Improving the assembly and metrology of the PS Modules for the CMS Phase-2 Tracker

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Abstract

The Silicon Tracker is the innermost sub-detector of CMS. It is built of thousands of silicon sensors that are used to reconstruct the trajectories of charged particles from LHC collisions. In the future, the LHC will be upgraded to the High-Luminsity LHC (HL-LHC). In order to cope with increased levels of both instantaneous and integrated luminosity expected during the HL-LHC, CMS will install a completely new tracking detector - the CMS Phase-2 Tracker. The DESY Tracker Upgrade group contributes to construct the new Outer Tracker. One of the activities of the group is the Pixel-Strip (PS) Module assembly. DESY will produce more than 1000 PS Modules. This report describes the improvements developed for two gluing steps of the PS module as well as a procedure (and related analysis software) to perform metrology on assembled PS prototypes. These procedures were successfully tested on multiple prototypes and represent a good starting point for further development of these aspects of the PS module assembly.

Contents

1. Introduction

1.1. The Large Hadron Collider

The Large Hadron Collider (LHC) is the largest and most powerful particle accelerator in the world [1]. It comprises of a 27-kilometre ring of superconducting magnets including many accelerating structures to increase the energy of the particles along the way. The LHC can accelerate different types of particle beams, leading to different collision events: these include proton-proton (p-p), lead ions (Pb-Pb) and protons on lead ions (p-Pb) collisions [2]. The beams inside the LHC collide at 4 locations around the accelerator ring, corresponding to the positions of 4 particle detectors - ATLAS, CMS, ALICE and LHCb. Figure 1 shows an aerial view of the LHC site with major CERN installations.

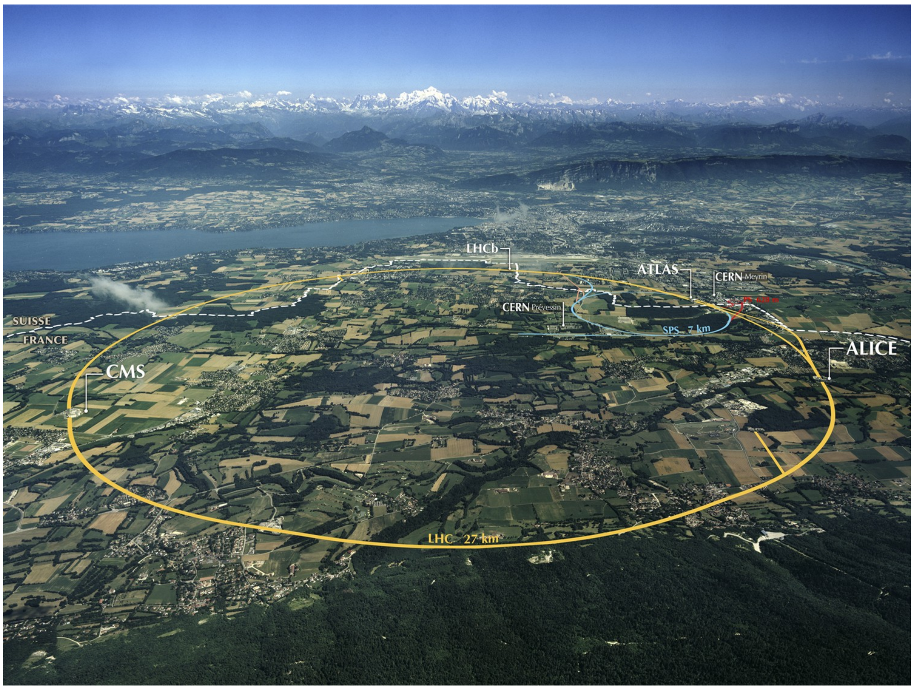

Figure 1: An aerial view of the LHC site, which straddles the border between France and Switzerland, with major CERN installations outlined and labeled [3].

1.2. The High-Luminosity Large Hadron Collider

The High-Luminosity Large Hadron Collider (HL-LHC) project aims to expand the performance of the LHC in order to boost the number of collisions [4]. The increased amount of events will be used by experiment to improve the measurements and expand the potential for discoveries. The objective is to increase luminosity by a factor of 7 beyond the LHC's design value.

Luminosity is a crucial factor of the performance of an accelerator [4]. It is proportional to the number of events detected in a certain time. The higher the luminosity, the more data the experiments can accumulate to enable them to observe rare processes. With the current capabilities of the LHC, the collision rate of p-p collisions increased steadily, with instantaneous luminosity of up to $2.14 \cdot 10^{34}$ cm^{-2} s^{-1} in 2018, which exceeded the LHCs initial design luminosity value of $1.00 \cdot 10^{34}$ cm^{-2} s^{-1} [2]. The HL-LHC will be upgraded to deliver an instantaneous luminosity up to $7.00 \cdot 10^{34}$ cm^{-2} s^{-1}. The integrated luminosity of the LHC equaled 150 fb^{-1} at the end of Run 2 in 2018 and it should gain up to 300 fb^{-1} at the end of Run 3 in 2023 [5]. The HL-LHC will be upgraded in 2024 and the experiment will start recording data in 2026 in order to enable integrated luminosity up to 4000 fb^{-1}.

1.3. The Compact Muon Solenoid

The Compact Muon Solenoid (CMS) is a general-purpose detector at the LHC [6]. It has a wide physics programme aiming to study the Standard Model (including the Higgs boson) and search for evidence of new physics phenomena.

