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# Automating the assembly of PS modules for the CMS Phase II Tracker

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for the DESY-CMS Phase II Tracker group

Forum on Tracking Detector Mechanics, 25-27 June 2018

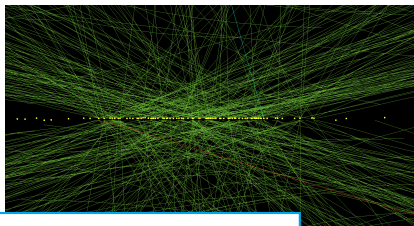
# Outline

- Introduction: the PS module for the CMS Phase II Outer Tracker
- The automated PS module assembly
- Results with first mechanical prototypes
- Next steps and summary



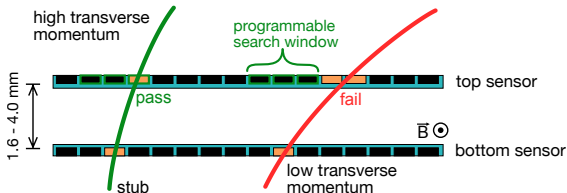
# Module concept for CMS Phase II Outer Tracker

- The challenge: High-Luminosity LHC
  - up to  $\times 5$  more pileup
  - up to  $\times 10$  higher integ. luminosity

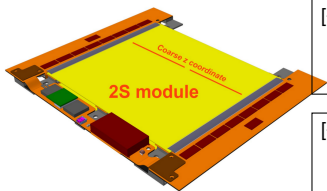


CMS will install new tracking detectors, and use tracking info at L1-Trigger

- Outer Tracker module concept: the  $p_T$  module
  - correlates signals from two closely-spaced silicon sensors
  - on-module stub reconstruction  $\Rightarrow$  local  $p_T$  measurement
  - rejection of low- $p_T$  stubs  $\Rightarrow$  10-fold data reduction allowing use of tracking info at 40 MHz

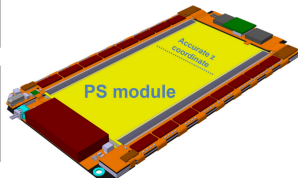


# Layout of the CMS Phase II Outer Tracker



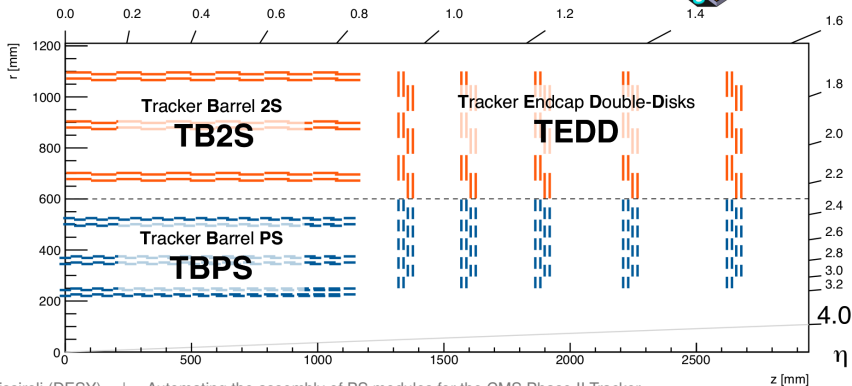
[ $r > 60$  cm] **2-Strip (2S)** modules

- Dimensions:  $\sim 10 \times 10$  cm<sup>2</sup>
- Spacings: 1.8 and 4.0 mm



[ $r < 60$  cm] **Pixel-Strip (PS)** modules

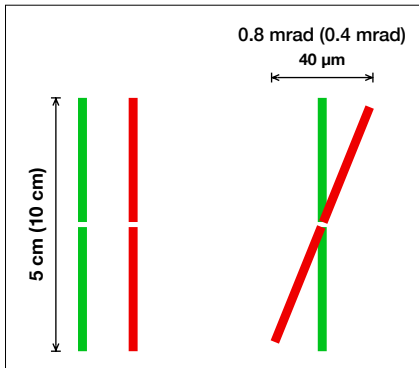
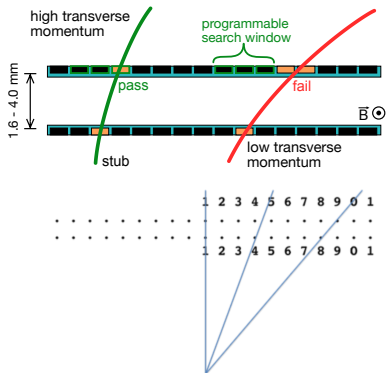
- Dimensions:  $\sim 5 \times 10$  cm<sup>2</sup>
- Spacings: 1.6, 2.6 and 4.0 mm



# The $p_T$ module: assembly requirements

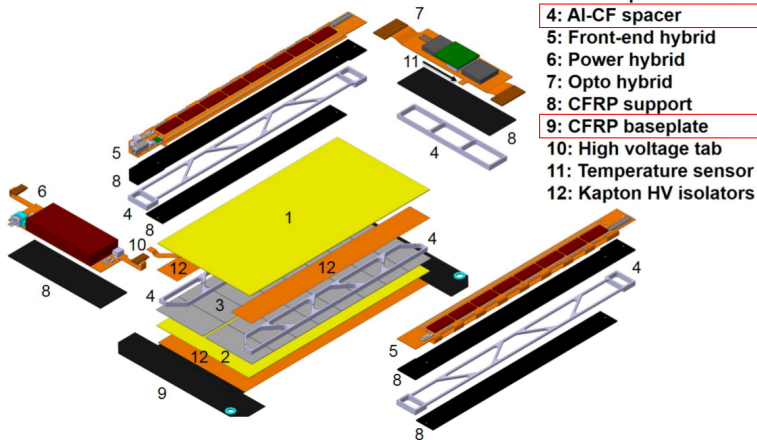
- $p_T$  module uses programmable search window to correlate sensor hits:
  - translational misalignment can be corrected for in the stub finding logic
  - rotational misalignment can't be corrected for (different offset along strip)

max. angular misalignment of PS sensors: **800  $\mu\text{rad}$**



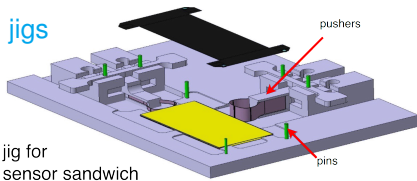
# The PS module: a closer look

- will focus on sensors, spacers, baseplate
- key: **rotational alignment** of PSp and PSs

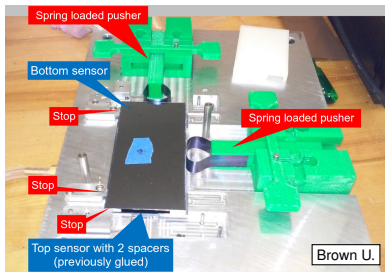


# Prelude: the *manual* PS module assembly

- standard method based on **mechanical jigs**
  - one jig for PSp-PSs assembly
  - sensors and spacers aligned through stops, pushers and pins
- some significant **drawbacks**:
  - alignment relies on precise **sensor dicing**
  - maximal **manual handling**



- any way we can improve this?
  - ⇒ DESY is exploring an alternative method



# The *automated* PS module assembly

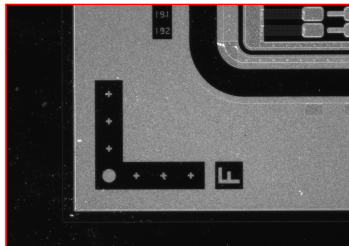
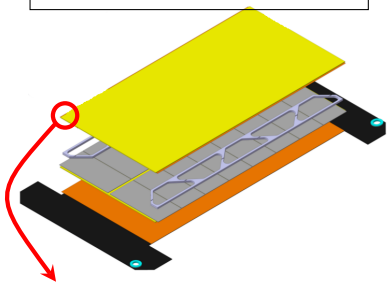
# What to automate, and how

