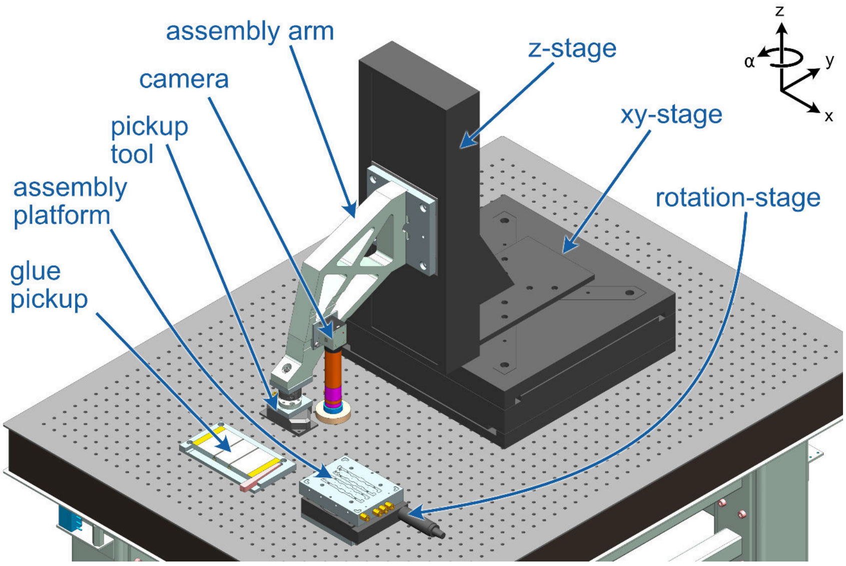


Figure 44: CAD image of the hardware setup of the automated assembly system. The motion (XYZ and rotation stages), handling (assembly platform, arm, pickup tool), and vision (camera) subsystems are indicated. The controlling hardware, vacuum tubing, and power supply cables are not shown. The purpose of the glue pickup blocks is explained in AppendixA.5.2.

The motion system performs the necessary movements to arrange the components constituting the sensor sandwich. It comprises two independent motorized parts, referred to as motion stages: a multi-axes translation stage (referred to as XYZ stage) capable of moving along the x, y, and z axes with a precision of 2.5 μm, and a rotation stage capable of rotating with a precision of about 175 μrad. All motion hardware is manufactured by Walter Uhl technische Mikroskopie GmbH & Co. KG [13, 14, 15] and controlled by a 4-axes control unit produced by LANG GmbH & Co. KG [16].

The handling system enables the accurate and safe manipulation of SSBA components. It consists of a vacuum subsystem, and two handling units referred to as the assembly platform and the pickup tool, respectively. Vacuum is used to hold the components in place. It is generated by a single vacuum pump and distributed to the handling units in two independent via plastic tubing and air-tight connectors. The individual vacuum lines are controlled by electromagnetic valves on a manifold that are in turn controlled by a USB relay card connected to the computer. Mounted on top of the rotation stage is the assembly platform, on which the different components are positioned and assembled. A CAD image of the assembly platform is shown in Figure 45. Several features are machined into this aluminum platform, which allow for the precise manual positioning of the spacers and baseplate. This platform includes two independent networks of vacuum inlets, outlets, and connecting vacuum channels to independently hold the spacers and the baseplate in place during the assembly process. The ability to rotate components on the assembly platform with high precision is essential to achieve the target angular alignment between the sensors. The pickup tool serves to lift up and move components. It consists of an ESD plastic block [17] housing an inner vacuum chamber providing vacuum suction through an array of holes at the bottom surface. The pickup tool is mounted at the end of a custom-built aluminum arm attached to the XYZ stage, using a ball joint. This ball joint makes it possible to adjust the pickup tool position such that its bottom surface rests flat against the assembly platform.

The vision system allows for the acquisition of high-resolution images. Upon processing the images with the pattern recognition algorithm described in Appendix A.5.3, the real-time position and orientation of a sensor may be inferred. This information is used to calculate the movements of the XYZ and rotation stages necessary to align components. The vision system consists of a high-resolution camera with a microscope lens mounted on the arm and facing the assembly platform. The camera is equipped with a low-power ring light to guarantee stable lighting conditions when acquiring images.