The CMS detector is built around a super-conducting magnet that can generate a magnetic field of 4 Tesla [6]. It is 21 meters long, 15 meters high and weighs 14,000 tons. CMS consists of various sub-detectors that exploit the properties of particles in order to catch and measure the energy and momentum of each one [7]. The sub-detectors are located on a circular plan about the collision point and composed of the following parts: Silicon Tracker, Electromagnetic Calorimeter, Hadron Calorimeter and Muon Chambers. Figure 2 shows the CMS detector including its various layers. The work described in this report relates to the Silicon Tracker, which is the innermost sub-detector of CMS. For a detailed description of this and other sub-detectors, the interested readers are referred to [8] and references therein.

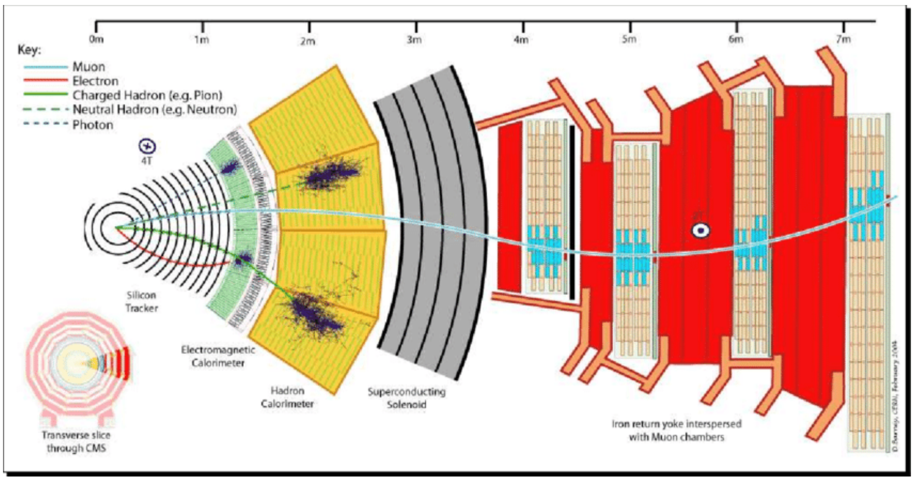

Figure 2: A transverse slice through one segment of the CMS detector [9].

1.4. The CMS Tracker

The CMS experiment has to very accurately identify the trajectories of charged particles [10]. An accurate measurement of the particle trajectory in the CMS magnetic field can be used to determine the particle's momentum. The CMS Silicon Tracker records the paths taken by charged particles by finding their positions at several key points. It can reconstruct the paths of high-energy muons, electrons and hadrons as well as see tracks coming from the decay of very short-lived particles.

The CMS Tracker is built of thousands of silicon sensors that are used to reconstruct the trajectories of charged particles from LHC collisions [10]. It works through the mechanism of a semiconductor, so if a charged particle hits the detector, its path can be identified. When particles fly through the CMS Tracker, sensors generate small electric signals that are amplified and detected. Figure 3 includes a picture of part of the current CMS Tracker.

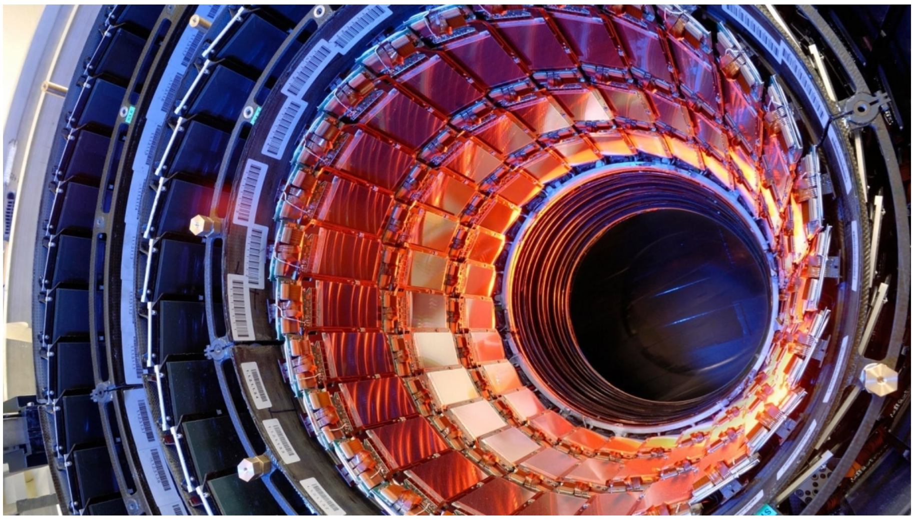

Figure 3: The CMS Tracker consists of silicon sensors [10].

The CMS detector will undergo several upgrades in order to cope with the more challenging data-taking conditions expected during the HL-LHC. [2]. A new tracking system, the CMS Phase-2 Tracker, will be installed for the HL-LHC. With respect to the current tracking detector, the new tracker will provide increased radiation tolerance, higher granularity and larger η-coverage, and will provide inputs to the Level-1 Trigger. It will be built of 2 parts: the Inner Tracker and the Outer Tracker. The DESY Tracker Upgrade group contributes to construct the new Outer Tracker. Two types of modules will be used in the Phase-2 Outer Tracker: Pixel-Strip (PS) Modules and Strip-Strip (2S) Modules. Figure 4 shows the layout of one quarter of the Phase-2 Outer Tracker, with PS Modules in blue and 2S Modules in orange. The work described in this report centers on the assembly of PS Modules.

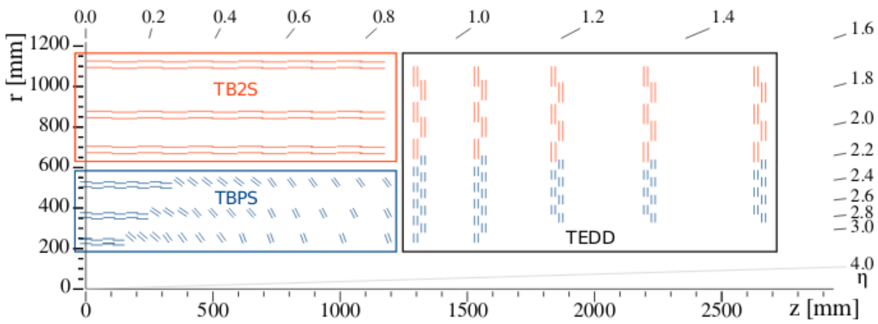

Figure 4: A layout of one quarter of the Phase-2 Outer Tracker. Blue lines represent PS Modules and orange lines - 2S Modules [2].

