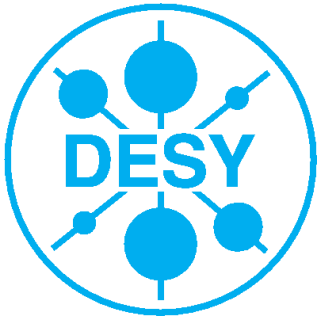
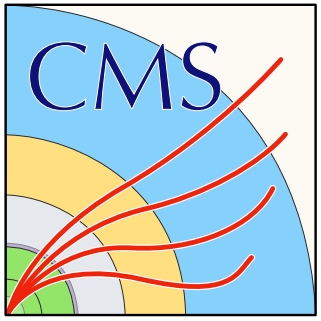




Automating the assembly of PS modules for the CMS Phase II Tracker

James Keaveney, Marino Missiroli and Andreas Mussgiller,

for the DESY-CMS Phase II Tracker group

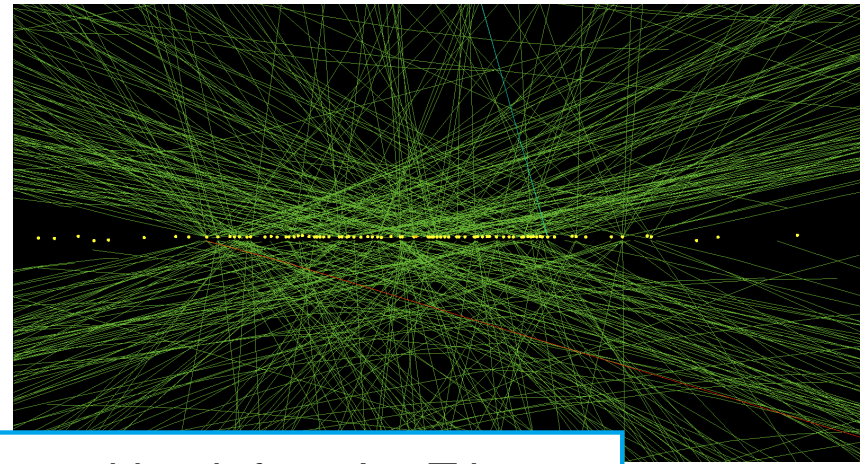
Forum on Tracking Detector Mechanics, 25-27 June 2018

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

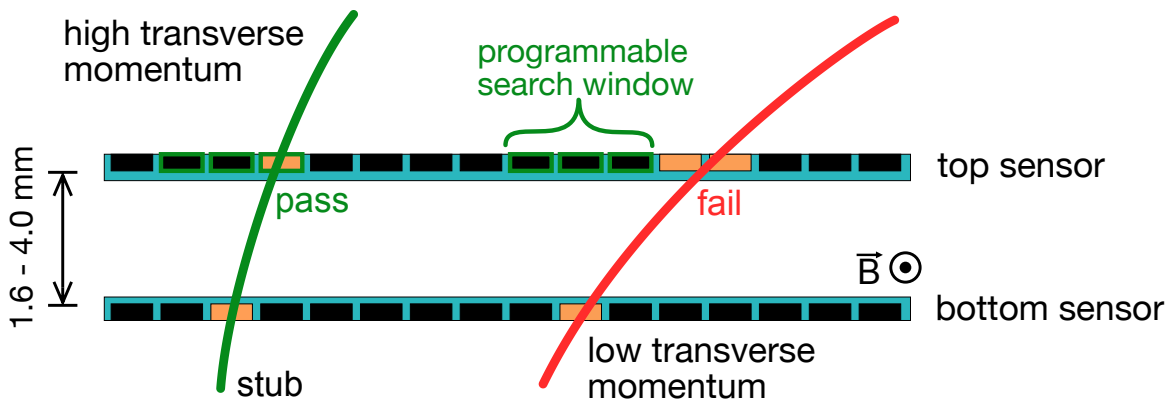
Module concept for CMS Phase II Outer Tracker

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

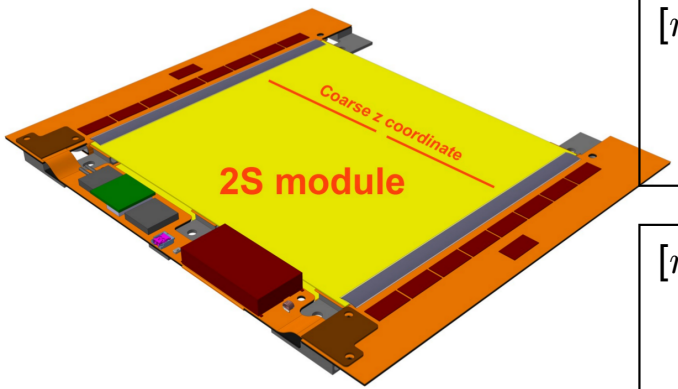


CMS will install new tracking detectors, and use tracking info at L1-Trigger

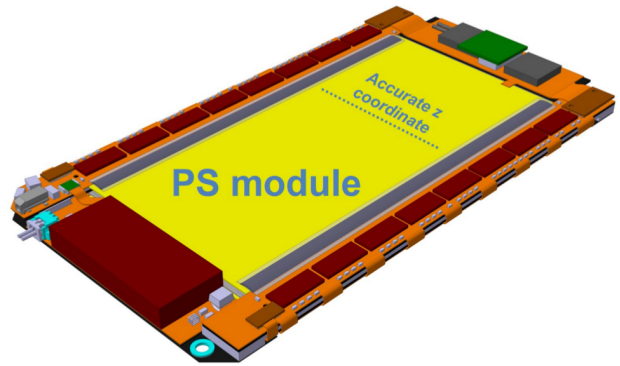
- Outer Tracker module concept: the p_T module
  - correlates signals from two closely-spaced silicon sensors
  - on-module stub reconstruction
    $\Longrightarrow$ local p_T measurement
  - rejection of low-p_T stubs
    $\Longrightarrow$ 10-fold data reduction allowing use of tracking info at 40 MHz

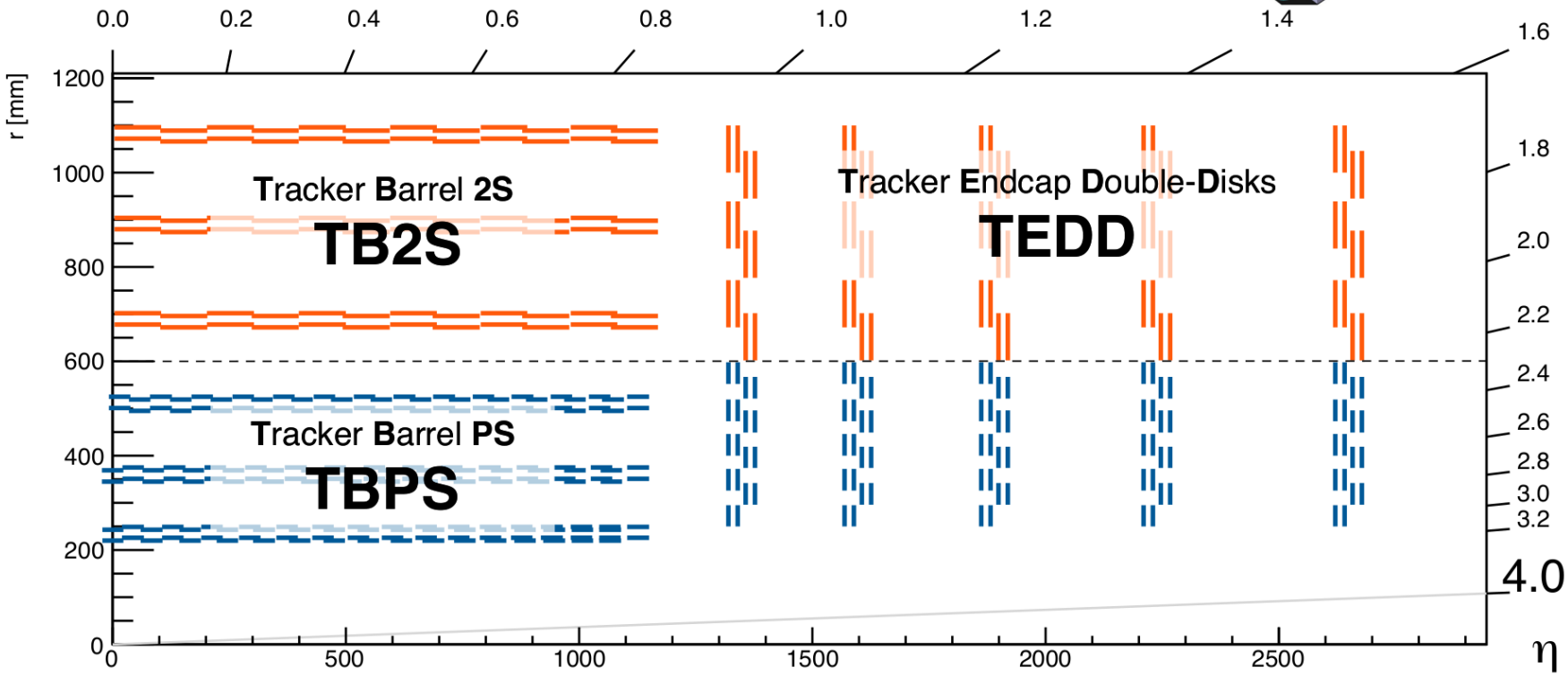


Layout of the CMS Phase II Outer Tracker



- $[r > 60\ \text{cm}]$ 2-Strip (2S) modules
  - Dimensions: $\sim 10 \times 10\ \text{cm}^2$
  - Spacings: 1.8 and 4.0 mm
- $[r < 60\ \text{cm}]$ Pixel-Strip (PS) modules
  - Dimensions: $\sim 5 \times 10\ \text{cm}^2$
  - Spacings: 1.6, 2.6 and 4.0 mm

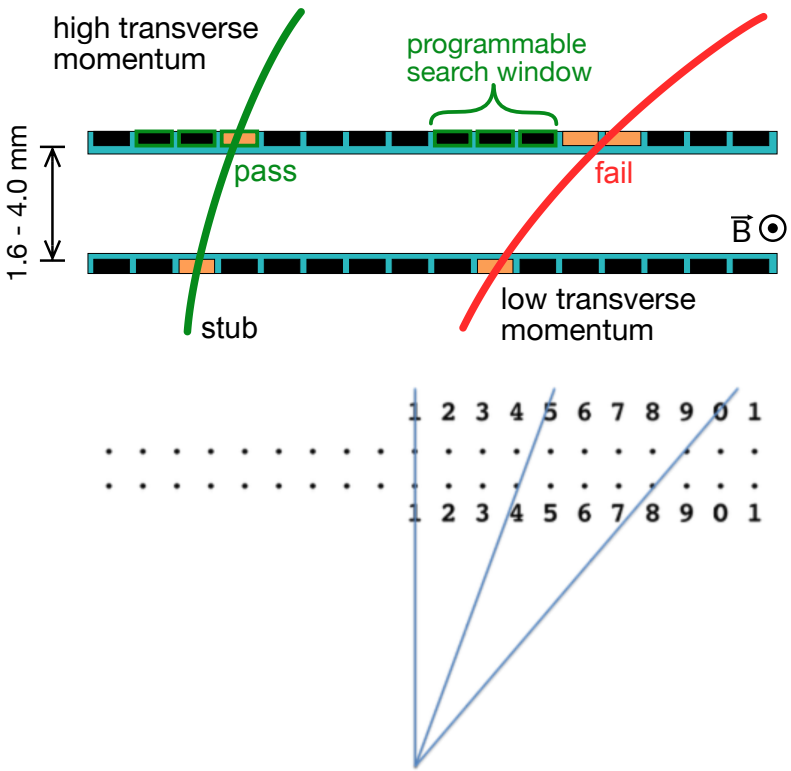


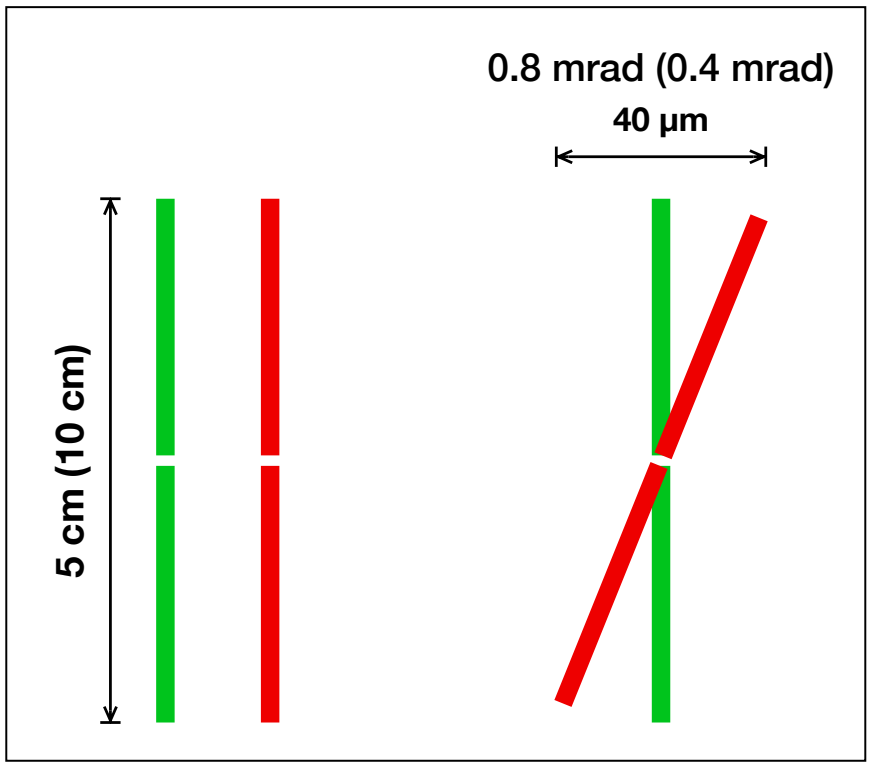


The p_T module: assembly requirements

- 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)