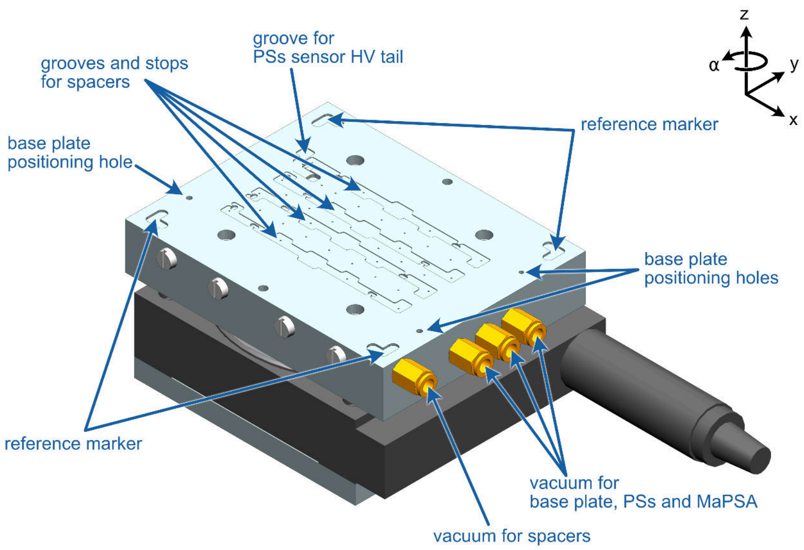


Figure 45: CAD image of the assembly platform.

A.5.2 Auxiliary tools and gluing of SSBA components

The SSBA components are attached to each other via adhesive bonding. Intercomponent alignment must remain stable after assembly and during the module's lifetime within the CMS tracker environment. The glue that is employed must therefore be radiation-hard and provide sufficient bonding strength over a wide range of temperatures. These requirements are satisfied by Polytec EP 601-LV [5], a low-viscosity two-components epoxy adhesive having a minimum curing time of 16 hours at 23°C (hereinafter referred to as "slow glue"). However, because the automated assembly procedure is sequential, this long curing time would greatly limit its throughput. Therefore, the layer of slow glue is complemented by a small amount of Loctite EA 3430 [18], a fast-curing medium-viscosity two-components epoxy ("fast glue") that must be applied within ten minutes after mixing. Slow and fast glue layers are always dispensed together, with specific patterns such that they do not overlap. The slow glue covers more than 99% (95%) of the surface area when gluing the sensor-to-spacer (sensor-to-baseplate) sub-assembly, and hence the properties of the glue layers after curing correspond to those of the slow glue. Once mixed, the fast glue layer develops sufficient bonding strength between components within 20 minutes, after which components can be manipulated to proceed with the assembly procedure.

Stainless-steel glue pickup blocks are used in two separate steps during the assembly sequence, to dispense the two different glues on the top and bottom surfaces of the spacers, respectively. Figure 46 shows the CAD image of the glue pickup blocks and an illustration of their working principle. In a first step, the blocks are combined depending on whether they are intended to be covered in slow or fast glue, and the corresponding glue layers are dispensed separately. Kapton tape strips with a thickness of 50 μm at the sides ensure that uniform layers of glue with a well defined thickness are produced when the glues are squeegeed on the top surfaces of each arrangement of blocks. In a second step the blocks covered with a layer of either slow or fast glue are rearranged to form three areas with a layer of slow glue interspersed with narrow strips of fast glue. The blocks are machined such that there is a 1 mm gap between the glue layer, which ensures that both types of glues do not get in contact with each other. Finally the spacers are dipped into the glue layers.