1.5. The Pixel Strip Module

An important characteristic of the Outer Tracker modules is their 2-sensors design [2]. The two silicon sensors will be assembled in a sandwich configuration and this will make it possible to perform the local reconstruction of high-pT tracks by correlating signals from 2 sensors. This concept is illustrated in Figure 5. If a particle hits the bottom sensor and then hits the top sensor inside a narrow selection window, it means that its transverse momentum is high. High-pT stubs can thus be selected and this information from the tracker can be used in the online reconstruction (Level-1 Trigger).

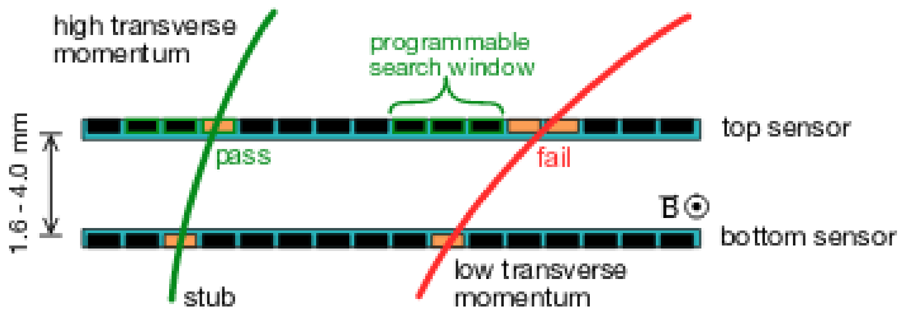

Figure 5: Illustration of the stub mechanism in the PS Module volume. The green and red lines represent the momentum of a particle, whereas the green channels show the selection window to define an accepted stub [2].

The PS Module will be comprised of 2 silicon sensors (1 Pixel, 1 Strip) with dimensions of approximately $10 \cdot 5$ cm^2 each and a thickness of 200 um [2]. The sensors have to be very precisely assembled on top of each other in a sandwich configuration separated by 2 spacers - maximal allowed rotational misalignment is < 800 urad. The module made this way will be placed onto baseplate with kapton foil and attached to readout electronics. The PS Module assembly is one of the activities of the DESY Tracker Upgrade group.

DESY will produce more than 1000 PS Modules. Currently the project is focused on the development of an assembly procedure using the following parts of the PS Module: baseplate, kapton foil, 2 glasses (instead of silicon sensors) and 2 spacers. Figure 6 shows an exploded view of the PS Module design with a circled parts that DESY group is currently working on.

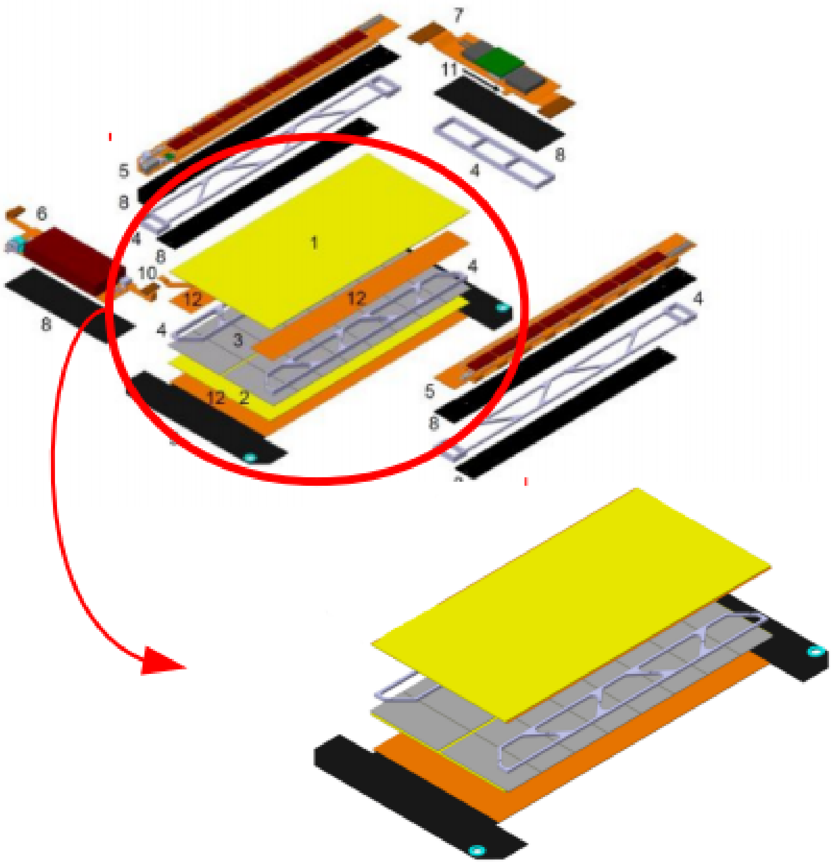

Figure 6: An exploded view of the PS Module design. The circle indicates the assembly used in the work described in this report: baseplate, kapton foil, 2 glasses (instead of silicon sensors) and 2 spacers [2].

2. PS Module assembly

In this section the baseplate+kapton and baseplate+sensors gluing steps are briefly discussed. The full documentation for the PS Module assembly including preparation, dispensing the glue and squeegeeing procedures can be found in the Appendices A.