(baseplate +) PSp + spacers + PSs

the **high-precision** steps of the module assembly

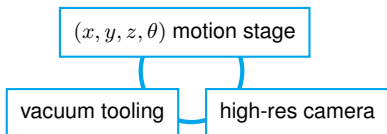
- the **core idea**:
  - markers on sensor corners aligned to pixels/strips to high precision
  - measure their positions and use it to align sensors
- the **goal**:
  - an automated system that can locate markers and move sensors into alignment

tolerance on PSp-PSs alignment:  $800 \mu\text{rad}$

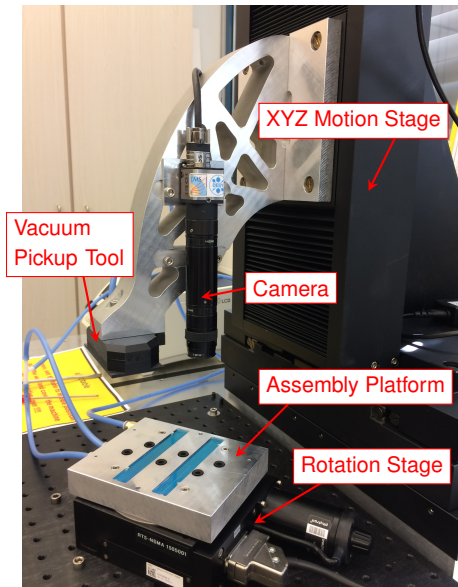


# Hardware

- integrated system comprised of



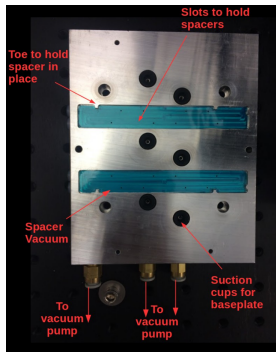
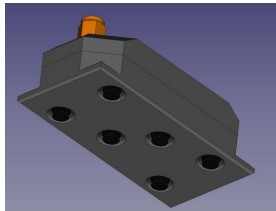
- motion stage precision:  
5  $\mu\text{m}$  in  $(x, y, z)$ , 175  $\mu\text{rad}$  in  $\theta$
- robot-arm with camera and vacuum handling to pick-up/put-down sensors
- custom-made assembly platform to be mounted on rotation stage





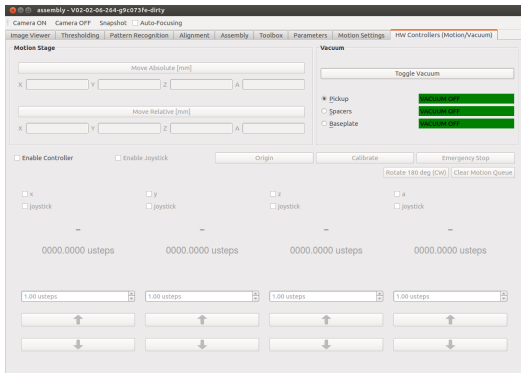
# Hardware / pickup tool and platform

- ESD plastic “pickup tool”
  - vacuum distributed via inner chamber and ESD rubber suction cups on lower surface
  - provides secure but non-destructive handling of sensors
- assembly platform on rotation stage
  - independent vacuum lines for spacers and baseplate/sensor
  - positioning pins for baseplate
  - positioning stops for spacers



# Software

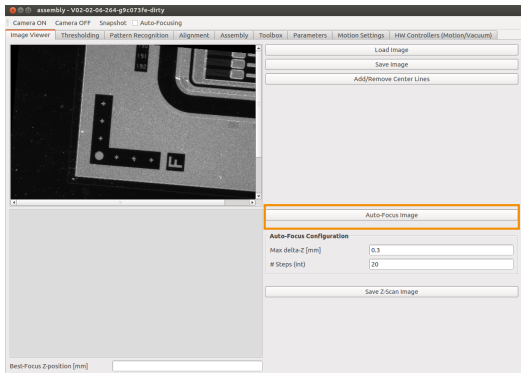
- dedicated software interface developed at DESY  
<https://github.com/DESY-FH-Elab/cmstkmodlab/assembly>
- controls motion, vacuum and image acquisition



- HW Controllers (motion, vacuum)
  - Image Viewer + Auto-Focusing
- ... more on SW-interface later

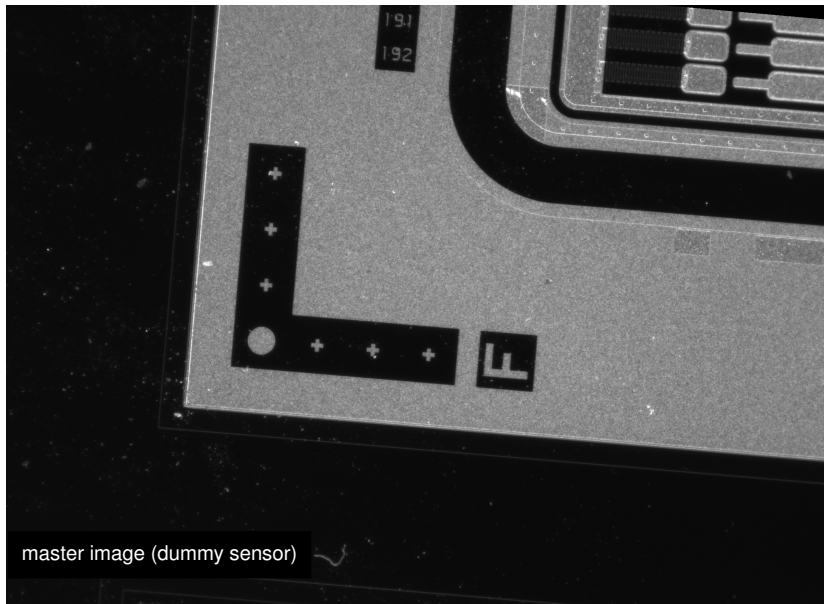
# Software

- dedicated software interface developed at DESY  
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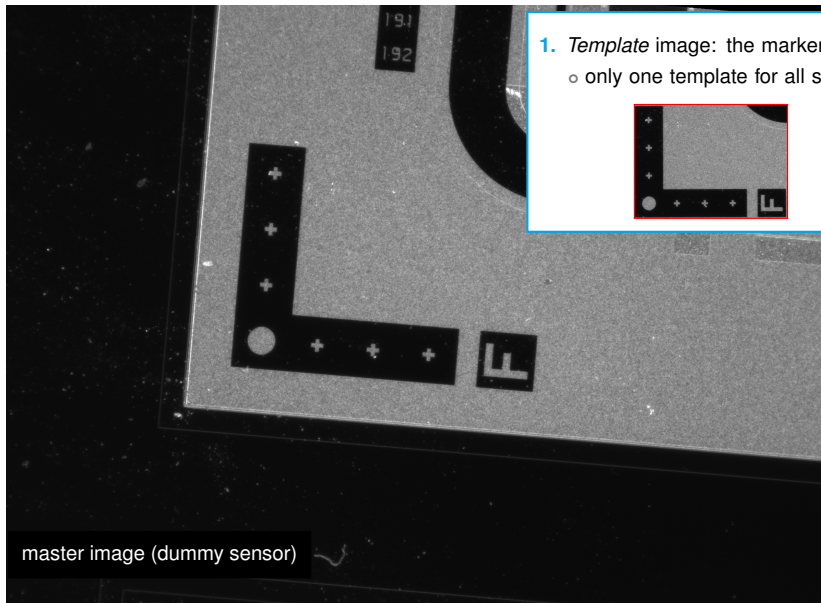
- HW Controllers (motion, vacuum)
- Image Viewer + **Auto-Focusing**
- ... more on SW-interface later