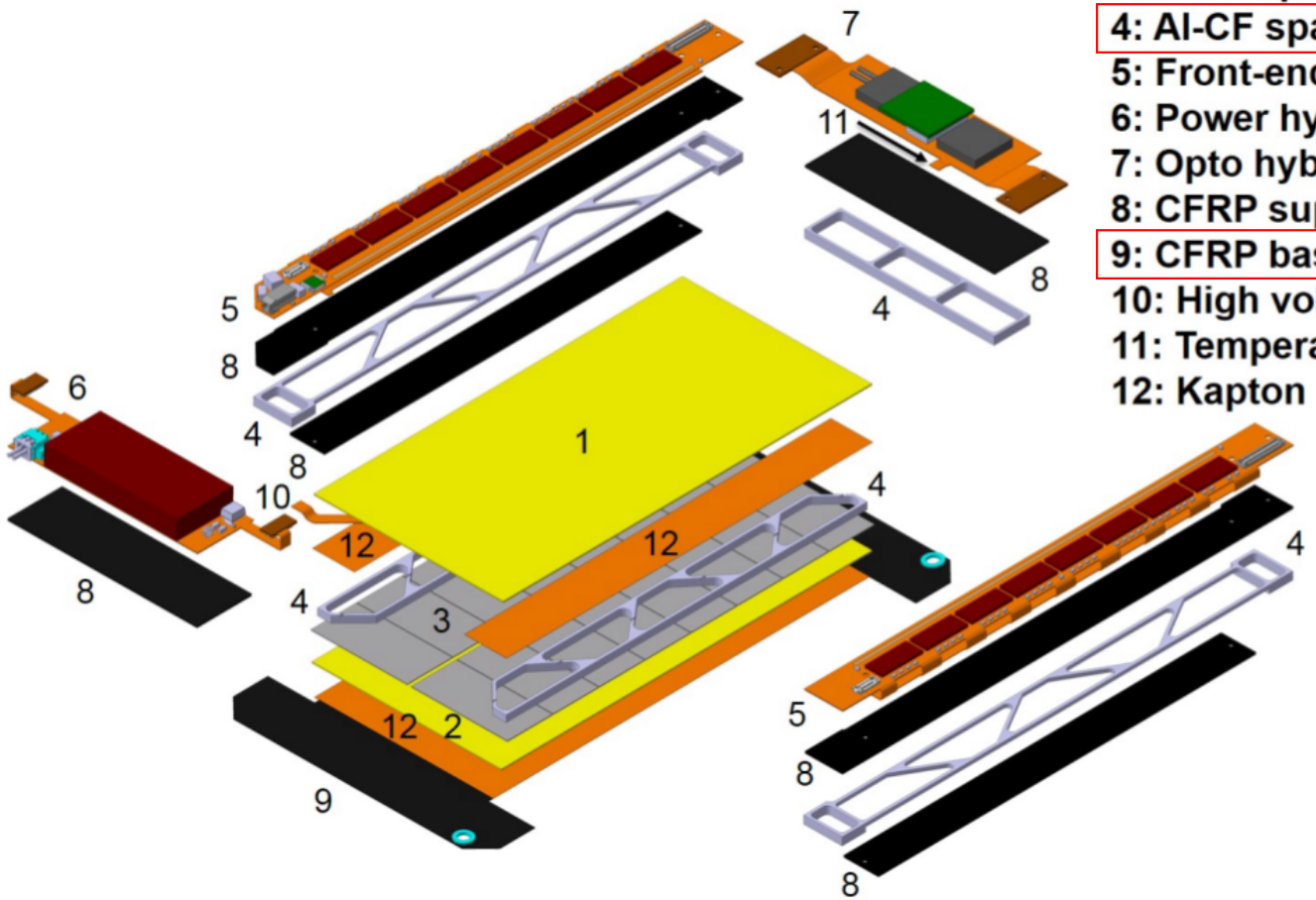
max. angular misalignment of PS sensors: $\mathbf{800\ \mu rad}$





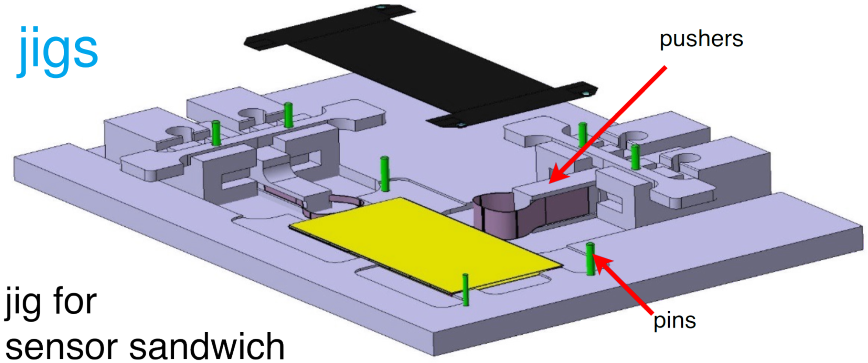
The PS module: a closer look

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

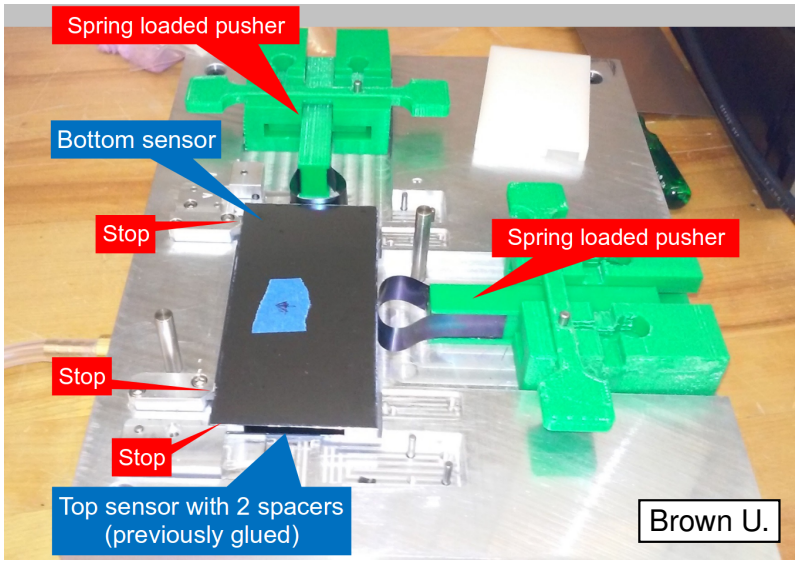


Prelude: the *manual* PS module assembly

- 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?

  $\Longrightarrow$ DESY is exploring an alternative method

The *automated* PS module assembly

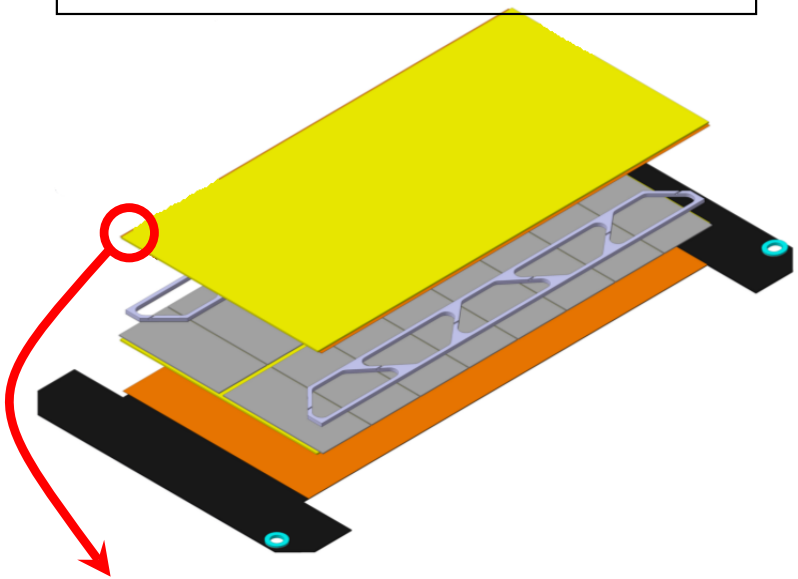
What to automate, and how

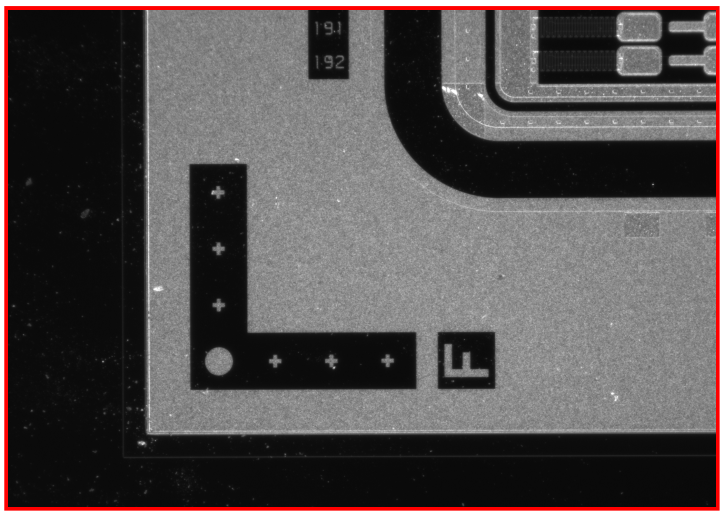
(baseplate +) PSp + spacers + PSs

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

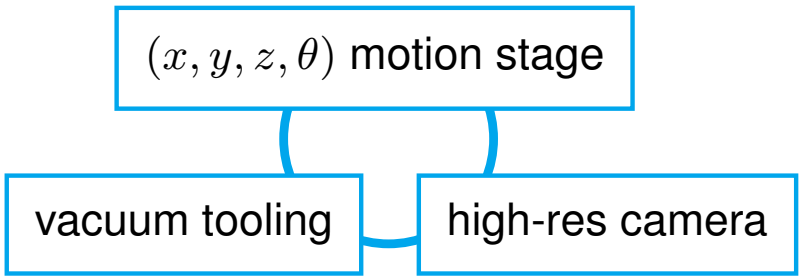
tolerance on PSp-PSs alignment: 800 μrad