2.1. Baseplate+kapton gluing

One of the first steps of the PS Module assembly is baseplate+kapton gluing. The PS Module will be attached to a baseplate made of carbon fiber reinforced polymer in order to support the structure (see Figure 7). A kapton foil (thick.: 25 um) on the baseplate is necessary to electrically isolate the baseplate from the PS-p sensor (the bottom one).

The motivation of this step was to develop a procedure to glue kapton foil to baseplate and perform this step in the reproducible way. Due to the above, the automatic dispenser (see Figure 8) was used to dispense the glue on baseplate. The glue mixture (Polytec EP 601 LV) was made of 2 components. A needle with a diameter of 0,11 mm and the pressure of 7 bars were used. A program to operate the automatic dispenser was developed and different patterns to dispense the glue were tested. After tests, the best configuration which was one 7,5 cm line in the middle was picked and it gave 30-40 mg of the glue.

Figure 7: CFRP baseplate.

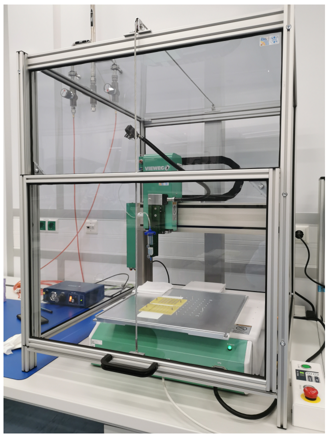

Figure 8: The automatic dispenser.

Considering this step, two important factors have to be accounted. First one is modification of the dispensing velocity regarding time passed after mixing the glue. The goal was to have constant amount of the glue. Figure 9 shows dependence between mass of the glue and time passed after mixing. Red points represent constant velocity (1.3 mm/s) and blue - adjusted velocity (from 1.3 mm/s to 0.7 mm/s with a step 0.1 mm/s after every 20 min). Both sets of data were fitted using different types of fits. A rule to adjust the dispensing velocity regarding time (for the first 2-3 hours after mixing the glue) was found.

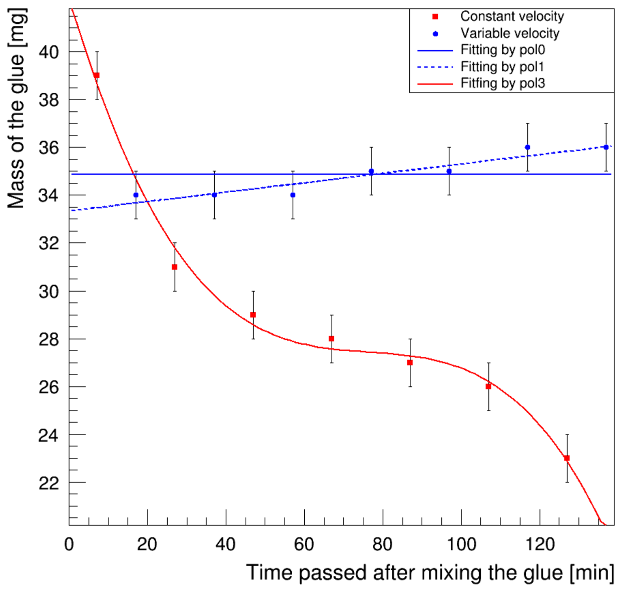

Figure 9: Dispensing velocity. Red points represent constant velocity and blue - adjusted velocity. Both sets of data were fitted using different types of fits.

Second important factor is a method of manually squeegeeing. After dispensing the glue, one has to put kapton foil manually onto baseplate and spread the glue around baseplate surface using squeegeeing tool. This part is crucial because improper squeegeeing can lead to appearance of air bubbles.

As a result of baseplate+kapton gluing tests, the procedure to dispense the glue was developed. 7 prototypes were glued using different methods and last 3 were without air bubbles. Figure 10 shows all glued baseplates. Next step of this part will be to improve the positioning of kapton on a baseplate that currently is being done manually.

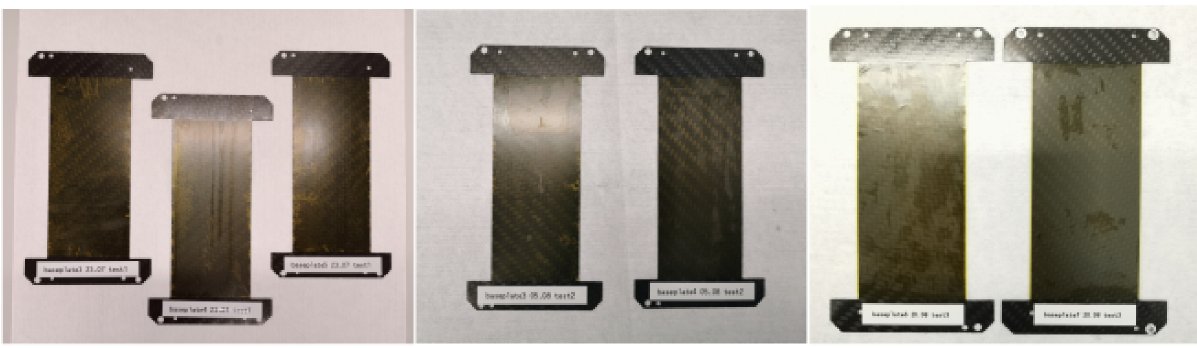

Figure 10: The images of all 7 glued baseplates.