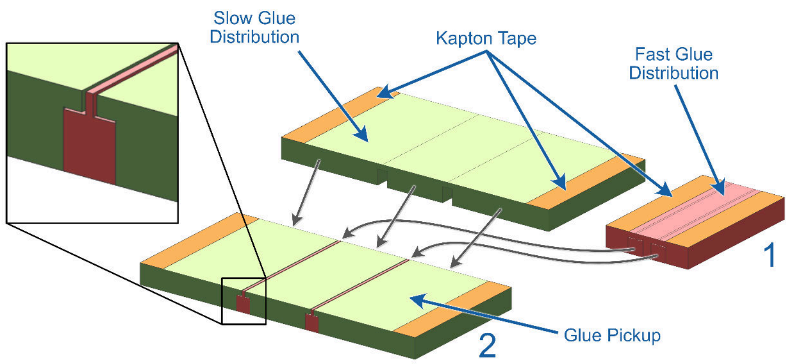


Figure 46: CAD images of the glue pickup blocks and illustration of their working principle.

A.5.3 Software and basic operations

The motion, handling, and vision hardware systems are connected to a computer via USB and controlled via a custom software application written in C++ and exploiting the `Qt` [19] framework and `openCV` [20] libraries. The GUI allows the user to command all relevant operations. This includes the following main features:

- *Motion stage movements* The XYZ and rotation stages can be moved by absolute or relative distances within their allowed boundaries. All movements performed during assembly are preprogrammed and accessible via dedicated buttons.
- *Image acquisition* Camera images can be acquired and visualized in real time. The raw pixels of a given camera image are first converted from colors to gray shades described by numbers ranging from 0 (black) to 255 (white); the color information is irrelevant for the pattern recognition and is disregarded. The grayscale image is then converted to black-and-white according to a configurable threshold value, which can be tuned to optimize the brightness and contrast while minimizing noise. Images may be navigated using the mouse pointer to update the camera position interactively.
- *Best focus* An algorithm finds the height (along z) for which the camera is best focused on an object. It relies on the `Laplacian` function of the `openCV` libraries to quantify the blurriness of an image. This algorithm is run in steps along the z axis. Its results are displayed in the GUI, and the camera is automatically moved to the best-focus height.
- *Pattern recognition* The pattern recognition algorithm uses the `matchTemplate` function of the `openCV` library to find the best-match (x, y, α) coordinates of a fiducial marker within a camera image.
- *Alignment* The alignment algorithm starts with the pattern recognitions of two fiducial markers opposite along x. Next, the assembly platform is rotated accordingly to align the sensor with the laboratory frame. This routine is repeated until the measured rotation angle becomes smaller than the precision of the rotation stage.
- *Vacuum* The vacuum networks connected to the pickup tool and assembly platform are controlled via the GUI.
- *Pickup and setdown* Once a component is on the assembly platform and its position is known (via pattern recognition for sensors, or using dedicated physical features of the platform for spacers and baseplate), vacuum is activated below the component to hold it in place. Next, the arm is lowered onto the platform (accounting for the predefined thickness of the component), the pickup tool's vacuum line is switched on and that of the assembly platform is switched off, and the arm is lifted up. The same pickup routine, when performed in reverse order, is used to set components down on the assembly platform.

All assembly steps involving the hardware system are fully automated as a sequential list of preprogrammed buttons in the GUI. Additional software functionalities include calibration routines, and the automatic logging of timestamps and relevant quantities into a log file that may be uploaded to a central production database.

A.5.4 Calibrations

The automated assembly procedure relies on several predefined movements and parameters, which must be determined beforehand ("calibrated"). Recalibrations of these quantities may be needed when modifying hardware subsystems, when updating the designs of SSBA components, or in case an incident disturbed the setup. This section describes the procedures that are performed to calibrate the entire setup.