## Finding the marker

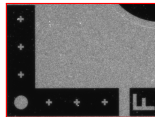


master image (dummy sensor)

# Finding the marker

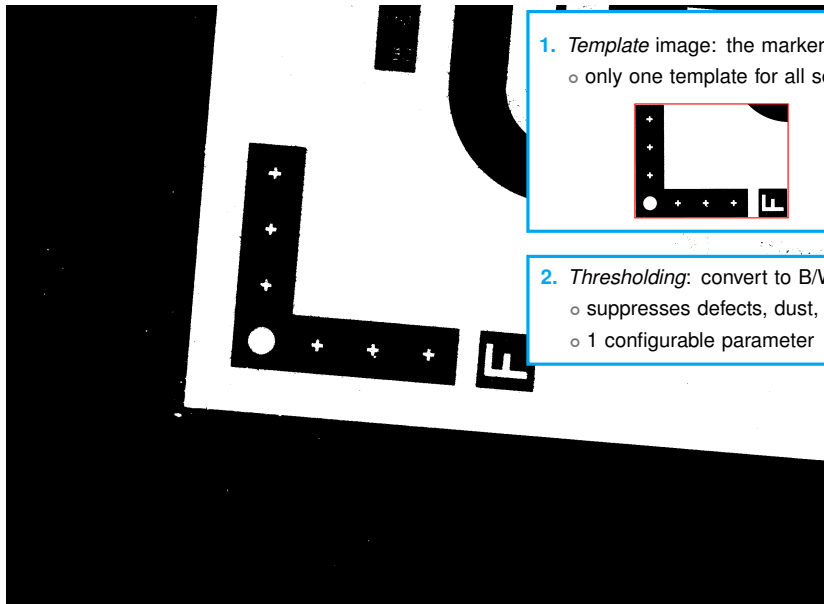


1. *Template* image: the marker
  - o only one template for all sensors



master image (dummy sensor)

# Finding the marker

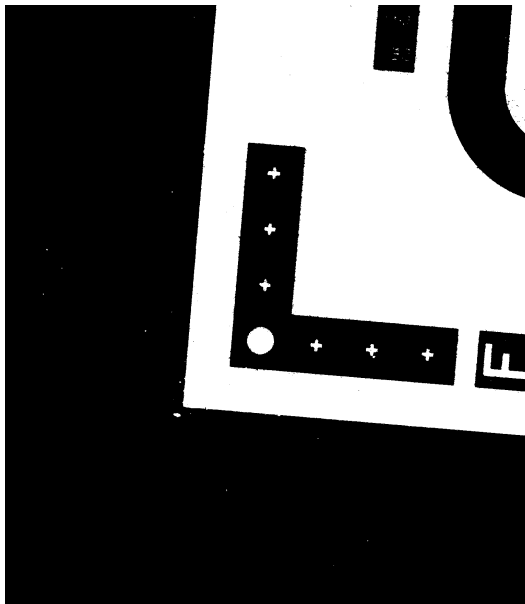


1. *Template image*: the marker
  - o only one template for all sensors



2. *Thresholding*: convert to B/W
  - o suppresses defects, dust, bkg
  - o 1 configurable parameter

# Finding the marker



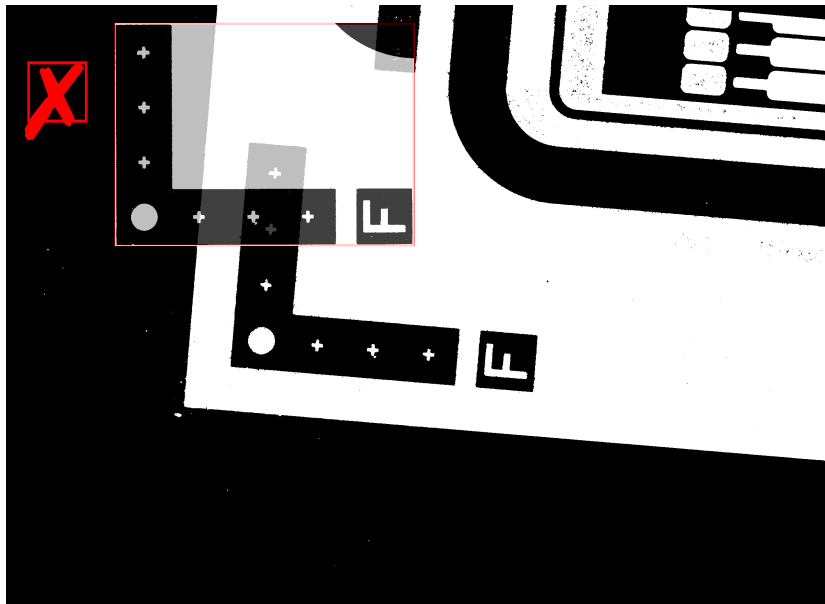
1. *Template image*: the marker
  - o only one template for all sensors



2. *Thresholding*: convert to B/W
  - o suppresses defects, dust, bkg
  - o 1 configurable parameter

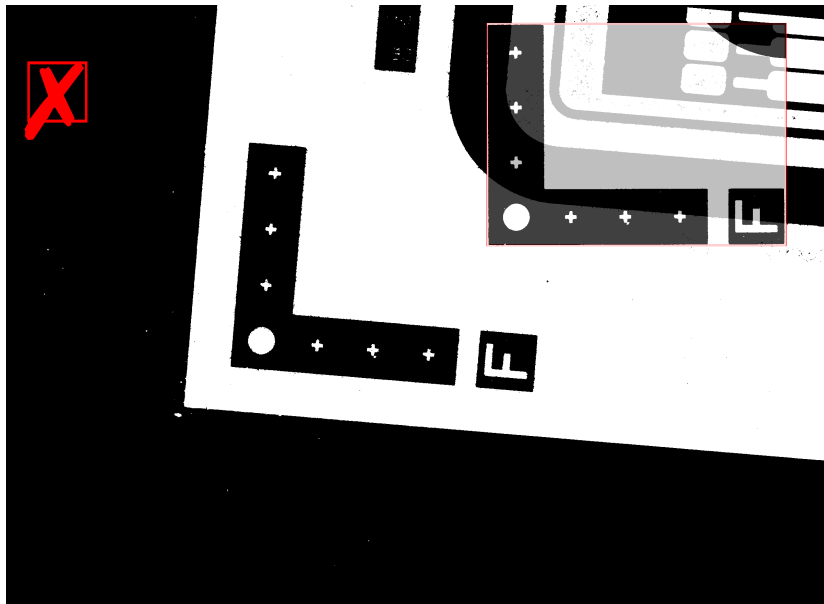
3. *Template matching*:
  - o **Pattern Recognition** routine from **OpenCV** package
  - o finds best-match position of template in master image