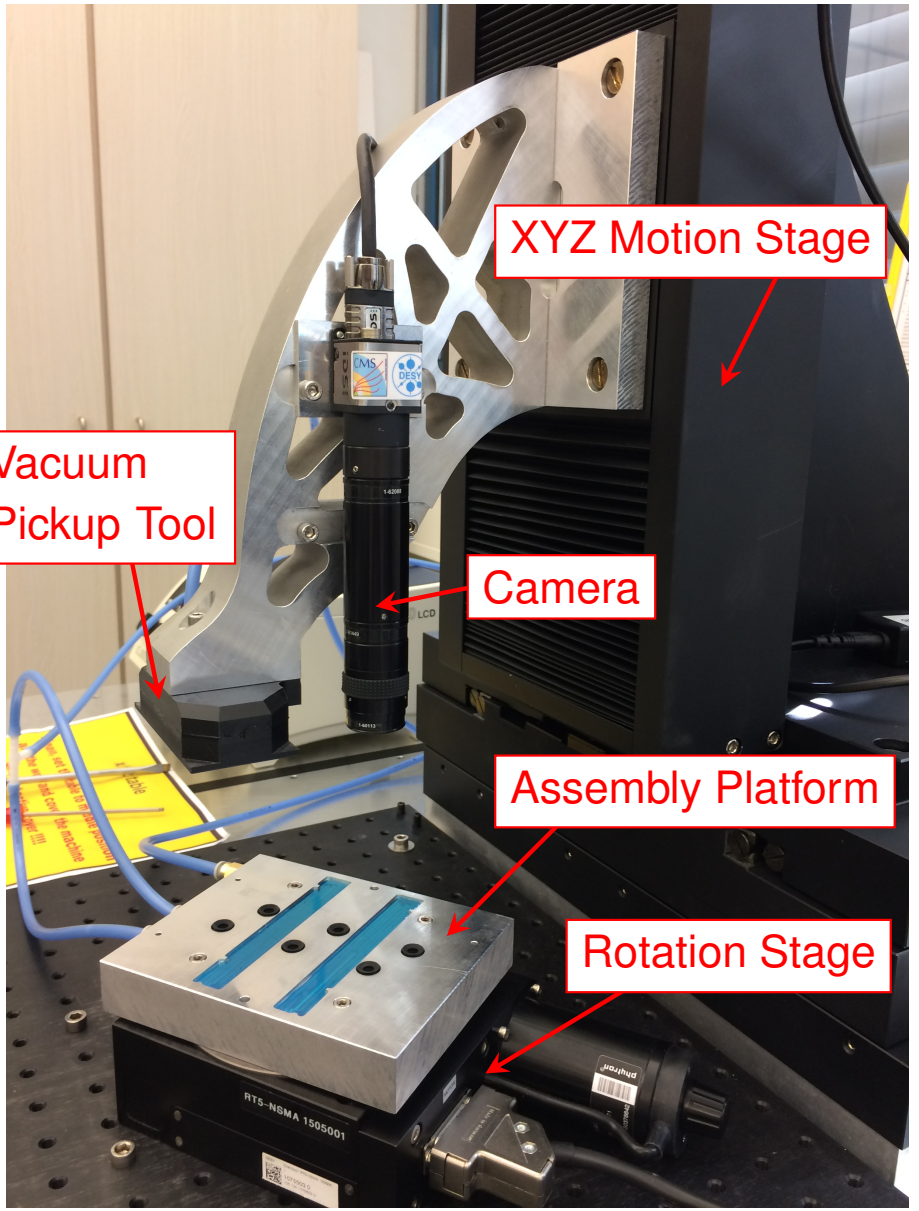


Hardware

- integrated system comprised of

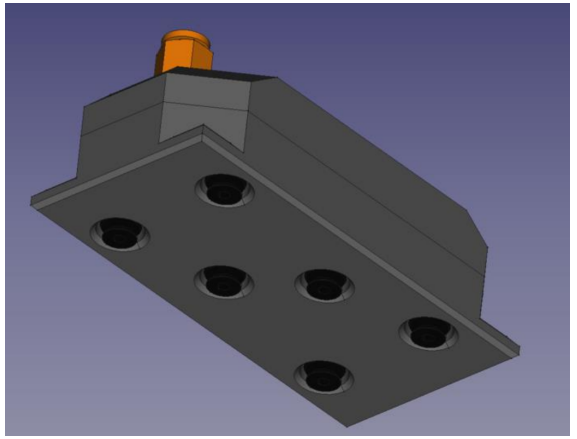


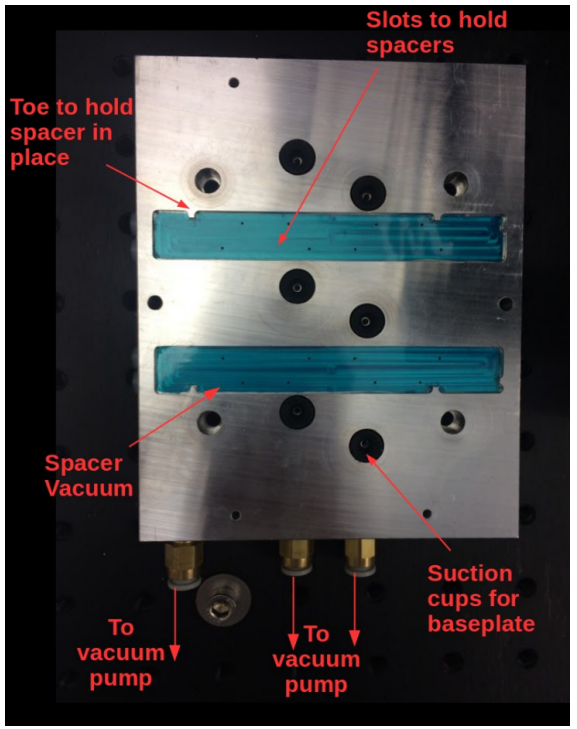
  - motion stage precision:
    $5\ \mu\mathrm{m}$ in (x, y, z), $175\ \mu\mathrm{rad}$ in θ
  - robot-arm with camera and vacuum handling to pick-up/put-down sensors
  - custom-made assembly platform to be mounted on rotation stage



Hardware / pickup tool and platform

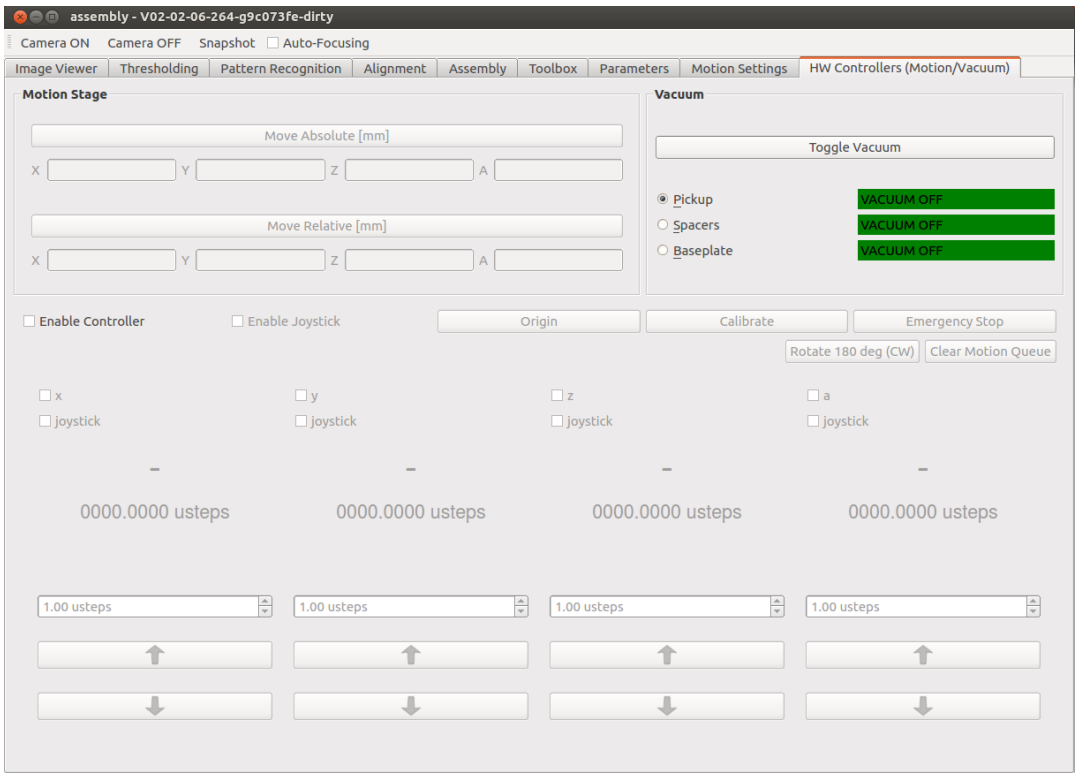
- ESD plastic “pickup tool”
  - vacuum distributed via inner chamber and ESD rubber suction cups on lower surface
  - provides secure but non-destructive handling of sensors
- assembly platform on rotation stage
  - independent vacuum lines for spacers and baseplate/sensor
  - positioning pins for baseplate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

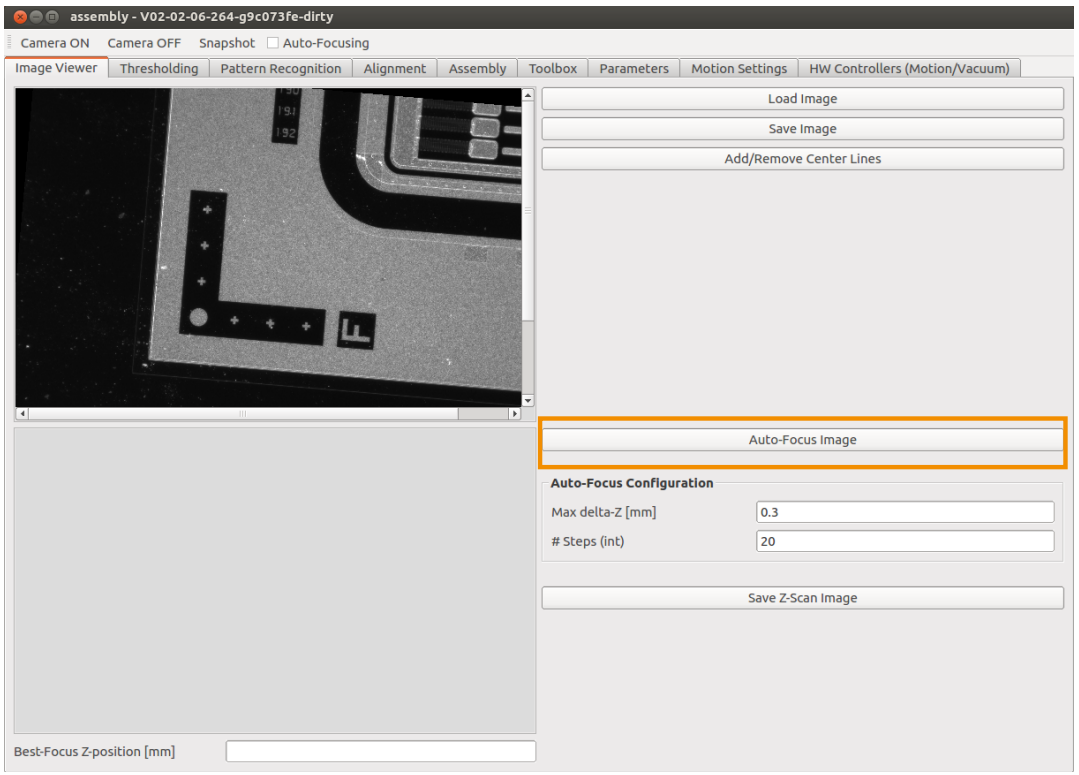


- HW Controllers (motion, vacuum)
- Image Viewer + Auto-Focusing

. . . more on SW-interface later

Software

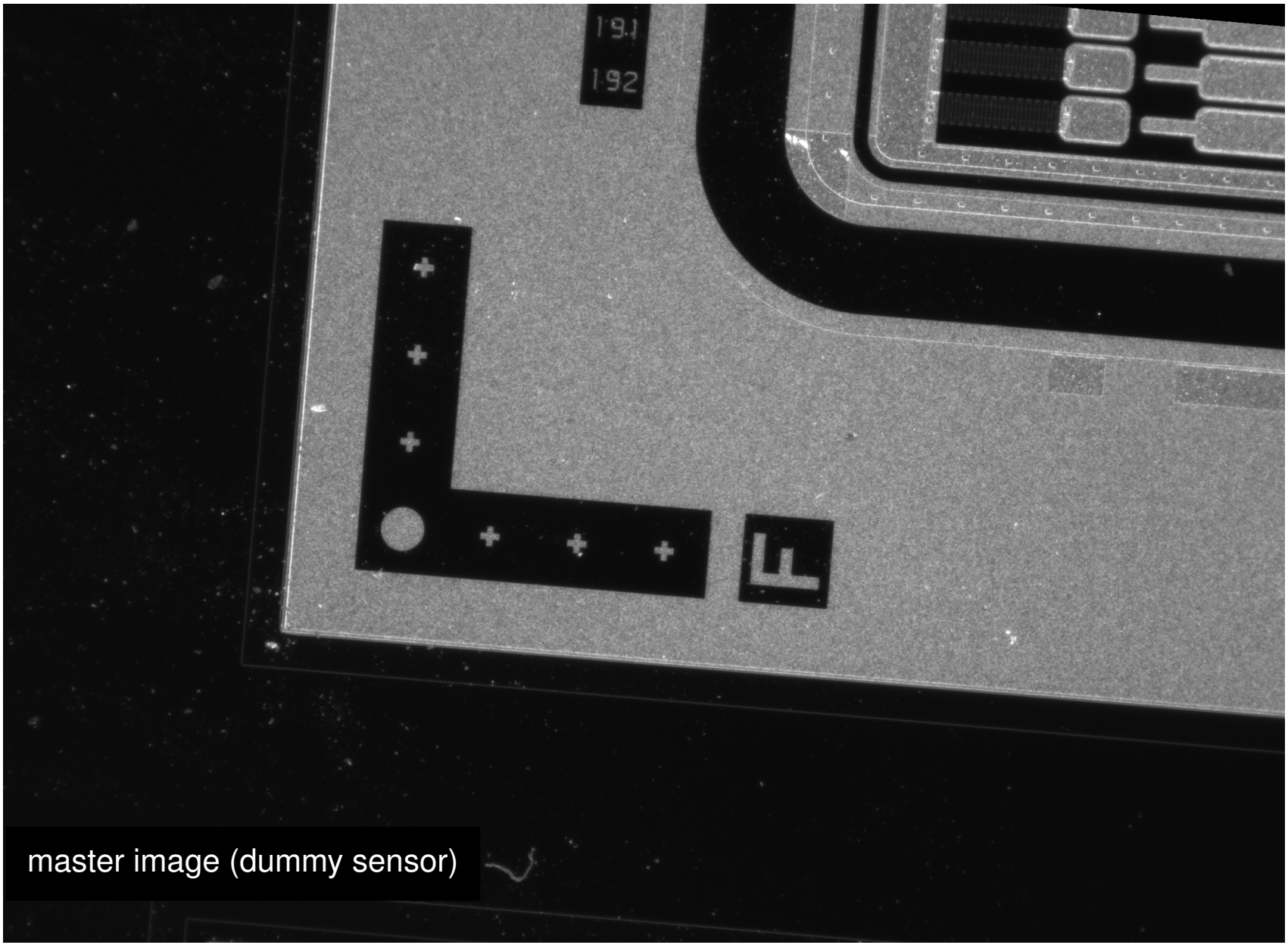
- dedicated software interface developed at DESY
  https://github.com/DESY-FH-Elab/cmstkmodlab/assembly
- controls motion, vacuum and image acquisition