- *Ball joint* The ball joint mechanism attached to the end of the robot arm makes it possible to adjust the mounting angle of the pickup tool, such that it rests flat against the surface of the assembly platform and applies uniform downwards pressure. For this calibration, the ball joint screws fixing the orientation of the pickup tool are loosened, and the pickup tool is lowered onto the assembly platform. Once it is sufficiently close to the surface, the screws are tightened again.
- *Camera angle in the laboratory frame* In order to relate camera images with motion stage movements, it is necessary to account for the angle between the reference frame of the camera and the laboratory frame. The pattern recognition routine is first run on two fiducial markers opposite along x; the corresponding motion stage positions and best-match coordinates of the fiducial markers in the camera images are saved. Two different values are then computed: first, the two best-match angles are averaged, and the resulting angle indicates the orientation of the sensor within the laboratory frame. Second, the motion stage positions and best-match (x, y) coordinates of the fiducial markers in the camera images are used to compute the orientation of the sensor in the camera frame. If the two values are different, the latter is recomputed after accounting for an offset angle of the camera frame. This procedure stops once both values are identical, i.e., once the sensor orientation is the same in the laboratory and camera frames.
- *Assembly platform orientation and reference point* Similarly, to align the assembly platform with the laboratory frame, the (x, y) coordinates of a reference marker machined into the assembly platform (see Figure 45) are determined using the camera. Next, the camera is moved along the x axis by the design distance separating that reference feature from a second, similar feature. If the assembly platform has the correct orientation, the camera image is perfectly centered on the second feature; otherwise, the orientation of the assembly platform is corrected accordingly and the procedure is repeated. Typically, up to two iterations are necessary to correct the orientation of the platform.
- *Focus heights* The best-focus heights of the camera on the assembly platform and the glue pickup blocks are simply determined by running the best-focus algorithm on camera images of their surfaces. The uncertainties on these calibrations constants is of about 5 μm, as evaluated by repeating the procedure several times.
- *Pickup height* Starting from the best-focus height of the camera on the assembly platform, the movement along z that must be performed to make contact with an object on the assembly platform must be determined. This calibration is done with the so-called "multi-pickup" routine, which consists in the following steps: the pattern recognition algorithm is run on the reference fiducial marker of a sensor; the pickup and setdown routines are performed, using a

user-defined distance along z; the pattern recognition algorithm is then run again on the same marker. This entire procedure is automatically repeated several times, and all pattern recognition results are compared. If the pickup position is perfectly calibrated, the results should all be identical, indicating that the position of the object was not disturbed by the pickup and setdown routines. Otherwise, the entire procedure is repeated changing incrementally the movement performed along z, until satisfying results are obtained.

A.6 Hybrid gluing jig

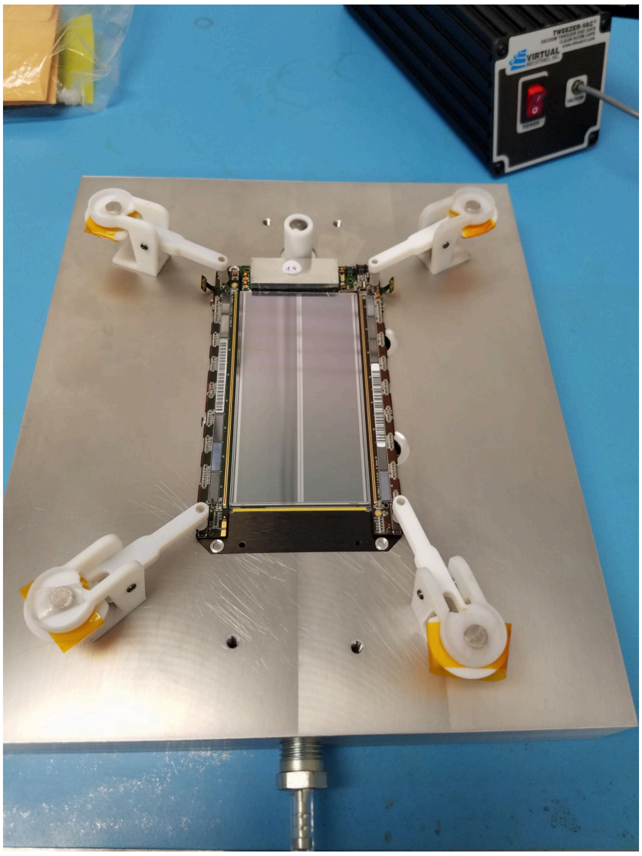


Figure 47: Prototype of hybrid gluing jig used for the assembly of a functional PS module.