2.2. Baseplate+sensors gluing

One of the following steps of the PS Module assembly is baseplate+sensors gluing. The goal was to develop a procedure to glue baseplate to sensors-sandwich obtaining thin glue layer with full coverage. Due to the above, a routine with the automatic dispenser was developed. The goal thickness of the glue layer was about 25 um and for that around 100 mg of the glue was needed. After tests, the best configuration which was one 8,5 cm line in the middle + 4 dots in the corners was picked. The chosen pattern was different than the one from baseplate+kapton gluing because instead of manually squeegeeing (to spread the glue around baseplate surface) the procedure was done by the assembly robot. Figure 11 shows the procedure of gluing baseplate to sensors-sandwich.

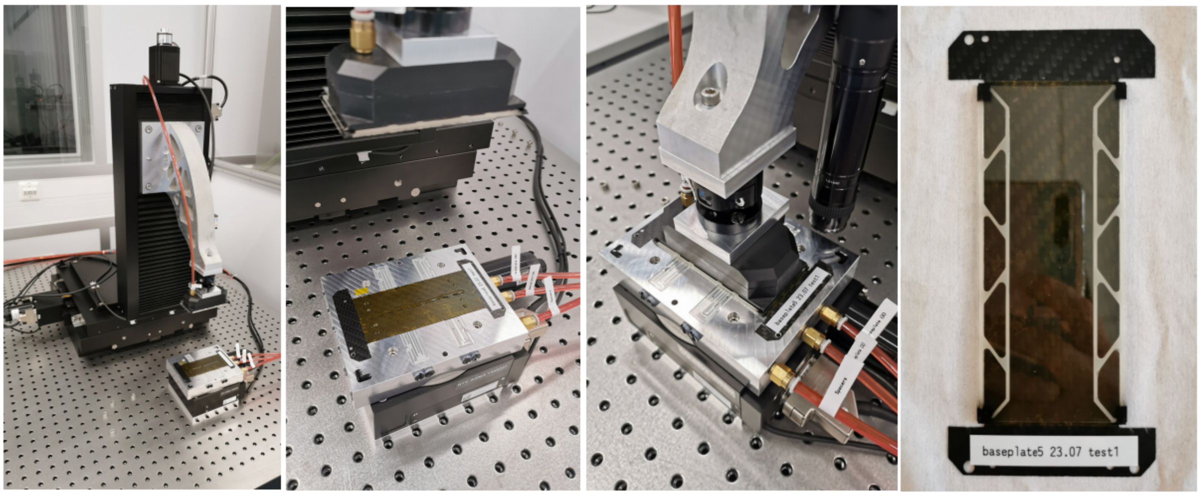

Figure 11: The procedure of gluing baseplate to sensors-sandwich. From left: the assembly robot; kapton+baseplate with the glue on top; gluing the parts together; assembled PS Module.

The procedure was successfully applied in the assembly of last the 2 mechanical PS prototypes (1 with 200um-thick glasses, 1 with 700um-thick glasses, shown in Figure 11). Both of them had good coverage of the glue layer, only limited amount of glue spilled onto the platform and there were just few small air bubbles between baseplate and glass. The next step of this part will be more testing (to avoid any spilling of glue or appearance of air bubbles) and measurement the thickness of the glue layer.

3. Metrology of assembled PS prototypes

The metrology measurement was done to verify if components of the PS Module prototypes had been positioned well. Each prototype has 2 glasses and each glass has 4 markers. For each marker one can measure the position of 6 corners. Figure 12 shows a sketch of a prototype with markers on the glasses.

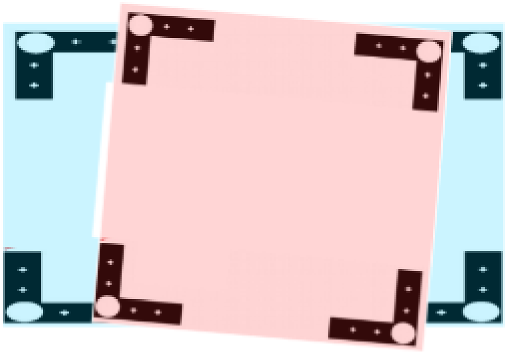

Figure 12: A sketch of a prototype. Blue rectangular represents bottom glass, red rectangular - top glass and black L-shape figures - markers.

The markers corners of 8 prototypes were measured using a microscope (see Figure 13) and 2 of them using SmartScope (to compare to microscope data). A rule to position and fix each prototype onto the microscope stage was developed to make this step reproducible (see Figure 14). The procedures to analyse microscope data (python, ROOT) including length, rectangularity and misalignment measurements were developed. The documentation for the PS Module metrology including preparation of the set up, routine of measurements and instruction for data analysis can be found in the Appendices B.

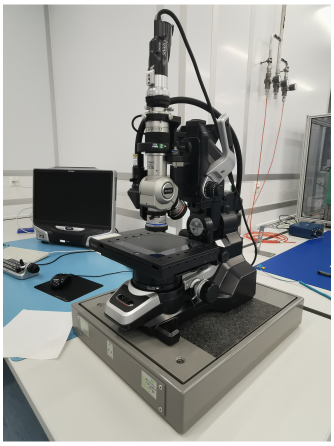

Figure 13: The microscope.

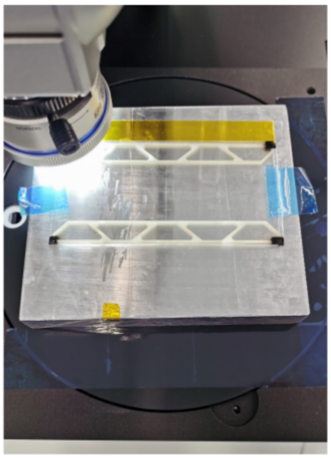

Figure 14: The microscope stage.

3.1. Length measurements

The length measurements were done to calculate the dimensions of the markers to verify if the glasses complied with the design. Figure 15 shows markers design that have following lengths: 700 um for the long side; 500 um for the medium side; 200 um for the short side. The markers dimensions of the 7 prototypes were measured using the microscope. The results are shown in Figures 16-18. In conclusion, for all the glasses the results are within design specification.