- HW Controllers (motion, vacuum)
- Image Viewer + Auto-Focusing

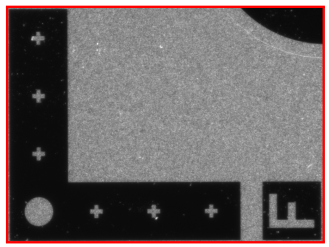
. . . more on SW-interface later

Finding the marker



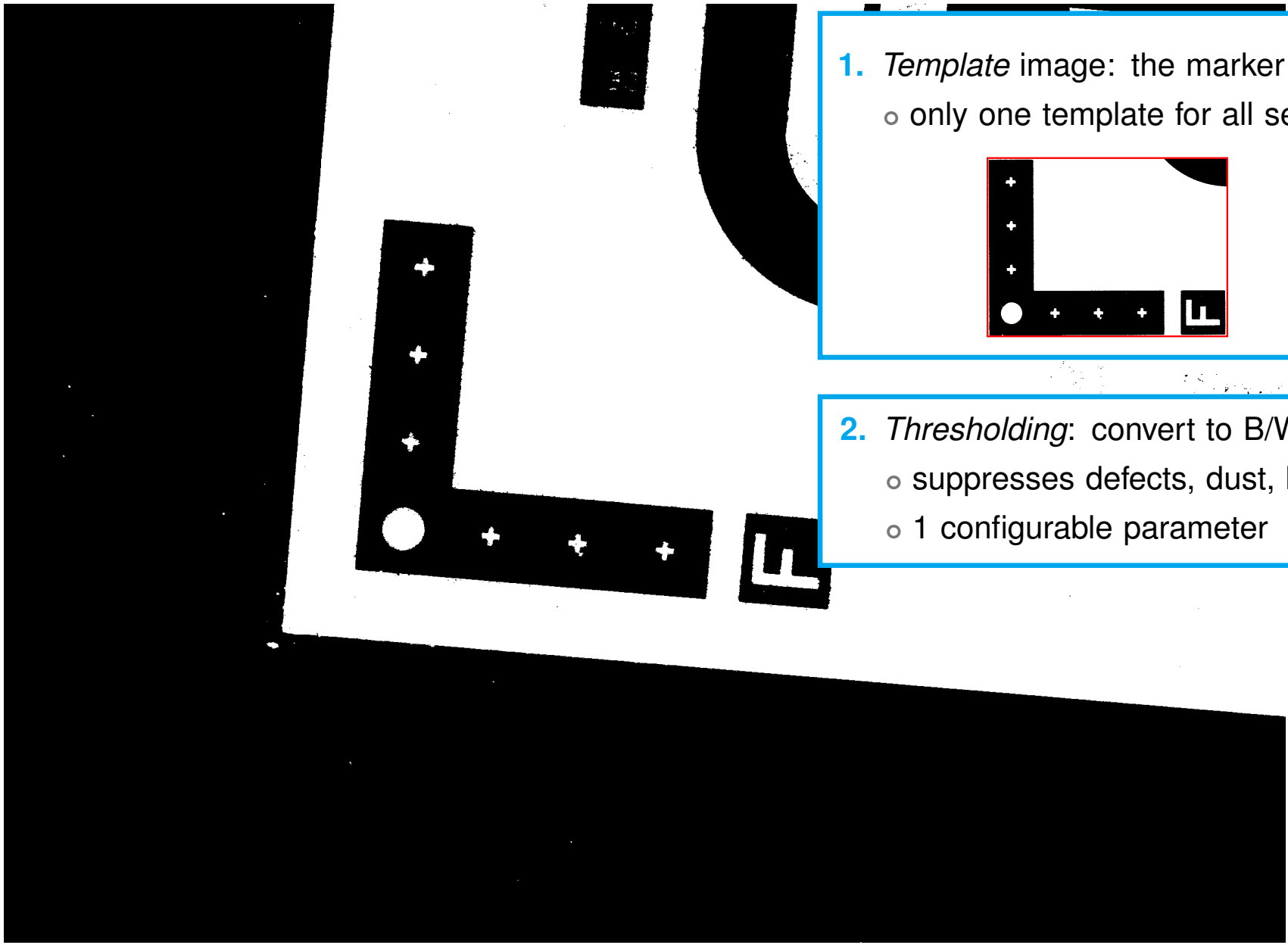
Finding the marker

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



master image (dummy sensor)

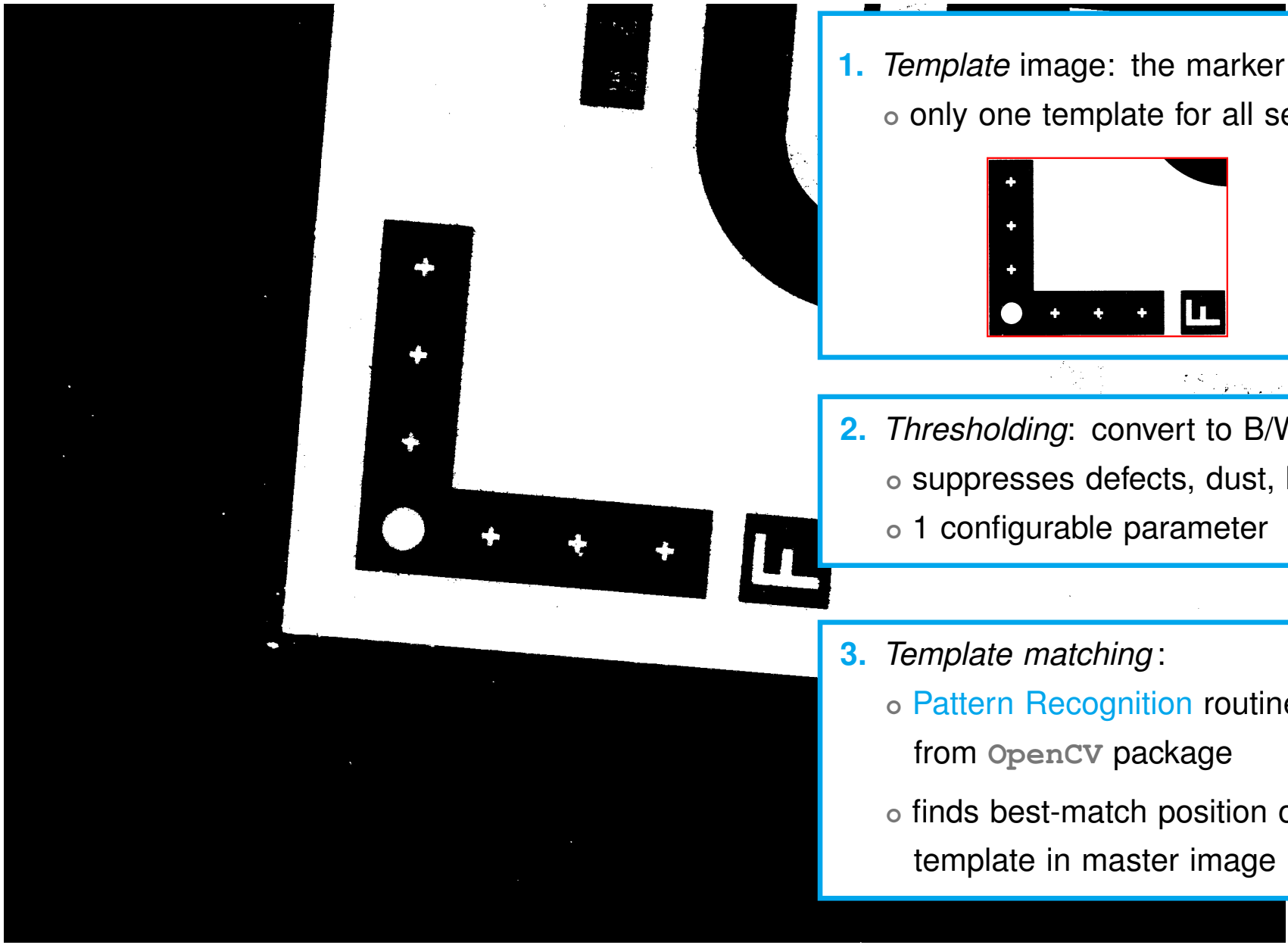
Finding the marker



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

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

Finding the marker

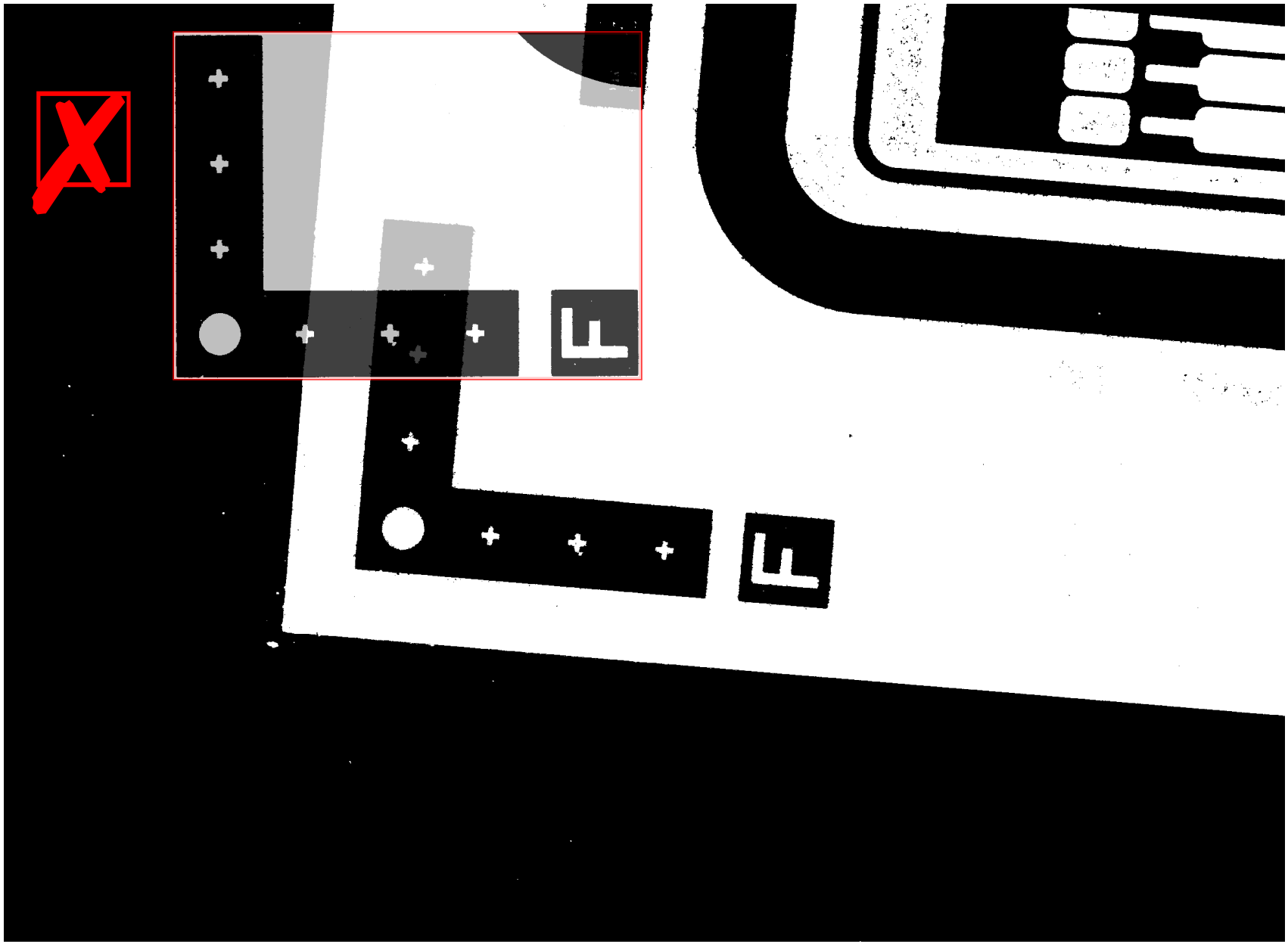


1. *Template* image: the marker
   - only one template for all sensors

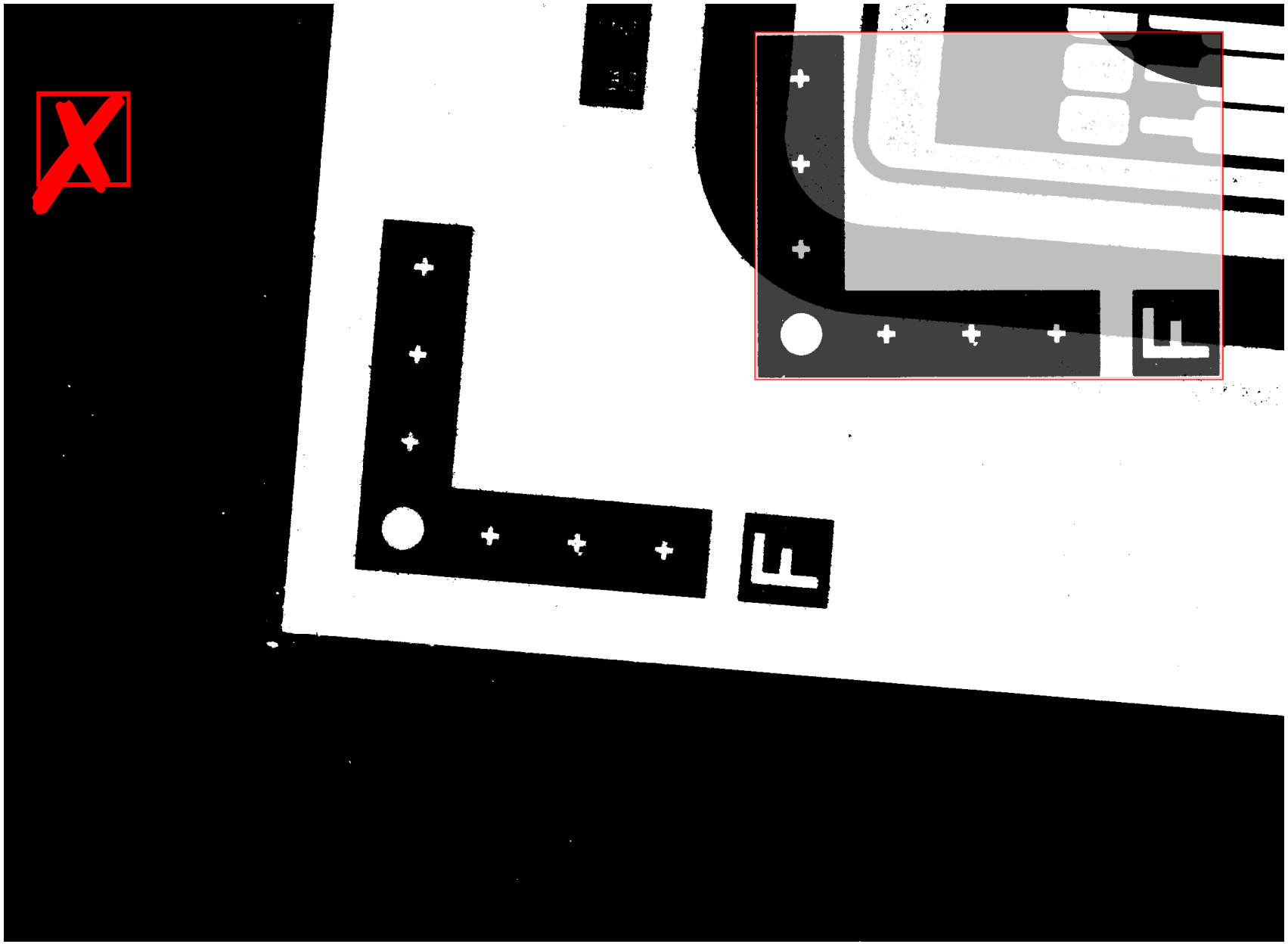
2. *Thresholding*: convert to B/W
   - suppresses defects, dust, bkg
   - 1 configurable parameter