Figure 47 shows a prototype of the PS hybrid gluing jig with a module in progress and four pushers attached The jig base is made of MIC-6 aluminum plate and has overall dimensions of 240mm x 200mm x 30mm. The jig base has an array of vacuum holes to hold the module in place during the hybrid gluing procedure. There are also a set of tapped holes to allow for fixing the module if the vacuum supply fails. The module is located on the jig base using three alignment pins with contact faces made of Delrin acetal plastic and bodies made of 52100 stainless steel. Nylon-tipped set screws are used to lock the module alignment pins into place on the jig base. The bodies of the module alignment pins have a flattened contact face to enable the set screws to make flush contact. The hybrids are located on the jig base using up to eight alignment pins made of 52100 alloy steel or M2 tool steel. The hybrids are held down during curing with magnetic pushers that are 3D-printed. The magnets used with the pushers are neodymium. The following is a list of parts including links to the drawings where applicable:

1× jig base

6× nylon-tipped set screw

1× barbed vacuum fitting

3× module alignment pin assembly

- 3× 12mm Delrin acetal resin sleeve, 20mm length
- 3× 8mm pin body with flat contact face, 40mm length

1× 0.9mm hybrid alignment pin, 16mm length

5× 1.0mm hybrid alignment pin, 16mm length

1× 1.2mm hybrid alignment pin, 16mm length

1× 1.3mm hybrid alignment pin, 16mm length

8× magnetic pusher assembly

- 1× pusher base
- 1× pusher arm
- 1× pusher tip
- 2× neodymium magnet
- 1× M4 machine screw

A.7 Wire bonding jigs

A.8 Encapsulation adapting plate

Figure 48 shows that the encapsulation adapting plate comes with four pins and will be mounted on the stage. The four pins are designed to nicely constrain the movement of a module during encapsulation process. Figure 49 shows how a module will be mounted for encapsulating wire-bonds on PS-s and PS-p sides.

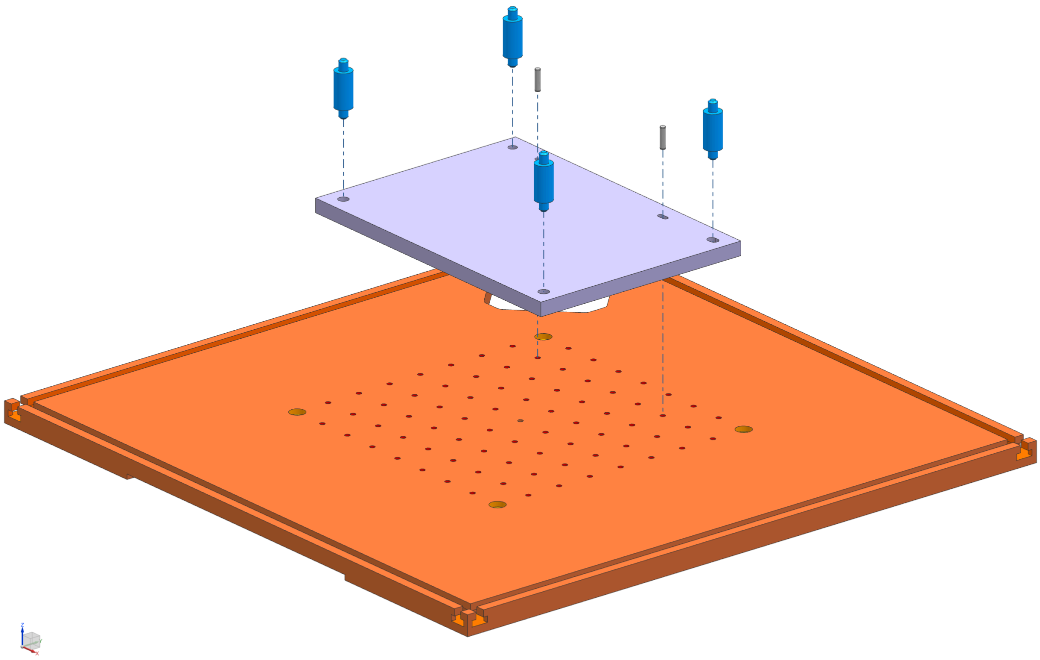


Figure 48: The adaptor plate for mounting a module carrier to encapsulation robot stage.