## Finding the marker

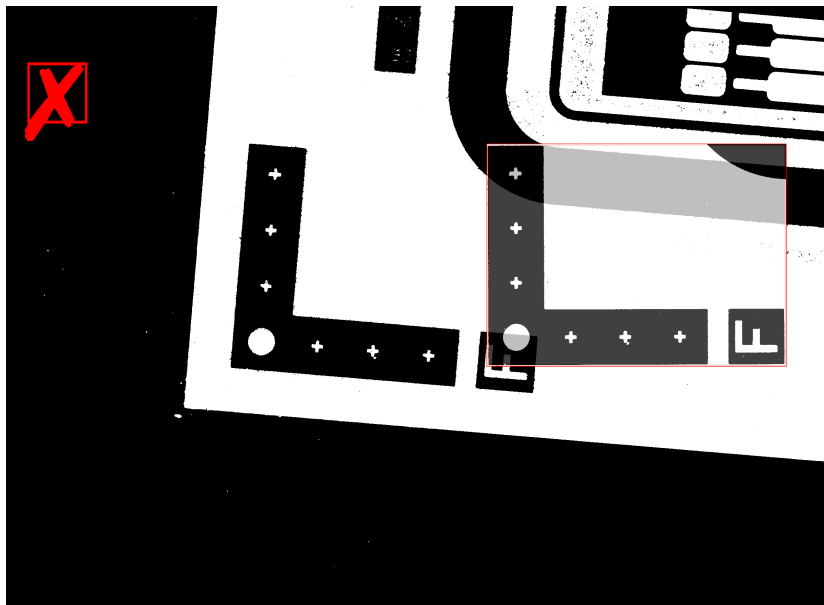




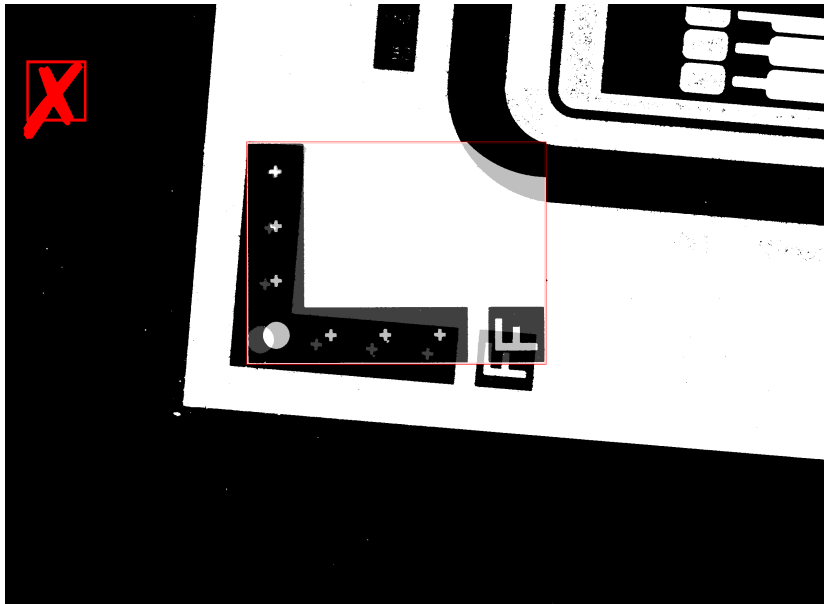
## Finding the marker



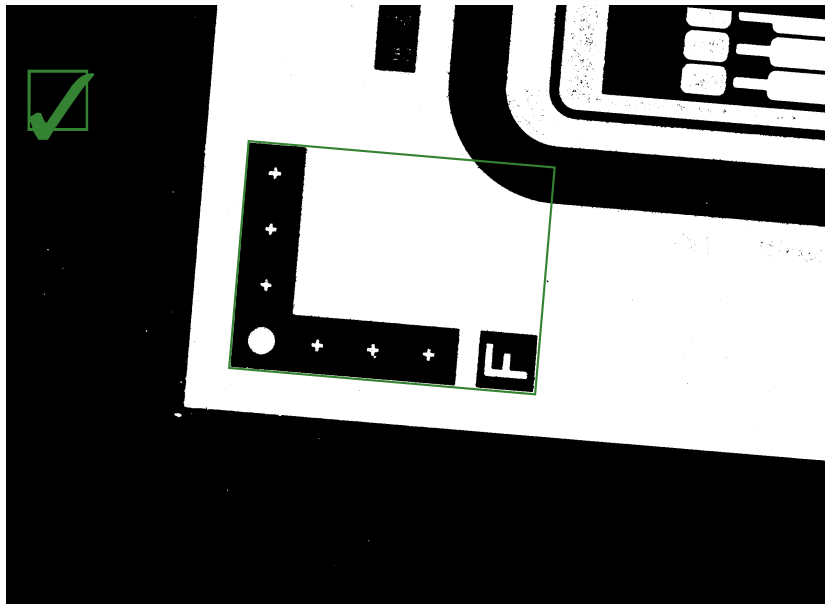
## Finding the marker



## Finding the marker



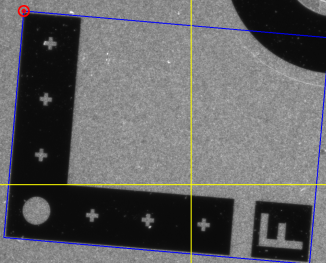
## Finding the marker



# Finding the marker

200  $\mu\text{m}$

What PatRec looks like in the SW interface



**Results of Pattern Recognition:** 3 values  $(x, y, \theta_m)$

- o **best-match XY** position
- o  $\theta_m$ : orientation of the marker

# Measuring the sensor's orientation

- not relying on single-marker measurement to define sensor orientation

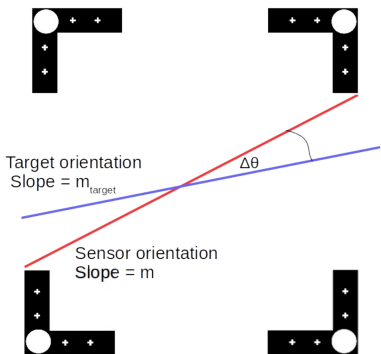
- exploit entire sensor length by measuring XY of opposite markers:

1 run PatRec on marker #1  $\Rightarrow (x_1, y_1, \theta_{m1})$

2 use measured  $\theta_{m1}$  to automatically move to opposite marker (sensor dim. known)

3 run PatRec on marker #2  $\Rightarrow (x_2, y_2, \theta_{m2})$

- sensor orientation**: measured slope  $(x_1, y_1) \rightarrow (x_2, y_2)$
- after rotating to target  $\theta$ , sensor orient. remeasured to validate alignment



# SW interface to PatRec and Alignment

- real-time feedback on PatRec/alignment results

assembly - V02-02-06-264-g9c073fe-dirty

Camera ON Camera OFF Snapshot  Auto-Focusing

Image Viewer Thresholding **Pattern Recognition** Alignment Assembly Toolbox Parameters Motion Settings HW Controllers (Motion/Vacuum)

**Pattern Recognition**

Standalone PatRec **FOUND MARKER**

**Configuration**

**Template Image**

Load Image /share/assembly/SensorPiece\_1\_clipC.png

**Master Image Thresholding**

Threshold (pos int) 100

Adaptive Threshold (pos odd int) 587

**Template-Matching Angular Scan**

Pre-Scan Angles (list) [deg] 3

Fine-Scan Maximum Angle [deg] 4

Fine-Scan Angular Step [deg] 0.2

**Results**

Delta-X to Best-Match Pos. [mm] 0.6072

Delta-Y to Best-Match Pos. [mm] 0.5856

Best-Match Template Orient. [deg] 5

# SW interface to PatRec and Alignment

- [real-time feedback](#) on PatRec/alignment results

Alignment interface / configuration

The screenshot shows the 'Alignment Configuration' window of the PatRec software. The window title is 'assembly - V02-02-06-264-g9c073fe-dirty'. The interface includes a top navigation bar with tabs: Image Viewer, Thresholding, Pattern Recognition, Alignment (selected), Assembly, Toolbox, Parameters, Motion Settings, and HW Controllers (Motion/Vacuum). Below the tabs, the 'Alignment Configuration' section is divided into several panels:

- Sensor Selection:** Radio buttons for 'PSS Sensor' (selected) and 'PSP Sensor'. Input fields for dX [mm] and dY [mm] are provided for each. For PSS, dX is 94.3 and dY is -48.7. For PSP, dX is 96.8 and dY is -48.7.
- Target Angle [deg]:** An empty input field.
- Completion Options:** A checkbox 'Go back to marker-1 position before completion' is unchecked. Radio buttons for 'Measure Angle' (selected) and 'Align Object' are present.
- PatRec Marker #1 [Bottom-Left Marker]:**
  - Template Image:** 'Load Image' button and file path 'ply/markedglass\_marker1\_drawing\_588x588.png'.
  - Master Image Thresholding:** Radio buttons for 'Threshold (pos int)' (selected, value 55) and 'Adaptive Threshold (pos odd int)' (value 587).
  - Template-Matching Angular Scan:** Input fields for 'Pre-Scan Angles (list) [deg]' (0), 'Fine-Scan Maximum Angle [deg]' (2), and 'Fine-Scan Angular Step [deg]' (0.2).
- PatRec Marker #2 [Top-Right Marker]:**
  - Template Image:** 'Load Image' button and file path 'ply/markedglass\_marker1\_drawing\_588x588.png'.
  - Master Image Thresholding:** Radio buttons for 'Threshold (pos int)' (selected, value 55) and 'Adaptive Threshold (pos odd int)' (value 587).
  - Template-Matching Angular Scan:** Input fields for 'Pre-Scan Angles (list) [deg]' (180), 'Fine-Scan Maximum Angle [deg]' (2), and 'Fine-Scan Angular Step [deg]' (0.2).

At the bottom of the window, there is a section labeled 'Alignment Results'.



# SW interface to PatRec and Alignment

- real-time feedback on PatRec/alignment results

Alignment interface / results

The screenshot displays the PatRec software interface. At the top, the window title is "assembly - V02-02-06-264-g9c073fe-dirty". Below the title bar, there are control buttons: "Camera ON", "Camera OFF", "Snapshot", and "Auto-Focusing". A menu bar includes "Image Viewer", "Thresholding", "Pattern Recognition", "Alignment" (which is highlighted), "Assembly", "Toolbox", "Parameters", "Motion Settings", and "HW Controllers (Motion/Vacuum)".

The main interface is divided into two sections: "Alignment Configuration" and "Alignment Results". In the "Alignment Results" section, a text box labeled "Measured Angle [deg]" contains the value "60.9646".

Below the text box are two side-by-side image windows. Each window shows a grayscale image of a square object with a smaller square inside it. A yellow crosshair is overlaid on each image. A blue dashed box is drawn around the inner square in both images. The left image shows the object centered within the crosshair, while the right image shows the object rotated and offset from the center. A scale bar in the top-left corner of each image indicates "200 um".

# Gluing

- two types of glue used in the assembly

## Polytec EP 601 LV

- standard glue for OT module assembly
- slow curing, approx. 24h
- full uniform layer on baseplate/spacers

## Loxeal 31-42

- fast curing, approx. 10m
- very small amounts (needle) applied on top of Polytec on baseplate/spacers

- fast-glue necessary to link together assembly steps
- similar dispensing for baseplate and spacers



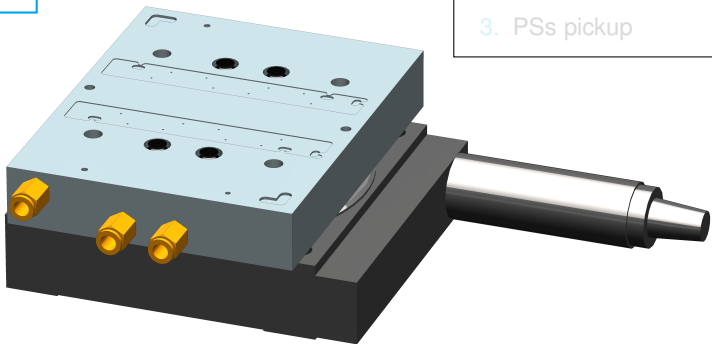
# The assembly procedure

# Assembly procedure

## Step #1 alignment and pickup of PSs

### Vacuum Lines

- Pickup tool
- Sensor/Baseplate
- Spacers



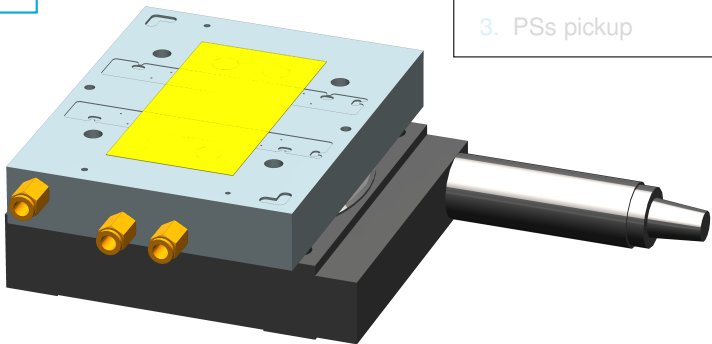
1. PSs on rotation stage  
(held in place by vacuum)
2. PSs alignment
3. PSs pickup

# Assembly procedure

## Step #1 alignment and pickup of PSs

### Vacuum Lines

- Pickup tool
- Sensor/Baseplate
- Spacers



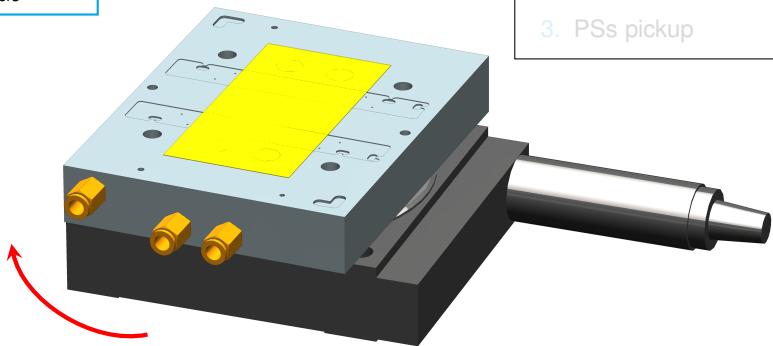
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# Assembly procedure

## Step #1 alignment and pickup of PSs

### Vacuum Lines

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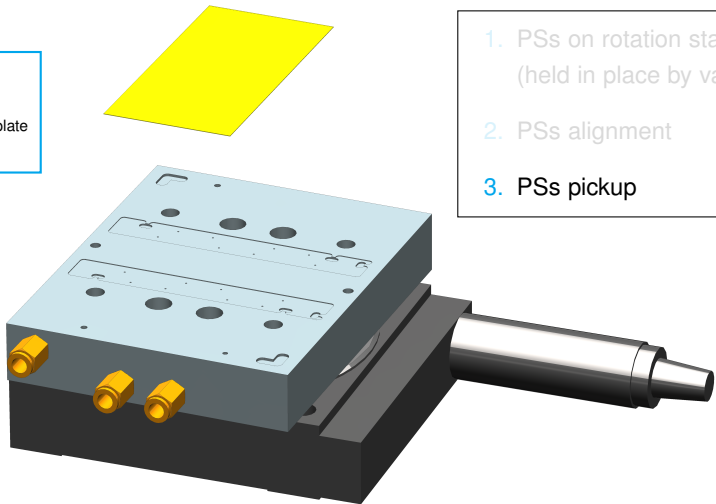
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## Step #1 alignment and pickup of PSs