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

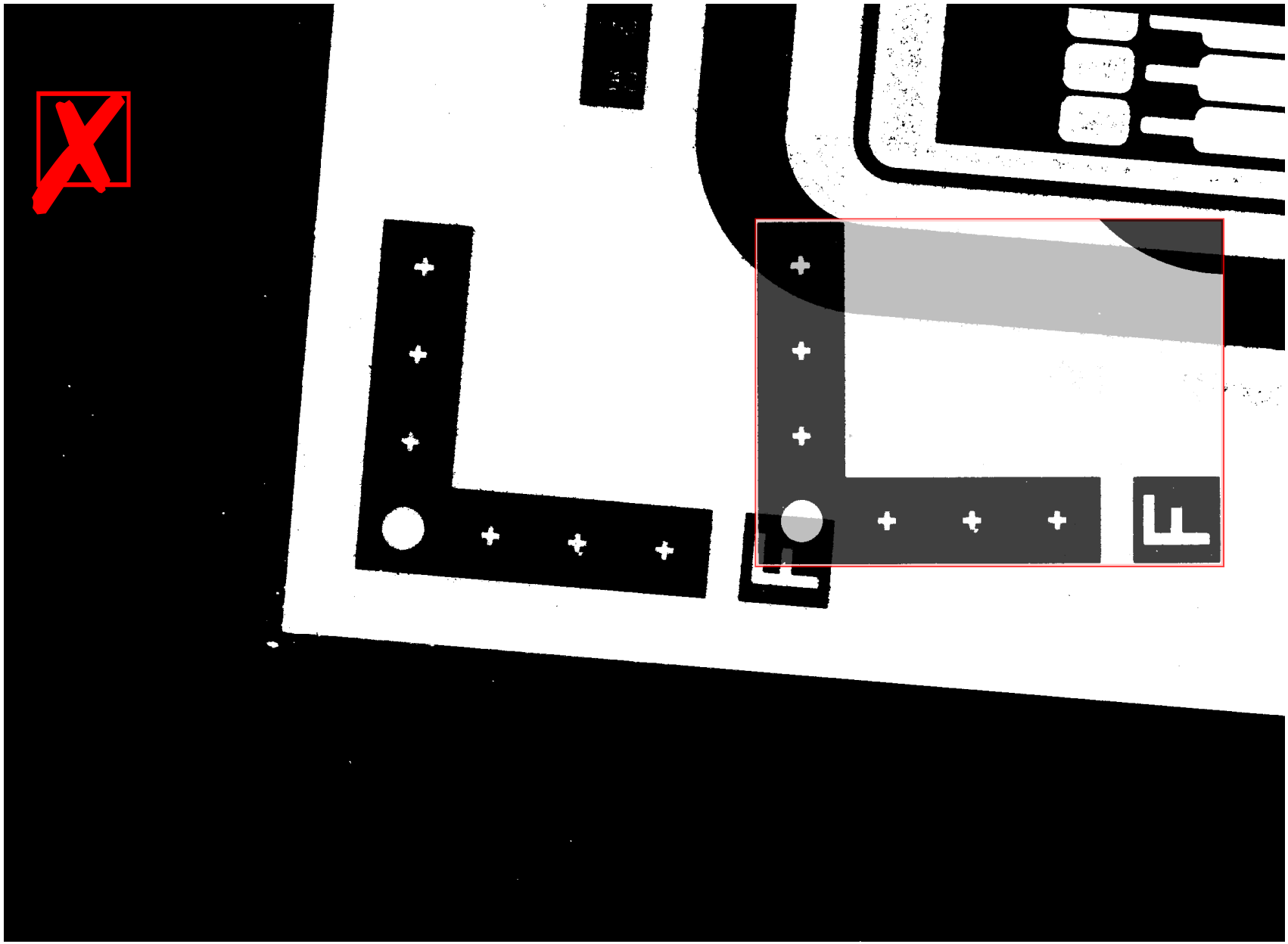
Finding the marker



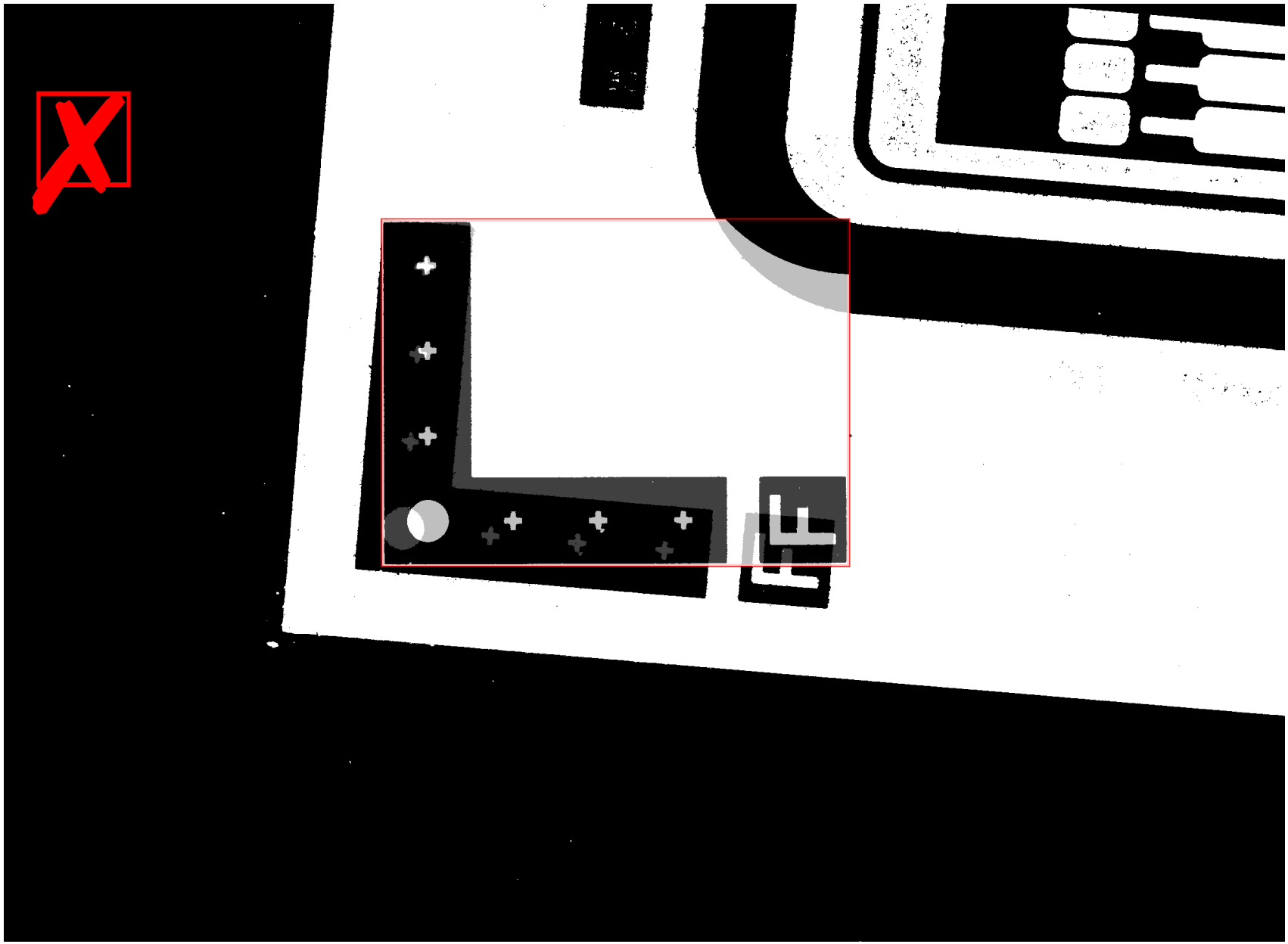
Finding the marker



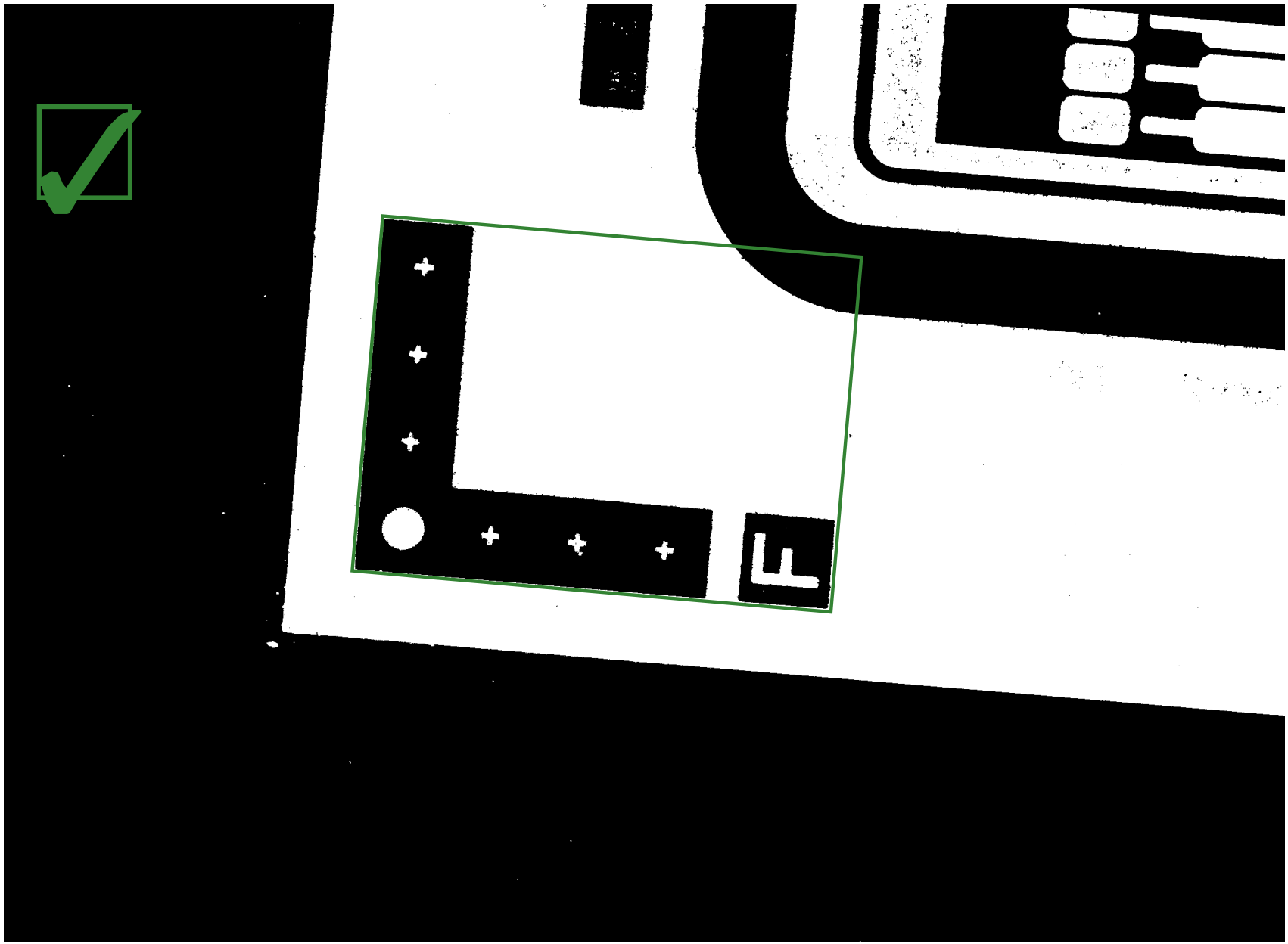
Finding the marker



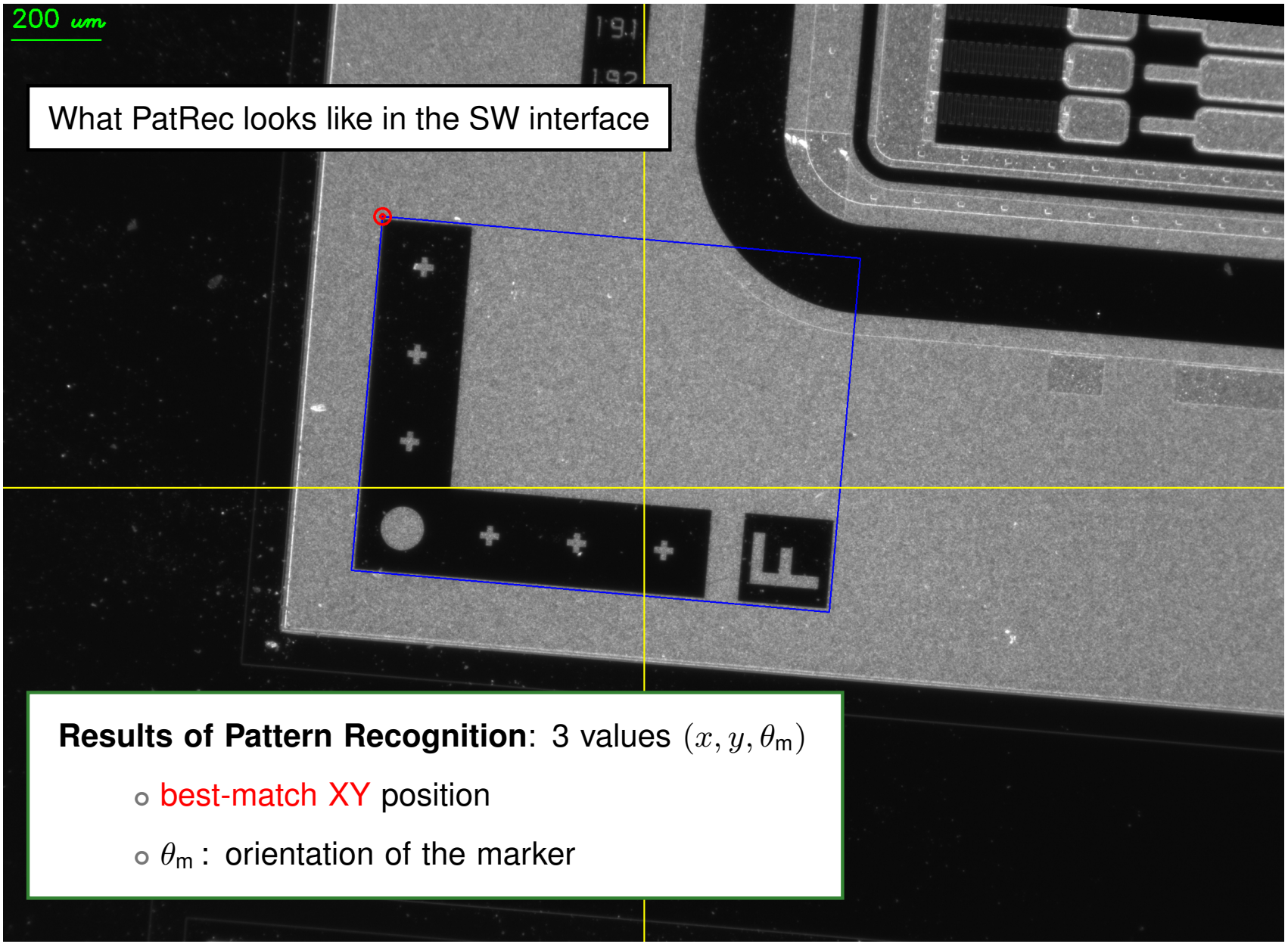
Finding the marker



Finding the marker



Finding the marker



Results of Pattern Recognition: 3 values $(x, y, \theta_{\mathrm{m}})$

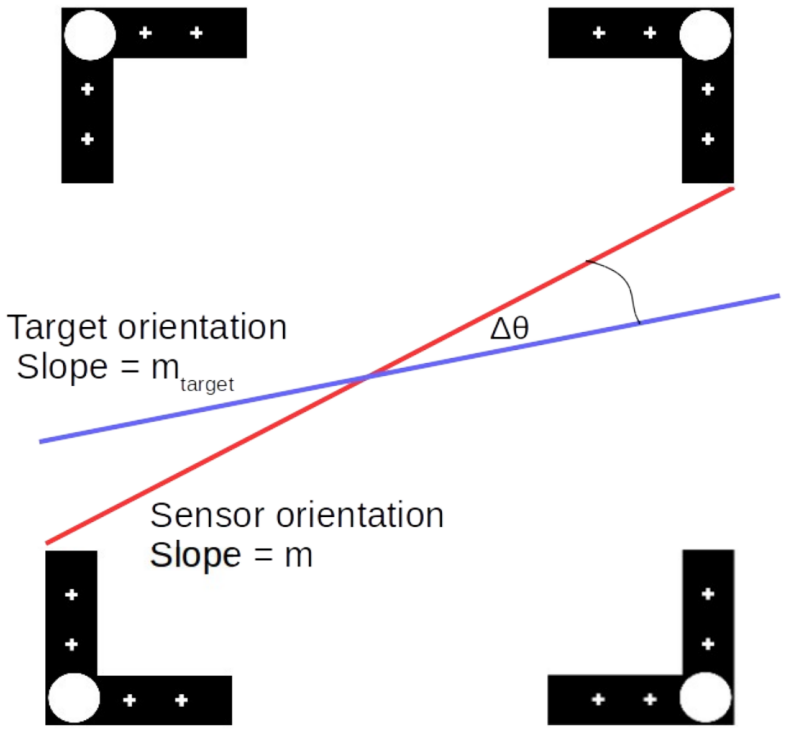
- best-match XY position
- θ_{m} : orientation of the marker