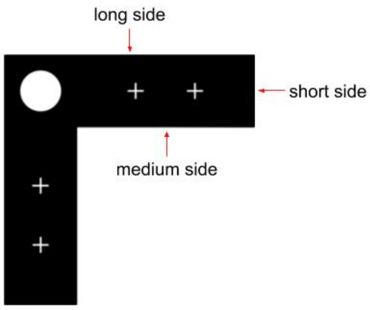

Figure 15: Markers design lengths: long side - 700 um; medium side - 500 um; short side - 200 um.

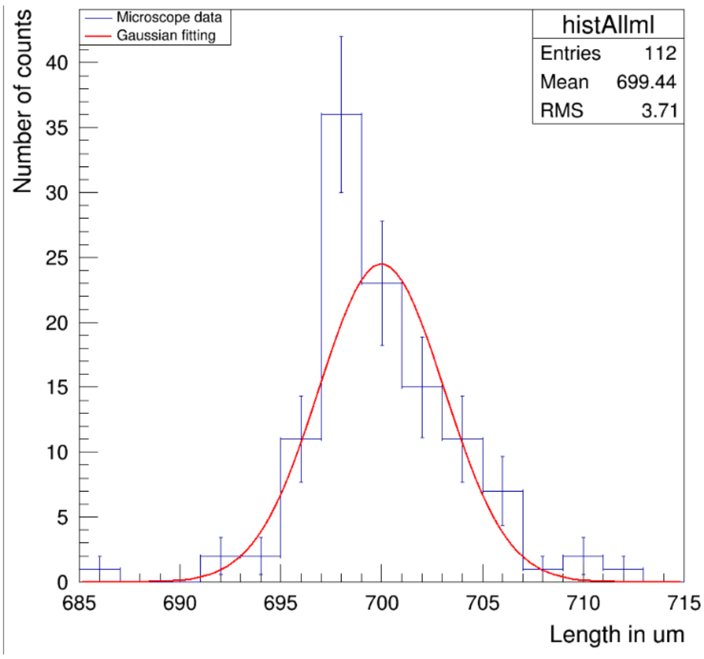

Figure 16: A histogram of markers long length of the 7 prototypes. The mean value with an error equals 699 $\pm$ 4 um.

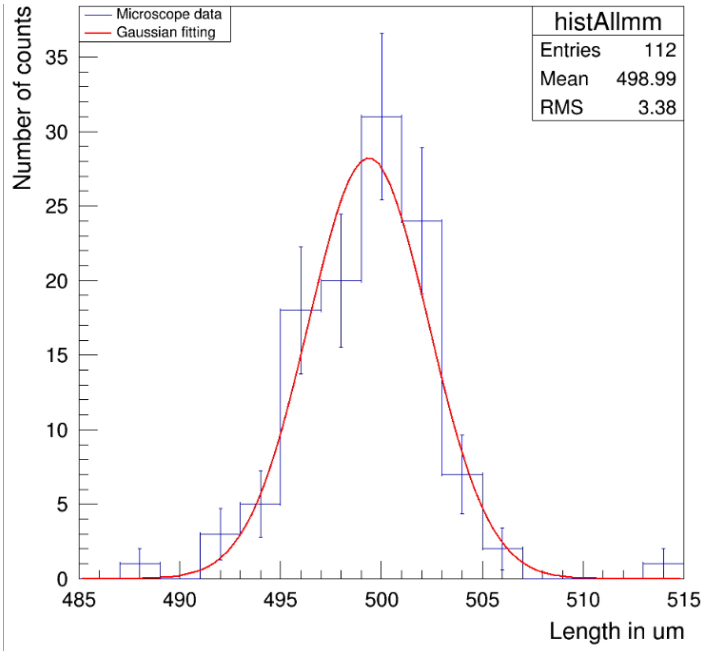

Figure 17: A histogram of markers medium length of the 7 prototypes. The mean value with an error equals 499 ± 3 um.

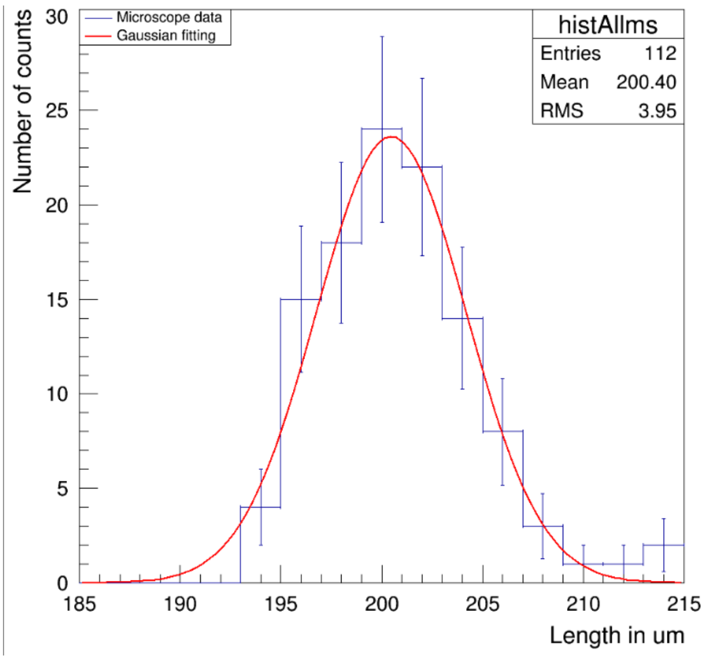

Figure 18: A histogram of markers short length of the 7 prototypes. The mean value with an error equals 200 ± 4 um.