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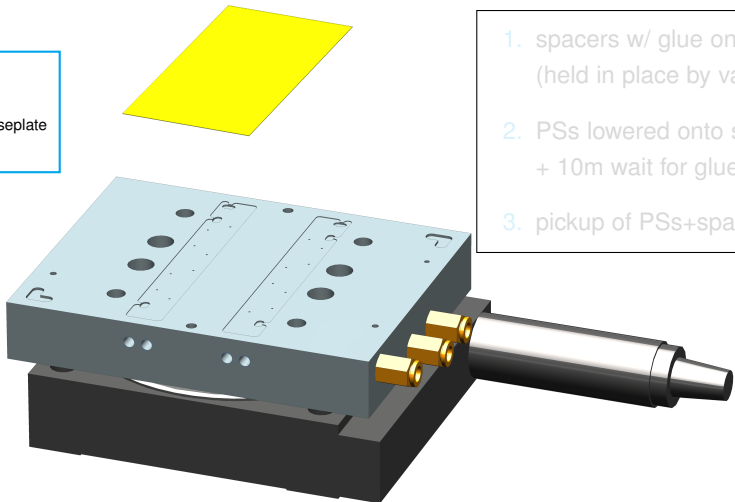
1. PSs on rotation stage  
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2. PSs alignment
3. PSs pickup

# Assembly procedure

## Step #2 PSs + spacers assembly

### Vacuum Lines

- Pickup tool
- Sensor/Baseplate
- Spacers

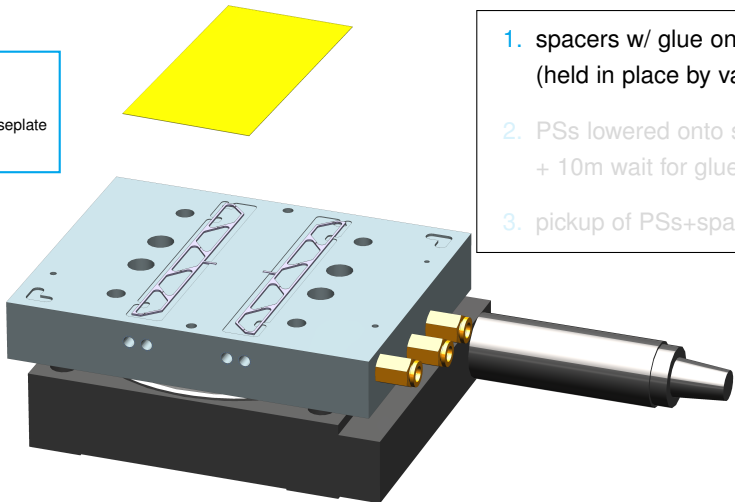
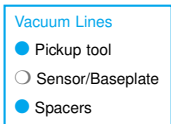


1. spacers w/ glue on stage  
(held in place by vacuum)
2. PSs lowered onto spacers  
+ 10m wait for glue curing
3. pickup of PSs+spacers



# Assembly procedure

## Step #2 PSs + spacers assembly



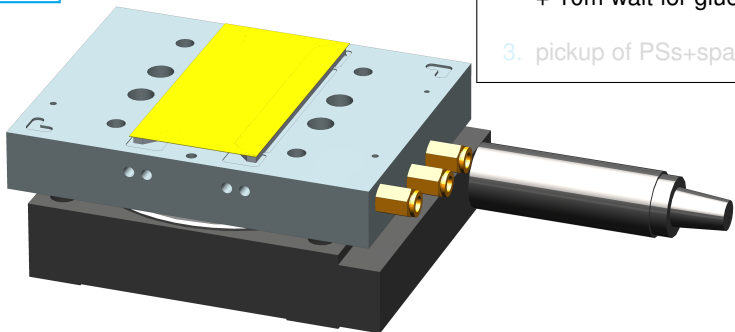
1. spacers w/ glue on stage (held in place by vacuum)
2. PSs lowered onto spacers + 10m wait for glue curing
3. pickup of PSs+spacers

# Assembly procedure

## Step #2 PSs + spacers assembly

### Vacuum Lines

- Pickup tool
- Sensor/Baseplate
- Spacers



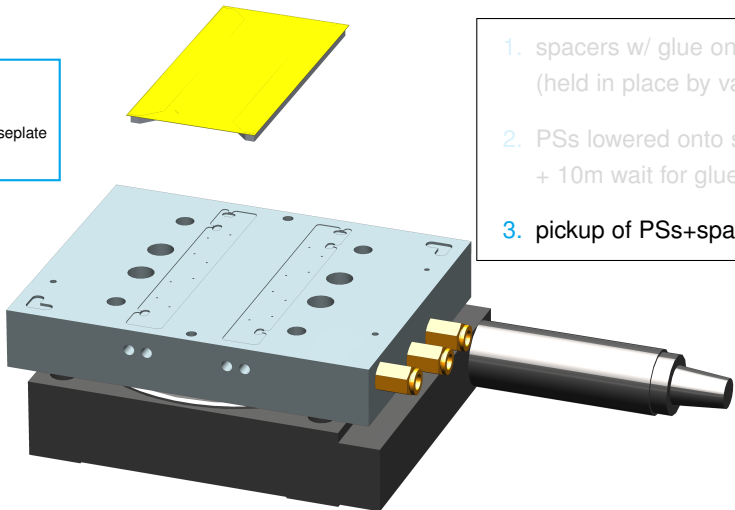
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## Step #2 PSs + spacers assembly

### Vacuum Lines

- Pickup tool
- Sensor/Baseplate
- Spacers



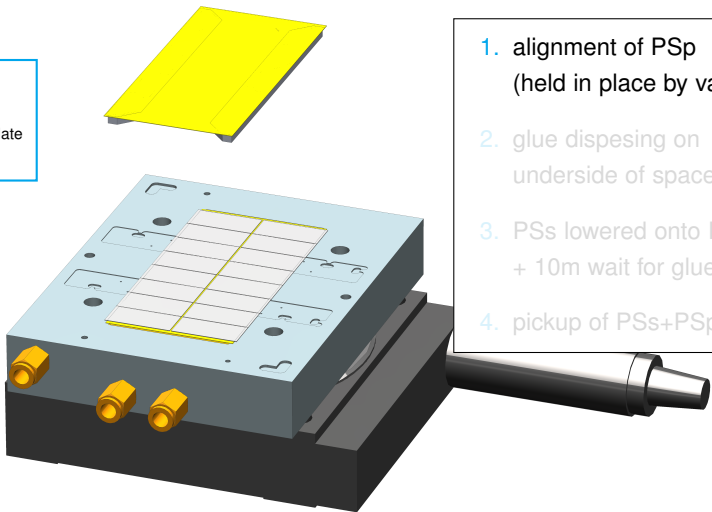
1. spacers w/ glue on stage  
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+ 10m wait for glue curing
3. pickup of PSs+spacers