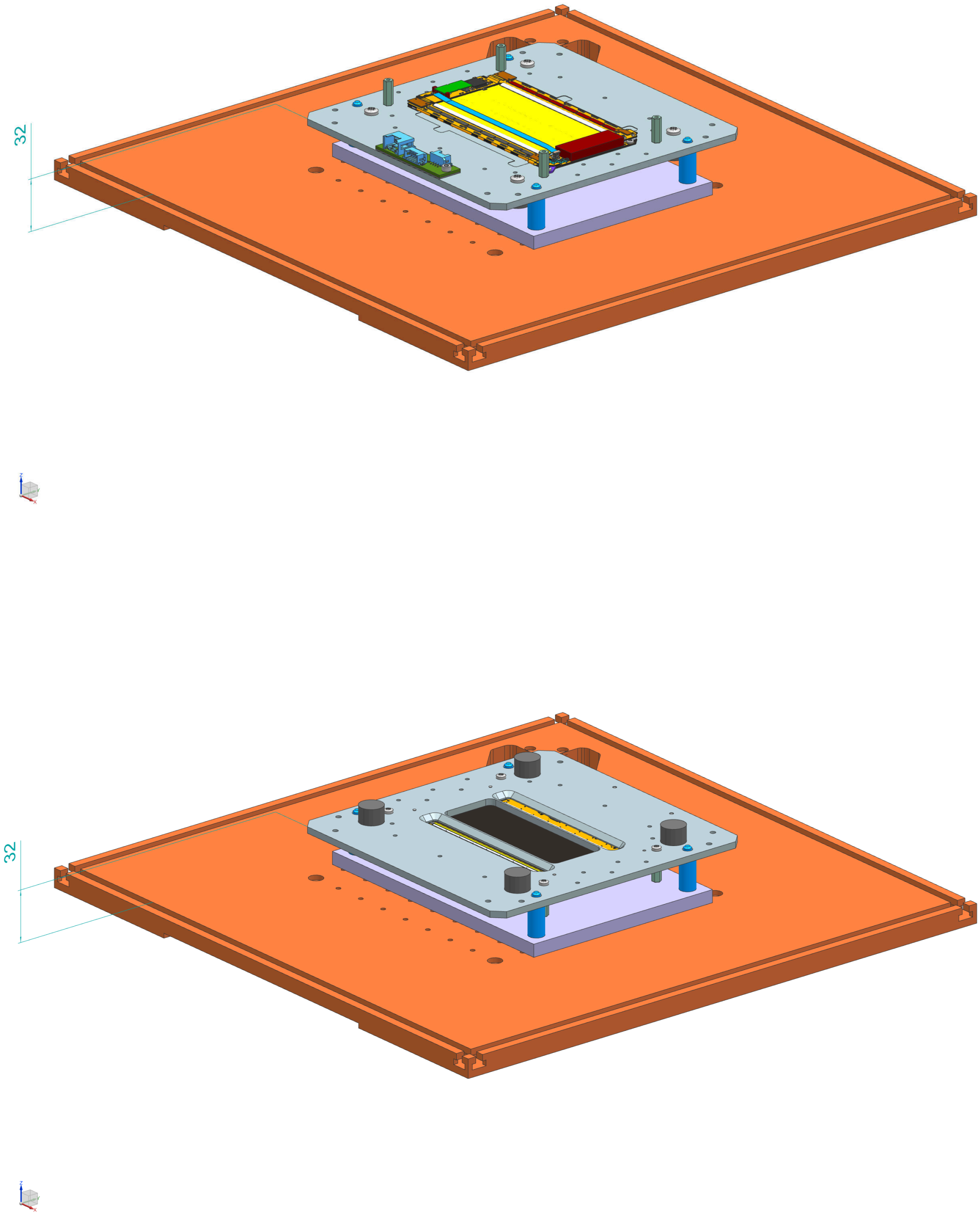


Figure 49: PS module carrier mounted on the robot stage. On the left is the arrangement of the module for encapsulating wire-bonds on the PS-s side and on the right is the arrangement for PS-p side.