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 θ_{m1} to automatically move to opposite marker (sensor dim. known)
  3. run PatRec on marker $\#2 \Rightarrow (x_2, y_2, \theta_{m2})$



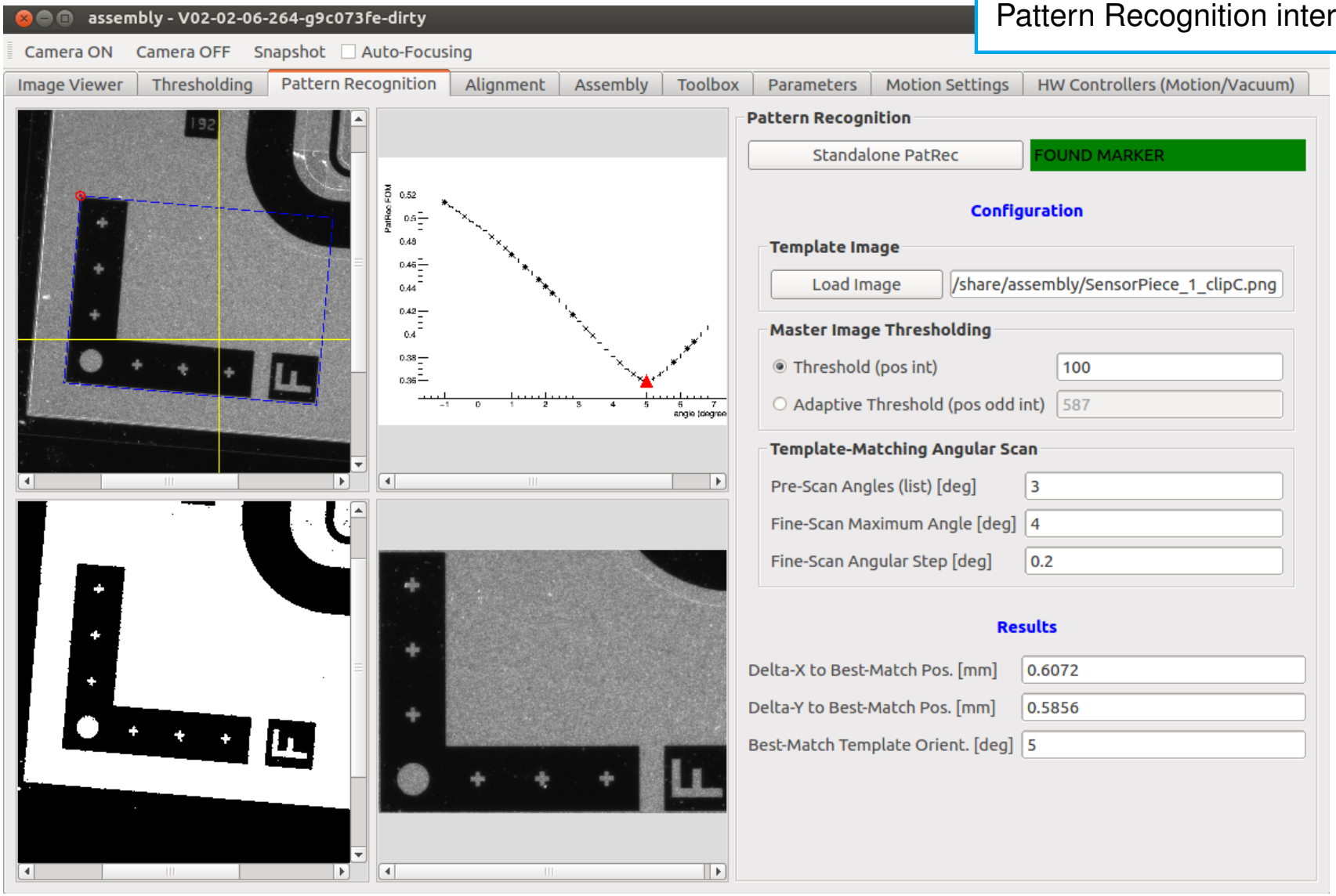
- sensor orientation: measured slope $(x_1, y_1) \rightarrow (x_2, y_2)$

- after rotating to target θ, sensor orient. remeasured to validate alignment

SW interface to PatRec and Alignment

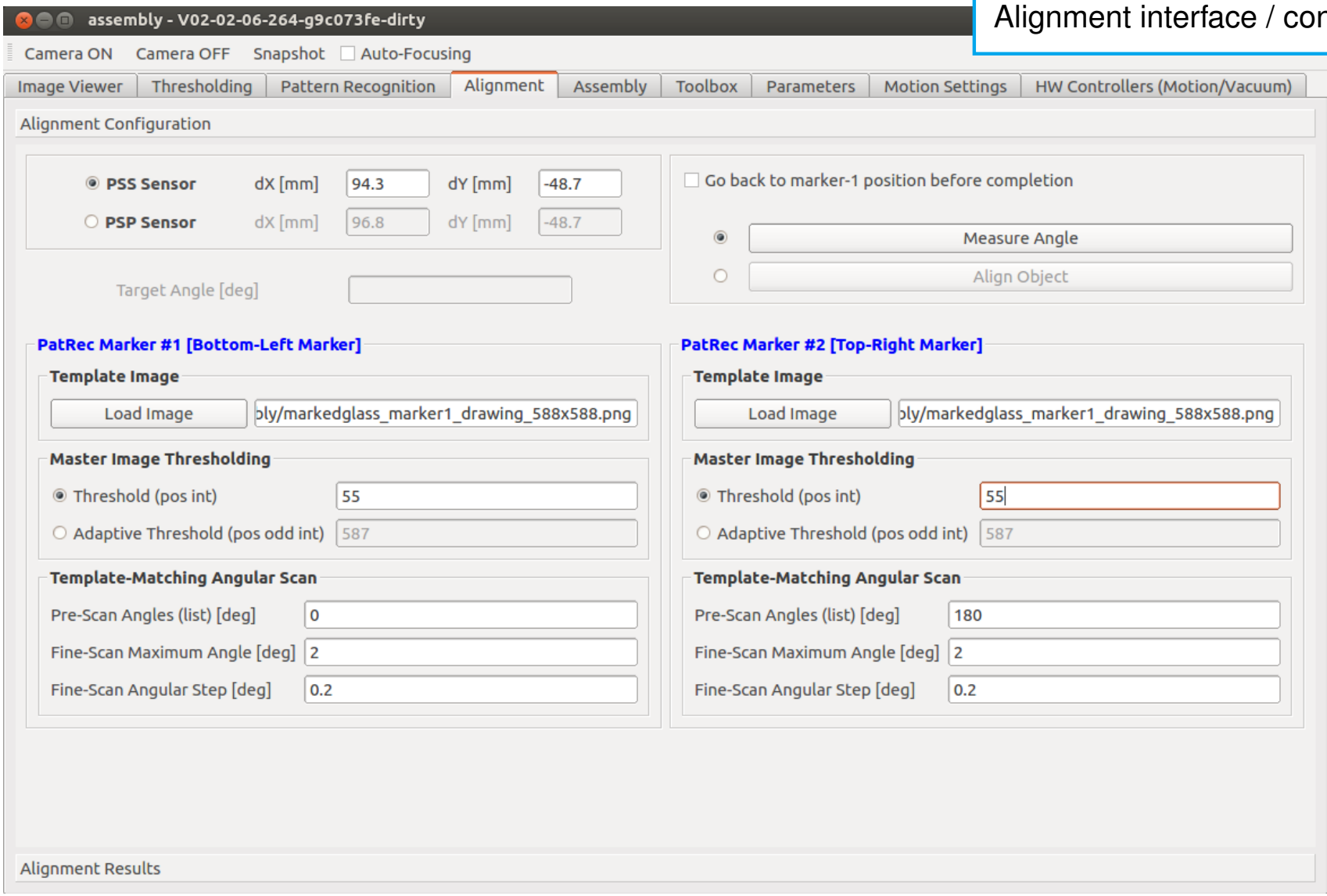
- real-time feedback on PatRec/alignment results