3.2. Rectangularity measurements

The rectangularity measurements were done to verify if angles between markers equal 90 degrees with the tolerance of 0,045 degrees. As it was mentioned, each glass has 4 markers and for each marker one can measure the position of 6 corners, which gives 24 independent points for each glass. The angles between 3 independent points for one glass can be calculated, which gives 8 different sets of data for one glass and 16 different sets of data for one prototype.

Due to the above, a program to calculate these angles was developed. After the measurement of 7 prototypes a histogram of rectangularity was made, which is shown in Figure 19. The mean value with an error equals 90,00 ± 0,01 degrees. The result is in a very good agreement with the requirements and an error is significantly smaller than the tolerance of 0,045 degrees. In conclusion, all the markers were positioned well.

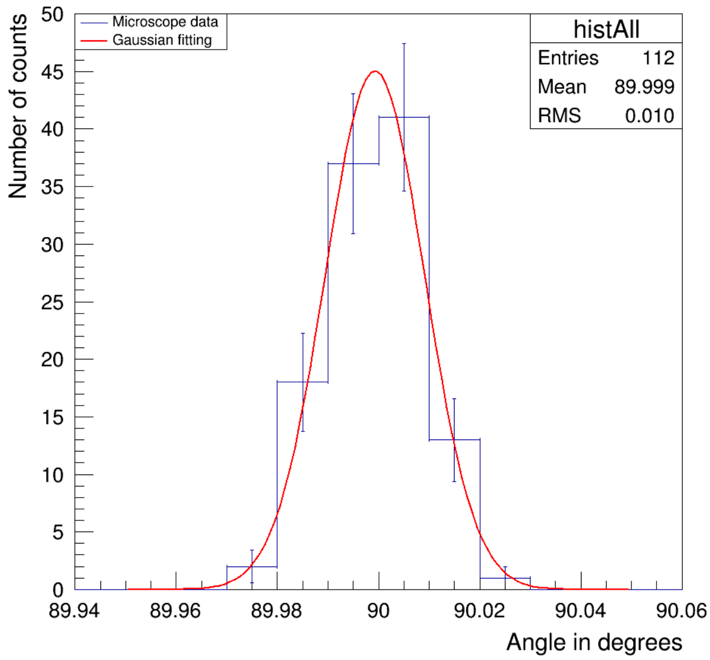

Figure 19: A histogram of rectangularity from the measurement of 7 prototypes. The mean value with an error equals 90,00 ± 0,01 degrees.

3.3. Misalignment measurements

The misalignment measurements were the most crucial from the metrology. They were done to verify if glasses of the PS Module prototypes are assembled well. As it was mentioned, each glass has 24 independent points. The misalignment between 2 glasses can be calculated using 2 independent points from the first glass and 2 corresponding points from the second glass, which gives 12 different sets of data for each prototype.

Due to the above, a program to calculate the misalignment was developed. The mean misalignment value with an error (standard deviation) were calculated for each prototype. Figure 20 shows the mean misalignment values for 8 measured prototypes using the microscope (black points) and 2 measured prototypes using the SmartScope (blue points). The red line at 800 urad indicates a maximal allowed rotational misalignment.

In conclusion, the microscope data verified really low misalignment values (the SmartScope data - even lower). 7 out of 8 prototypes have rotational misalignment within specifications - less than 800 urad. The prototype 3 is an older prototype from an unsuccessful test. The prototype 8 is the latest prototype that was made on August, 20th. In the future, described procedures and tools can be applied to new PS Modules.

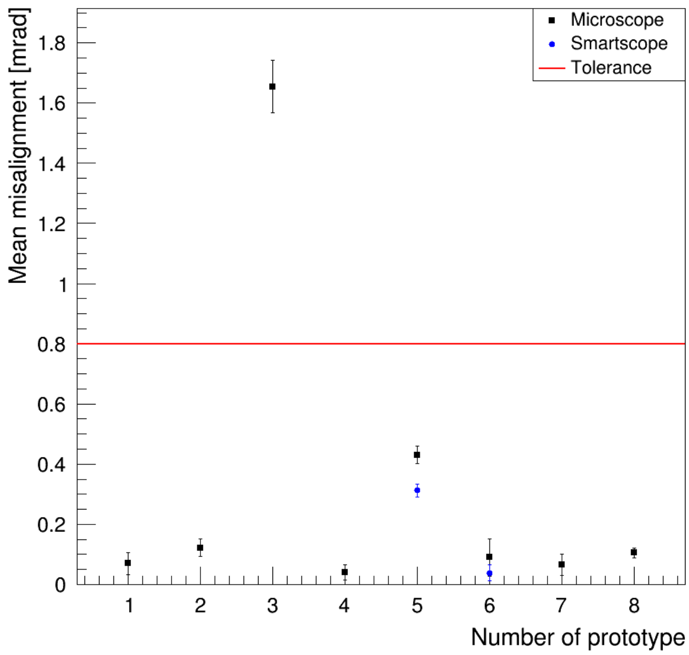

Figure 20: Mean misalignment values for 8 measured modules. Black points represent the microscope data and blue points - the SmartScope data. The red line at 800 urad indicates a maximal allowed rotational misalignment. 7 out of 8 prototypes have rotational misalignment within specifications.

4. Summary

In conclusion, the procedures to perform 2 steps of the PS module assembly were developed: the baseplate+kapton and the baseplate+sensors gluing steps. The procedures were successfully applied in the assembly of the last 2 prototypes (1 with 200um-thick glasses, 1 with 700um-thick glasses). In both cases, the resulting glue layer was found to have good coverage (very limited number of air bubbles). In addition to this, a procedure was developed to acquire and analyze microscope data for the metrology of assembled PS prototypes. With this procedure, it was verified that 7 out of 8 of the existing prototypes have a glass-to-glass rotational misalignment within specifications (i.e. smaller than 800 urad). In the future, the next steps of the project will include improving the positioning of kapton on baseplate, measuring the thickness of the glue layer between baseplate and sensors-sandwich and further improving the software for the metrology measurements.