# Assembly procedure

## Step #3 alignment of PSp, PSp+PSs assembly

### Vacuum Lines

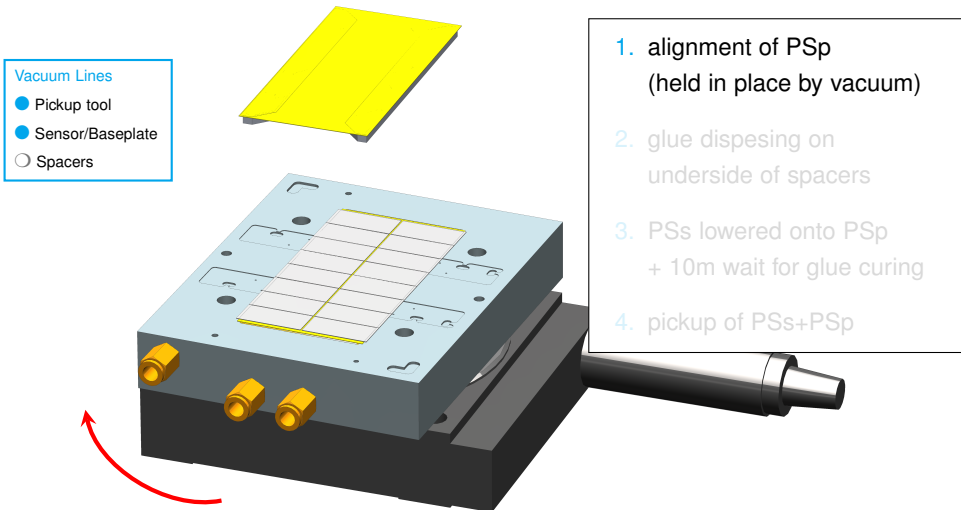
- Pickup tool
- Sensor/Baseplate
- Spacers



1. alignment of PSp  
(held in place by vacuum)
2. glue dispesing on  
underside of spacers
3. PSs lowered onto PSp  
+ 10m wait for glue curing
4. pickup of PSs+PSp

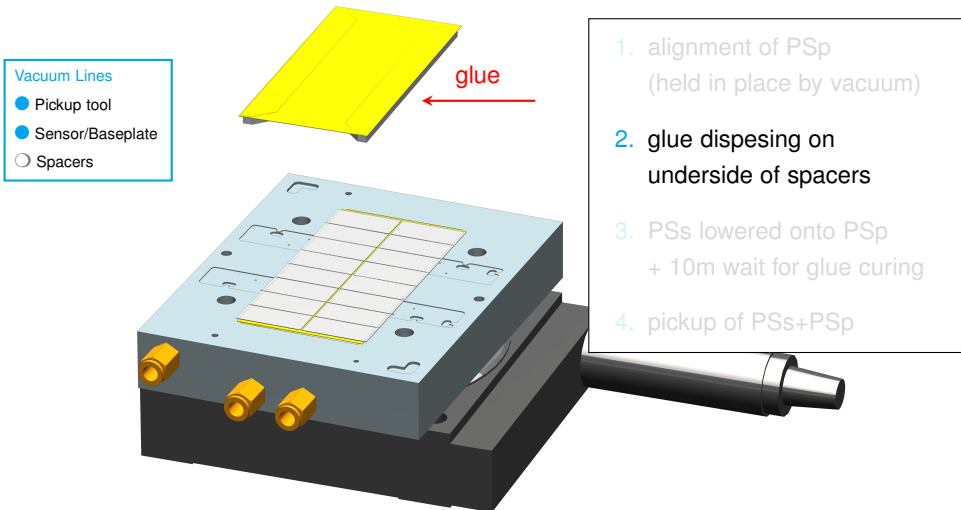
# Assembly procedure

## Step #3 alignment of PSp, PSp+PSs assembly



# Assembly procedure

## Step #3 alignment of PSp, PSp+PSs assembly

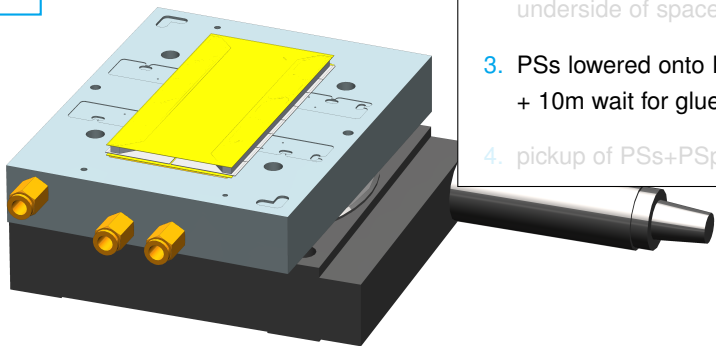


# Assembly procedure

## Step #3 alignment of PSp, PSp+PSs assembly

### Vacuum Lines

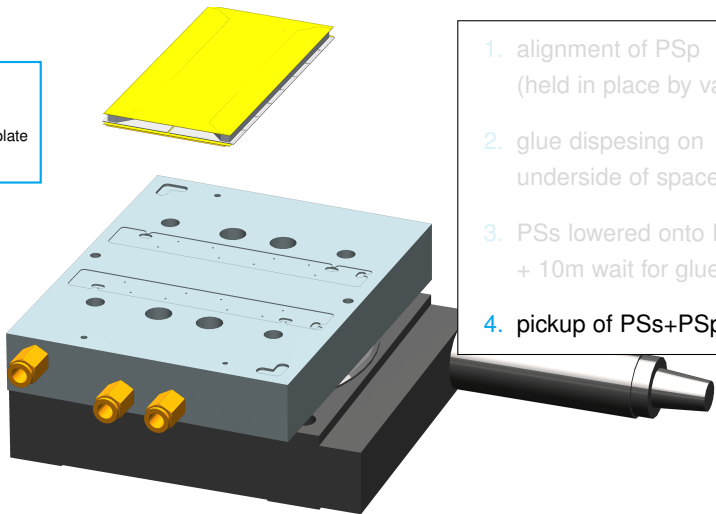
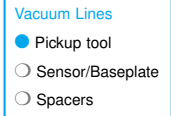
- Pickup tool
- Sensor/Baseplate
- Spacers



1. alignment of PSp  
(held in place by vacuum)
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underside of spacers
3. PSs lowered onto PSp  
+ 10m wait for glue curing
4. pickup of PSs+PSp

# Assembly procedure

## Step #3 alignment of PSp, PSp+PSs assembly



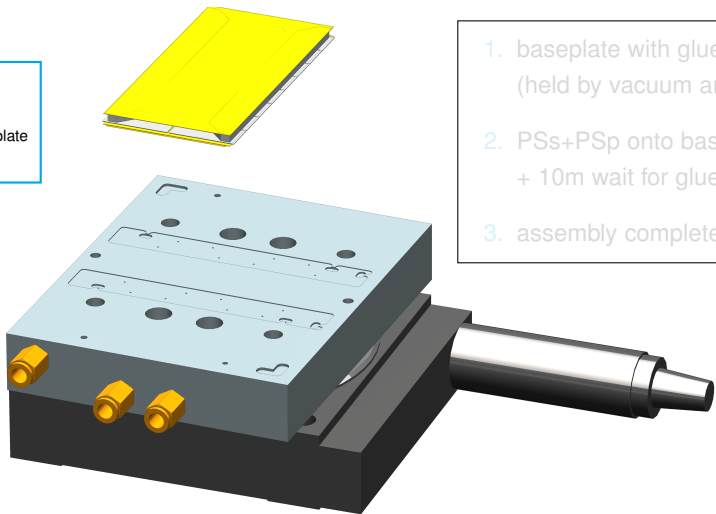


# Assembly procedure

## Step #4 PSp+PSs glued to baseplate

### Vacuum Lines

- Pickup tool
- Sensor/Baseplate
- Spacers



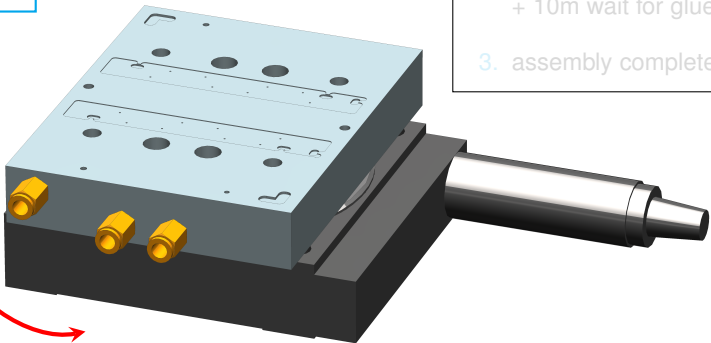
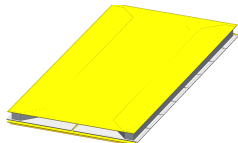
1. baseplate with glue  
(held by vacuum and pins)
2. PSs+PSp onto baseplate  
+ 10m wait for glue curing
3. assembly completed