A.9 PS Module Carrier

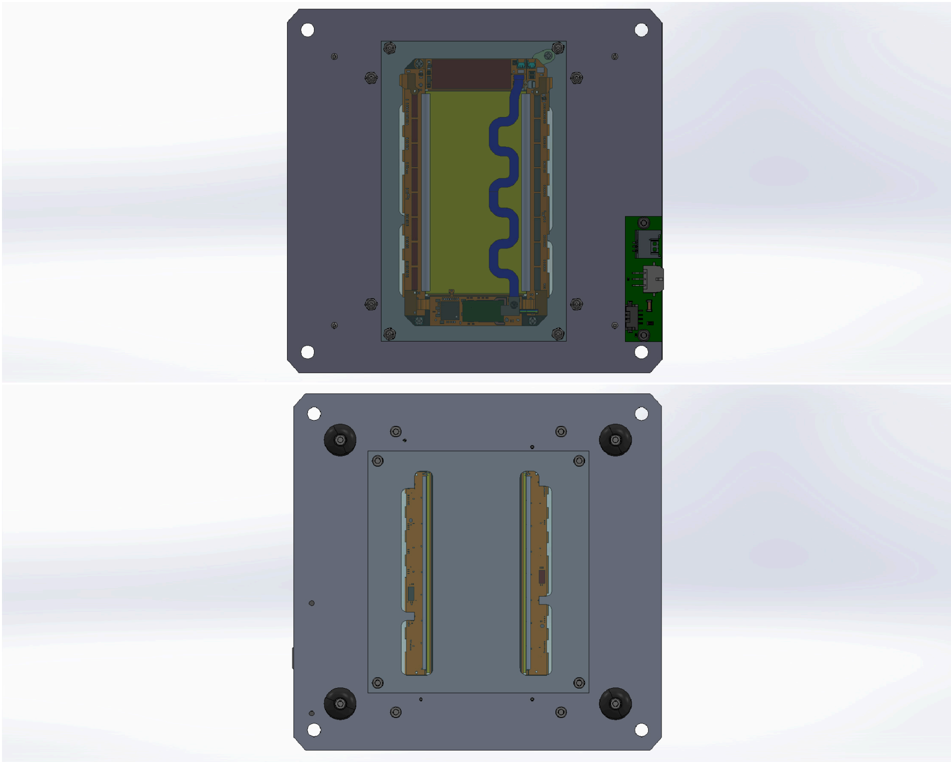


Figure 50: CAD generated views of a PS module carrier.

Figure 50 shows a model of the PS module carrier with the top and bottom protective covers made transparent. This module carrier is designed to be used with the same burn-in box setup as the 2S module carrier. The overall carrier dimensions are 182.5mm x 176.6mm x 29.5mm. The carrier plate on which the module is mounted is made from MIC-6 aluminum plate and measures 182.5mm x 176.6mm x 4.06mm. The top protective cover is made from acrylic and measures 90mm x 146mm x 3.175mm. The bottom protective cover is made from acrylic and measures 110mm x 120mm x 3.175mm. An aluminum shim clamp of 8mm x 6.35mm x 0.8mm is mounted onto the carrier plate that allows for fixing the PS module in the corner that does not have a fixation hole. The following is a list of parts for a PS module carrier:

- 1× carrier plate
- 1× top protective cover
- 1× bottom protective cover
- 4× M2 x 0.4mm machine screw, 5mm length, McMaster-Carr p/n 92005A019
- 1× aluminum shim clamp
- 4× Rubber foot, 15.875mm OD, 9.525mm height, McMaster-Carr p/n 9540K869
- 4× M3 x 0.35mm machine screw, 12mm length, McMaster-Carr p/n 90751A113
- 4× M3 x 0.5mm machine screw, 12mm length, McMaster-Carr p/n 91292A114
- 4× M3 x 0.5mm machine screw, 20mm length, McMaster-Carr p/n 91292A123

4× aluminum unthreaded spacer, 3.2mm ID, 8mm length, McMaster-Carr p/n 94669A103

8× M3 x 0.5mm nylon-insert locknut, 4mm height, McMaster-Carr p/n 93625A100

1× services board

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