Pattern Recognition interface



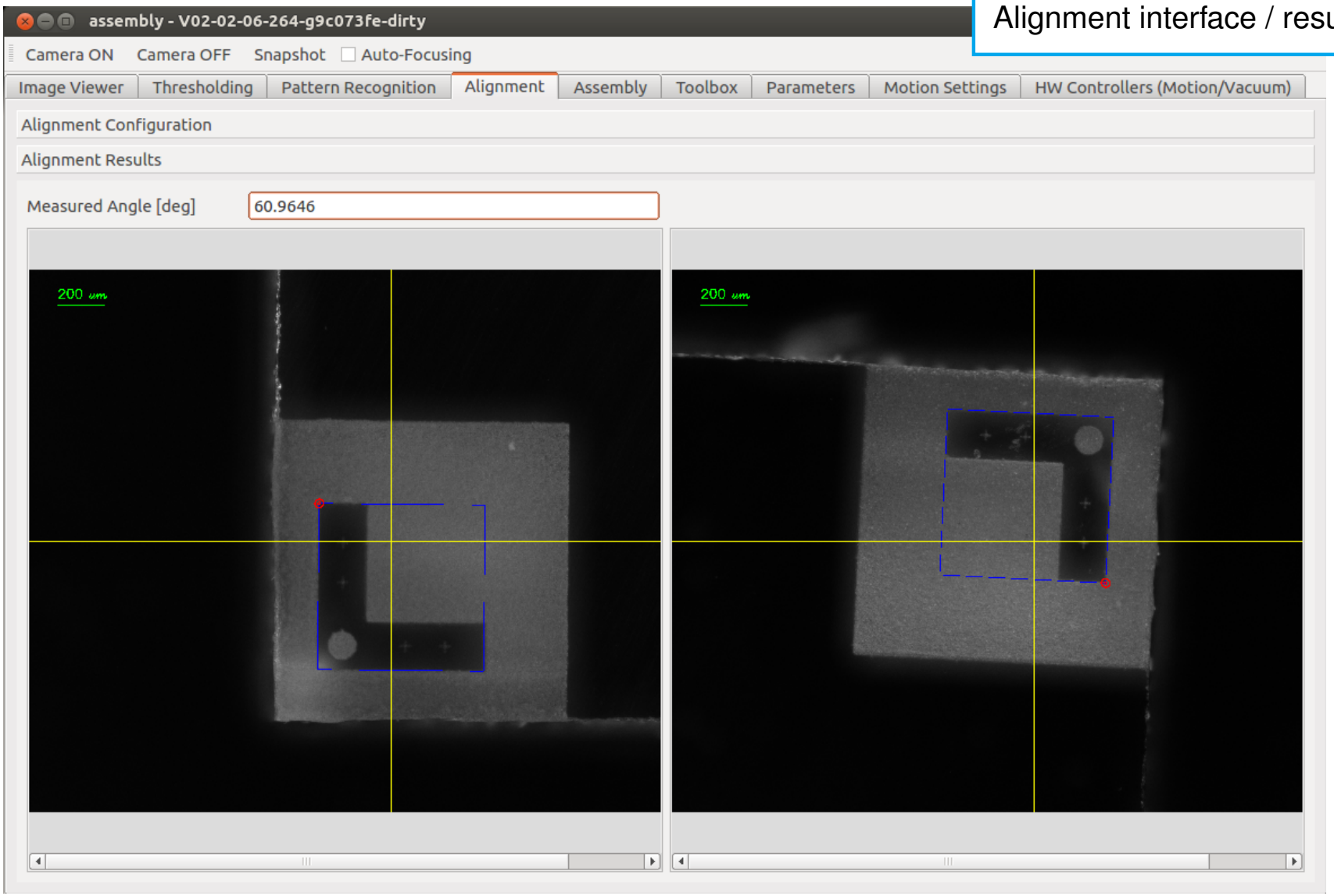
SW interface to PatRec and Alignment

- real-time feedback on PatRec/alignment results



SW interface to PatRec and Alignment

- real-time feedback on PatRec/alignment results



Gluing

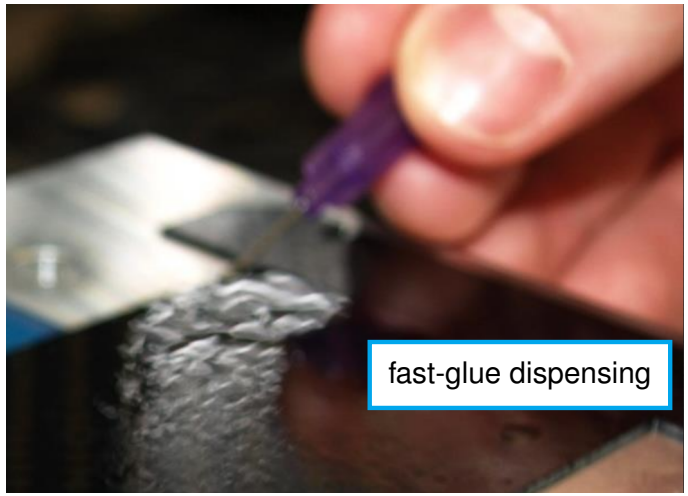
- two types of glue used in the assembly