# Assembly procedure

## Step #4 PSp+PSs glued to baseplate

### Vacuum Lines

- Pickup tool
- Sensor/Baseplate
- Spacers



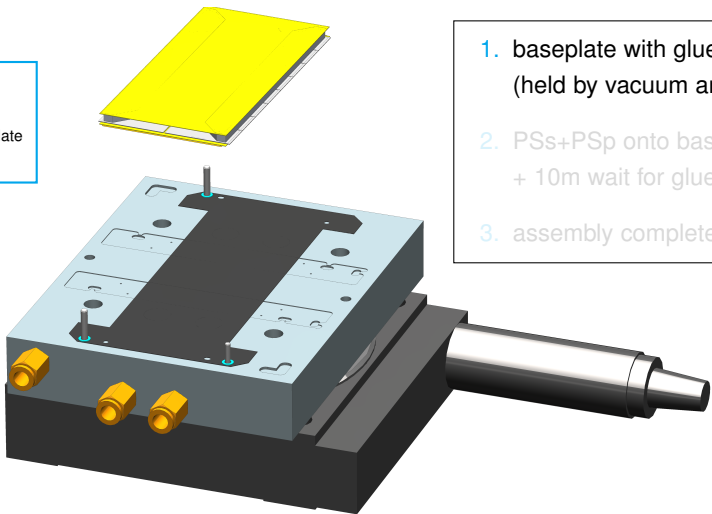
1. baseplate with glue  
(held by vacuum and pins)
2. PSs+PSp onto baseplate  
+ 10m wait for glue curing
3. assembly completed

# Assembly procedure

## Step #4 PSp+PSs glued to baseplate

### Vacuum Lines

- Pickup tool
- Sensor/Baseplate
- Spacers



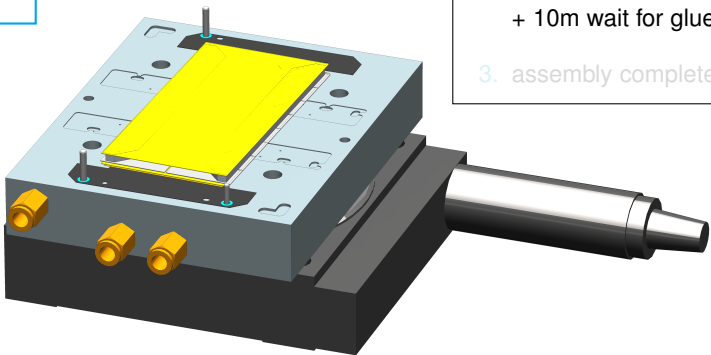
1. baseplate with glue  
(held by vacuum and pins)
2. PSs+PSp onto baseplate  
+ 10m wait for glue curing
3. assembly completed

# Assembly procedure

## Step #4 PSp+PSs glued to baseplate

### Vacuum Lines

- Pickup tool
- Sensor/Baseplate
- Spacers



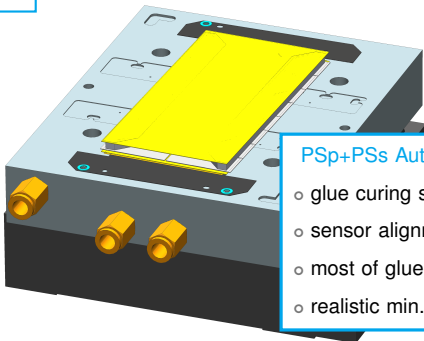
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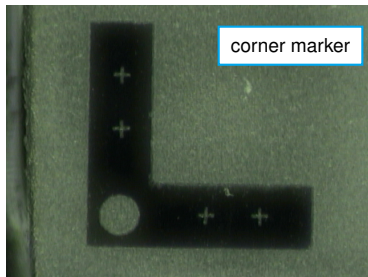
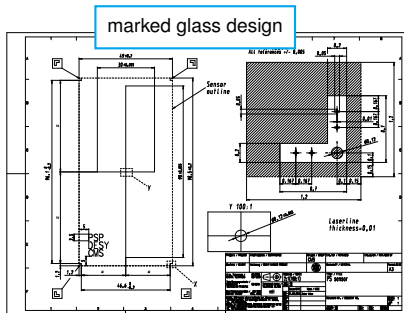
### PSp+PSs Auto-Assembly:

- o glue curing steps: tot. ~**30m**
- o sensor alignment (x2): tot. ~**10m**
- o most of glue dispensing can be done in parallel
- o realistic min. time for 1 assembly: **1 hour** (1-2 people)

# First mechanical prototypes

# Components for first dummy modules

- first assemblies using **marked glasses** with PSs/PSp XY dimensions
  - designed in house and produced by external company
  - precision of laser-etched fiducial markings within specs ( $\delta_\theta \lesssim 60 \mu\text{rad}$ )
- **Al spacers** produced in house and by external vendor
- **CFRP baseplates** produced in house



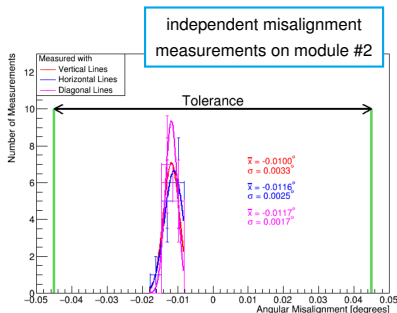
# Metrology on first dummy modules

- 3 mechanical prototypes (baseplate+“sensors”+spacers) *auto*-assembled at DESY



- sensor-to-sensor alignment measured with high-resolution 3D microscope
- all within tolerance ( $800 \mu\text{rad}$ )

assembly #	glue	spacers	alignment ( $\mu\text{rad}$ )
1	Loxeal	Al (DESY)	<b>279</b>
2	Loxeal	Al (external)	<b>175</b>
3	Loxeal+Polytec	Al (external)	<b>523</b>





# Next steps and summary

## Next steps

- many improvements in the works to make the system as efficient (and user-friendly) as possible
- **speed** and **repeatability**: improve automation of assembly steps
  - all the core pieces are there, now we can link them together
- introduce stage for **glue dispensing**
  - avoid manual glue dispensing on (PSs+)spacers when held on pickup tool
  - plan: use dedicated platform and lower pickup tool onto it
- test full procedure with **dummy silicon sensors**
  - thinner, more fragile compared to glass (but sharper markers!)

# Next steps

- focus shifting towards scaling up procedure to **4-6 modules per day**
- full auto-assembly setup being installed in the **DESY Detector Assembly Facility (DAF)** for Phase II Tracker



# Summary

- presented method to **automate part of the assembly of PS modules** for the CMS Phase II Tracker
  - method based on **pattern recognition** on sensor markers
  - no reliance on sensor dicing, real-time feedback on alignment
- proof-of-concept of the method:
  - **first mechanical prototypes** with marked glasses
  - angular misalignment of dummy modules well **within tolerance**
- **work ongoing** to scale up the procedure towards **full-scale production**
  - improvements to software interface to further automate assembly steps
  - complete auto-assembly setup being installed at DESY DAF