Appendices

A. Procedure for baseplate+kapton and baseplate+sensors gluing steps

PREPARATION

1. Turn on the computer and the dispenser (using switcher at the back of the robot).
2. Connect the computer to the dispenser (on the front) using the network cable.
3. Put an empty syringe with a needle into the robot's holder.
4. Clean a baseplate using Isopropanol and weight it.
5. Position the baseplate on a robot stage (a corner without inserts should be on the left down edge) and fix it with the kapton tape.
6. Open the program to dispense the glue and select "Mechanical initialization" to set the robot in default position.=
7. Add/choose a routine to dispense the glue and test it before final dispensing (e.g. pattern, height, etc.).
8. If the routine is finished, send the data to the robot by selecting: 'Robot' - 'Send CT data' - 'Send' - 'Ok'.

DISPENSING THE GLUE

1. Prepare the glue mixture following the instructions placed text to the mixer.
2. Pour the glue mixture into the syringe, put a pusher into the syringe and push it until there will be no air between the pusher and the needle (it is useful to turn on the needle to release the air from the syringe).
3. Put the syringe into the robot's holder and connect it with a pressure line.
4. Turn on the pressure using switcher at the back of the pressure device. Set the pressure at 7 bars. The timer on the pressure devise must be off.
5. Run the routine (the door of the dispensing robot must be closed).
6. Weight the baseplate with dispensed glue and calculate the amount of the glue.

SQUEEGEEING

1. Clean a kapton foil using Isopropanol.

2. Put the kapton foil onto the baseplate trying to position it exactly in the middle.
3. Spread the glue around the baseplate surface using the squeegeeing tool and following the instructions:
   - At first, spread the glue on the left and right sides but stop around 0.5 cm before the end of the baseplate.
   - Then, spread the glue up and down but stop around 0.5 cm before the end of the baseplate.
   - At the end, spread the rest of the glue till ends of the baseplate+kapton.
4. Leave the baseplate+kapton for 36 hours for glue curing.

B. Procedure for PS metrology measurements

PREPARATION

1. Turn on the microscope and use the blue lens.
2. Put the steel platform with the yellow kapton tape on the microscope stage and push it against the blue kapton tapes which are on the microscope stage.
3. Put the module on the steel platform. The scratch 'PSS DESY CMS' must be on the left up corner of the platform. Push the module against the yellow tape. The right edge of the bottom glass must be in line with the end of the yellow tape. This step is common for both types of module: with and without baseplate.
4. Fix the module in the platform using kapton tape.
5. Make sure that the lighting is optimal. To do that find any marker (the best option is the left up of the top glass).

MEASUREMENT

1. Prepare the program for the measurement. Click: 'Measure', then 'XY stage measurement', then 'Multi pt'.
2. Start the measurement with the top glass.
3. Measure left up marker and continue clockwise (right up, right down, left down):
   - for each marker measure all six corners;
   - start with the one between two longest sides of the marker;
   - save the point by clicking: 'Define point';
   - measure and save other points clockwise;
   - after finishing the marker go to the next one.

4. Repeat step B3 for every marker on the glass.
5. Go to the bottom glass and repeat steps 3 and 4.
6. After finishing the measurement (48 points) save it by clicking: 'Define multi pt'.
7. Save the file by clicking: 'Save CSV', select a folder and type the name.
8. You can copy your files using the option: 'Album'.

ANALYSING DATA

1. There are five scripts for the analysis:
   - prototypeMeasurementsMicroscope.py - to analyse each file from the prototypes measurement using Microscope;
   - prototypeMeasurementsSmartscope.py - to analyse each file from the prototypes measurement using Smartscope;
   - prototypeLenghtAll.py - to make histograms of markers lenghts from all the measurements;
   - prototypeRectangularityAll.py - to make histograms of rectangularity from all the measurements;
   - prototypeMisalignmentAll.py - to make a graph of misalignment from all the measurements.

   The scripts and input files must be in one folder.
2. Go to the terminal and connect to the 'NAF' account.
3. Change directory to the folder in which there are scripts and input files.
4. Type 'python prototypeMeasurementsMicroscope.py x abc' or 'python prototypeMeasurementsSmartscope.py x abc' (depending on the file), where:
   - 'x' is the number of your prototype;
   - 'abc' is the name of your file WITHOUT '.csv';

   and press enter.
5. Repeat step 4 for each file.
6. For making histograms of markers lenghts and rectangularity: type 'python prototype...All.py x abc abc abc ...', where:
   - prototype...All.py is prototypeLenghtAll.py or prototypeRectangularityAll.py (depending which program you want to run);
   - 'x' is the number of Microscope files that you analyzed in point 4;
   - 'abc' is the name of your final Microscope file WITH '.csv'.

7. For making graph of misalignment: type 'python prototypeMisalignmentAll.py x abc abc abc ... y def def ...', where:
   - prototype...All.py is prototypeLenghtAll.py or prototypeRectangularityAll.py (depending which program you want to run);
   - 'x' is the number of Microscope files that you analyzed in point 4;
   - 'abc' is the name of your final Microscope file with calculated misalighment WITH '.csv';
   - 'y' is the number of Smartscope files that you analyzed in point 4;
   - 'def' is the name of your final Smartscope file with calculated misalighment WITH '.csv'.
8. For each run type as many 'abc' as the number 'x', e.g.:
   " python prototypeMisalighmentAll.py 3 prototype1.csv prototype2.csv prototype3.csv 2 prototype5smartscope.csv prototype6smartscope.csv "
9. All the results are saved in the same folder as the scripts and input files.

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