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

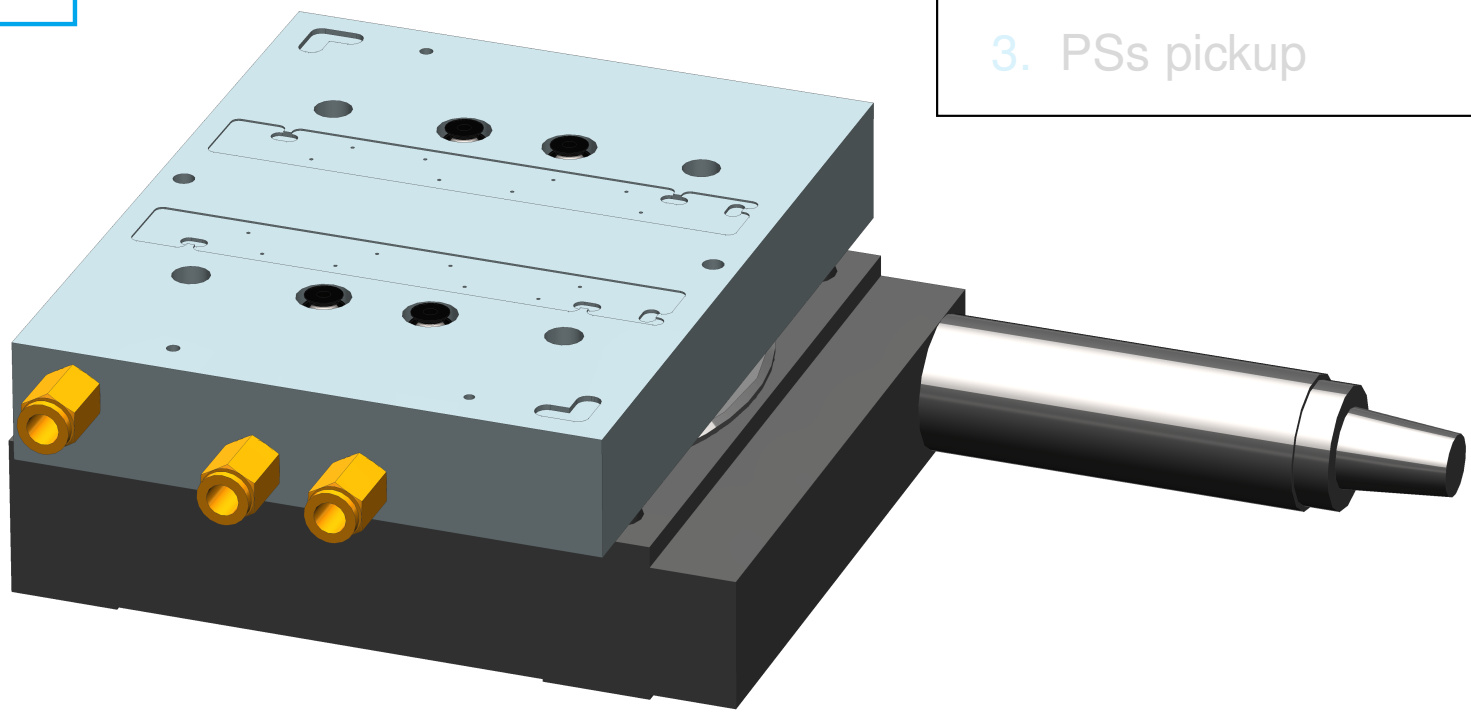
The assembly procedure

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

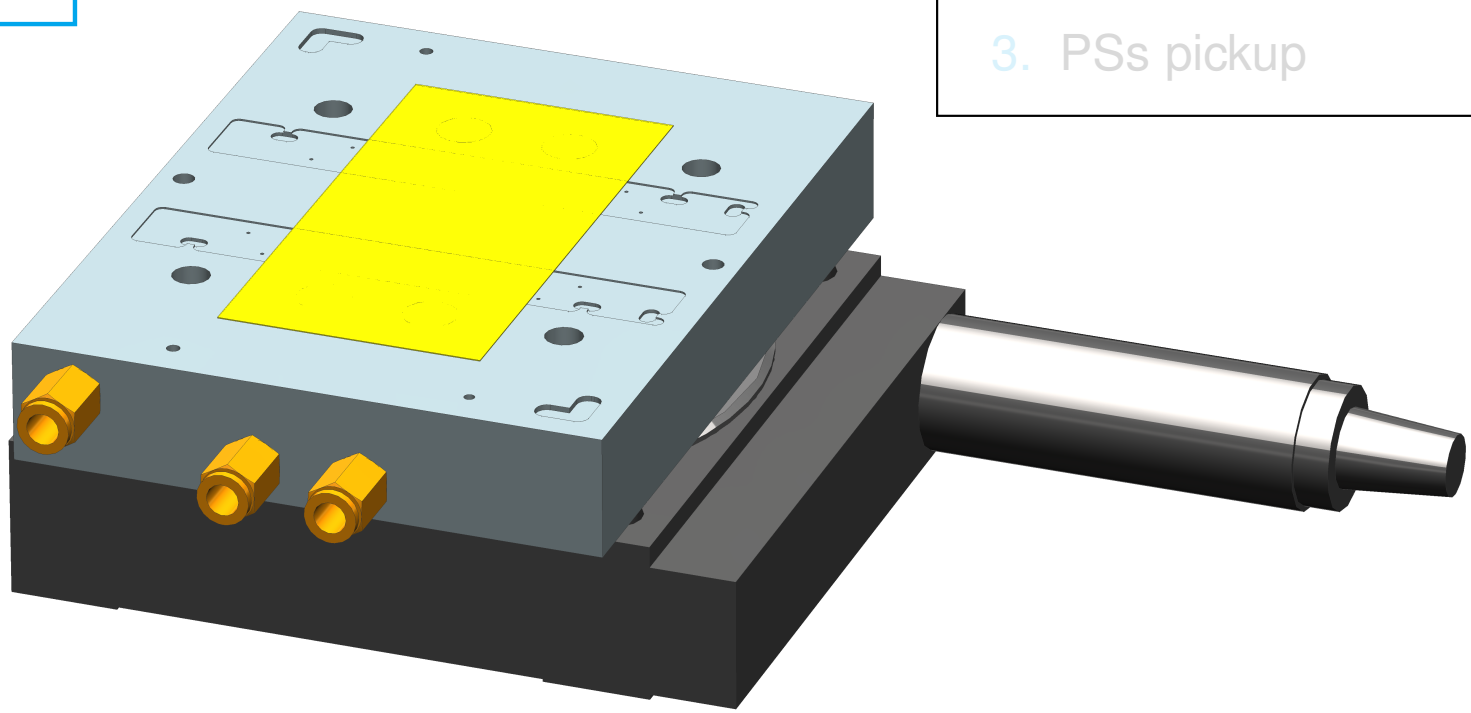


Assembly procedure

Step #1 alignment and pickup of PSs

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers

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

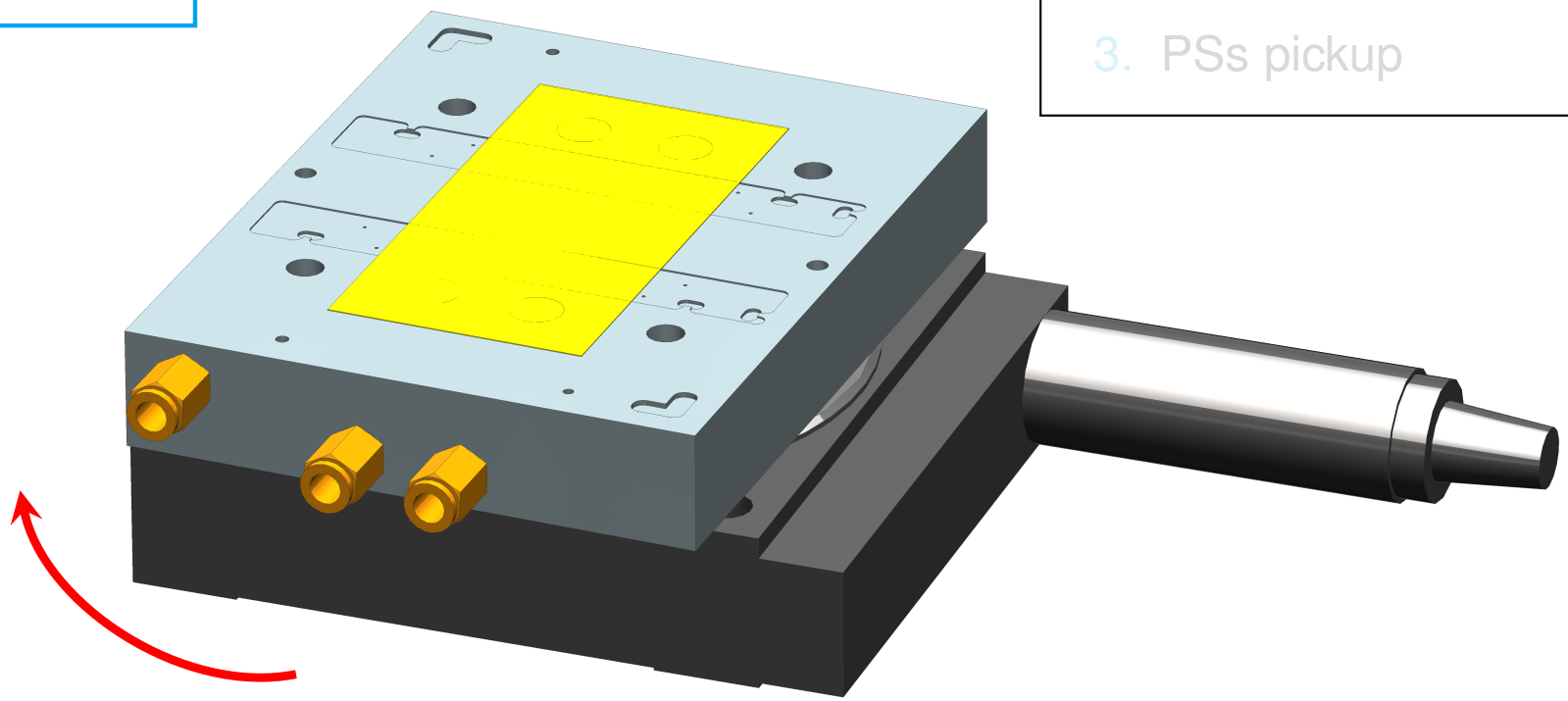


Assembly procedure

Step #1 alignment and pickup of PSs

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers

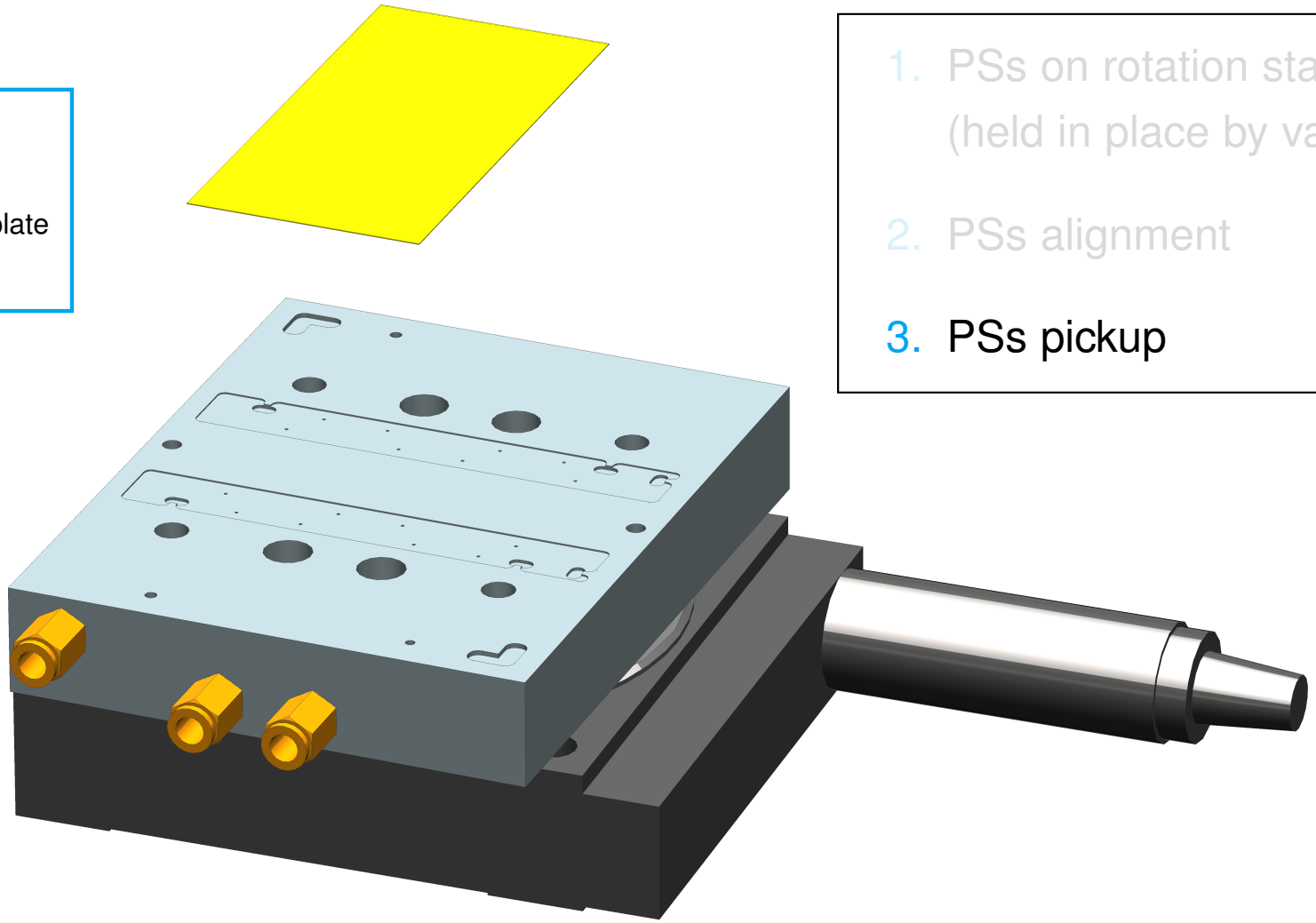
1. PSs on rotation stage (held in place by vacuum)
2. PSs alignment
3. PSs pickup



Assembly procedure

Step #1 alignment and pickup of PSs

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers

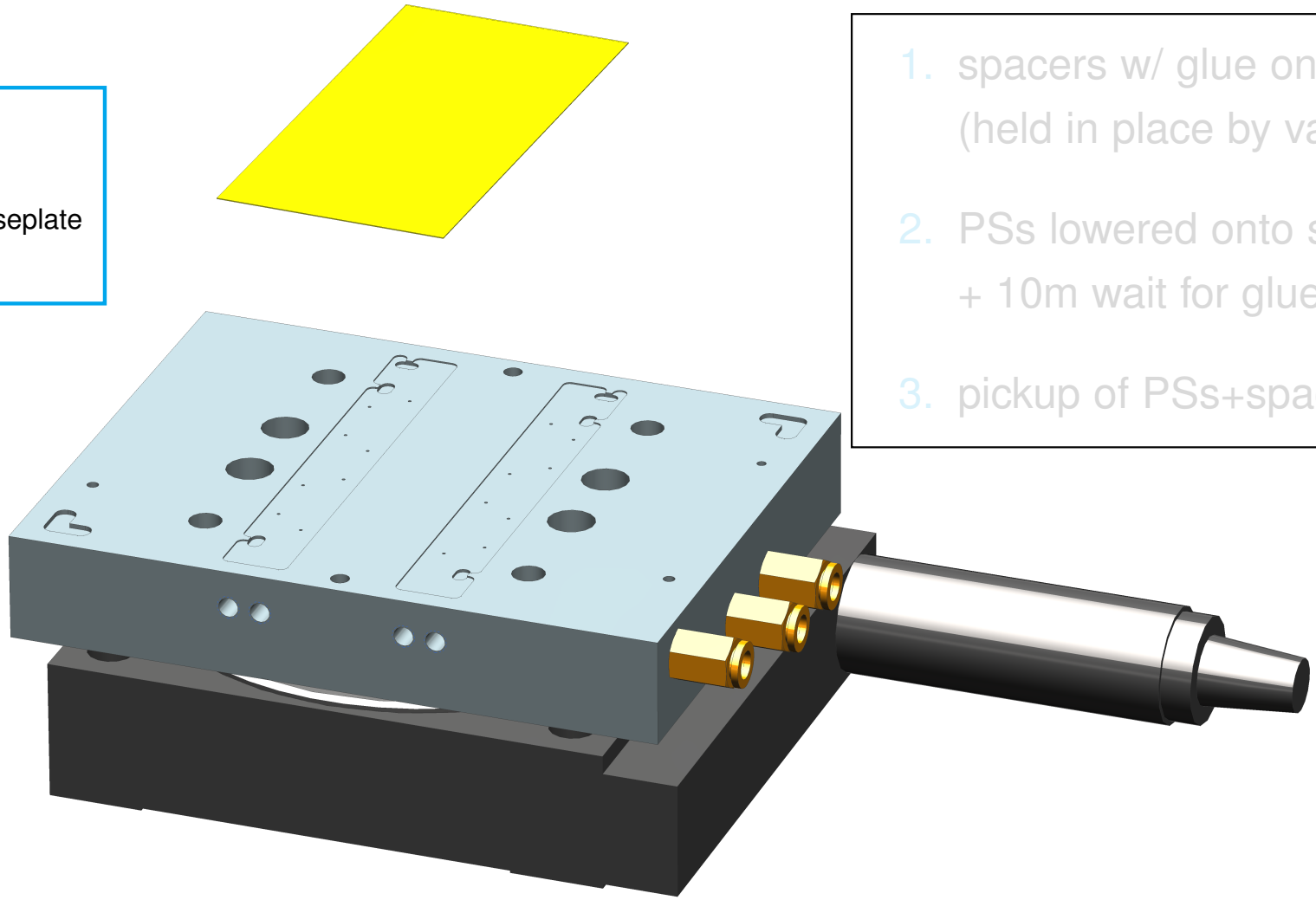


1. PSs on rotation stage (held in place by vacuum)
2. PSs alignment
3. PSs pickup

Assembly procedure

Step #2 PSs + spacers assembly

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers

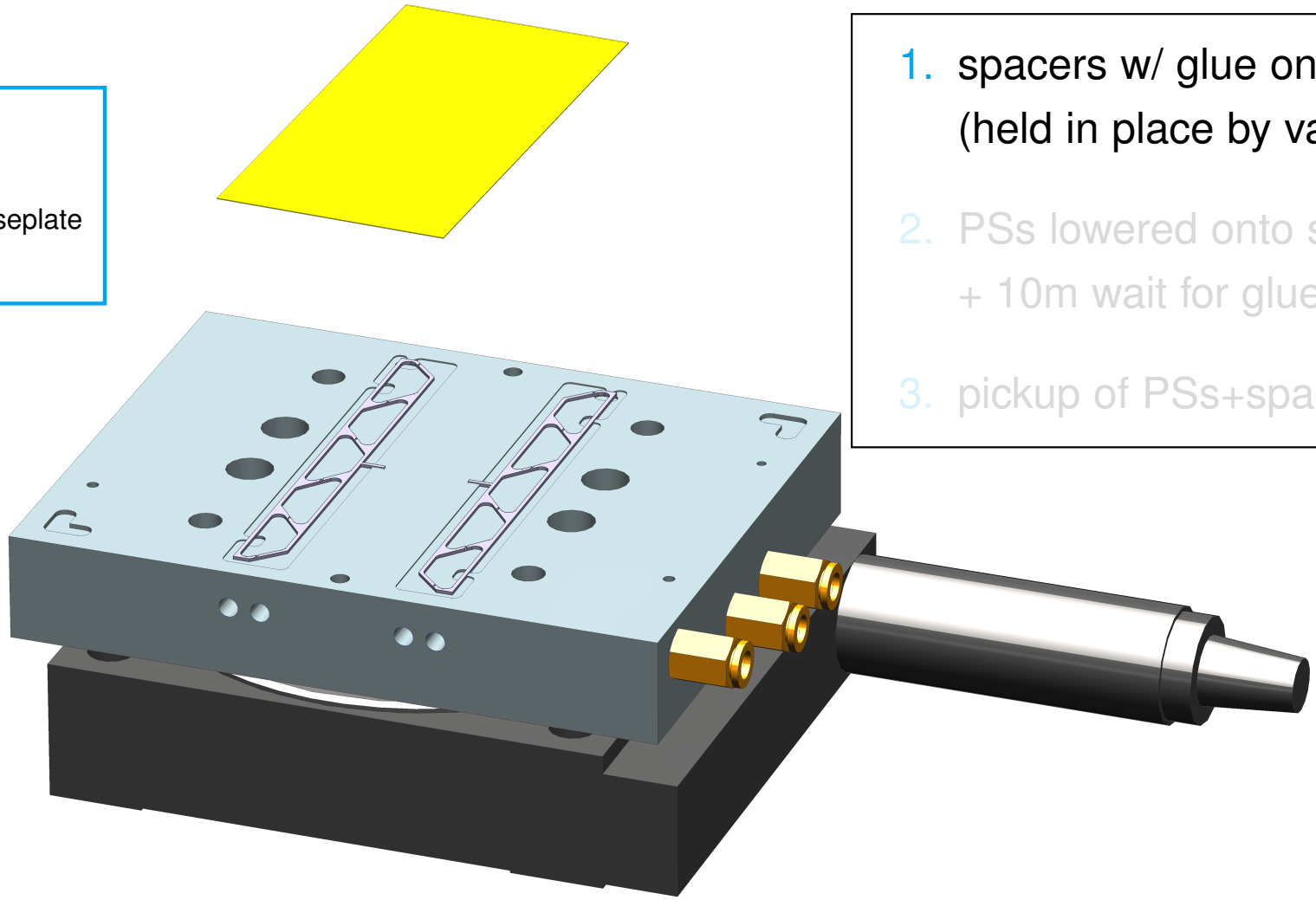


1. spacers w/ glue on stage (held in place by vacuum)
2. PSs lowered onto spacers + 10m wait for glue curing
3. pickup of PSs+spacers

Assembly procedure

Step #2 PSs + spacers assembly

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers



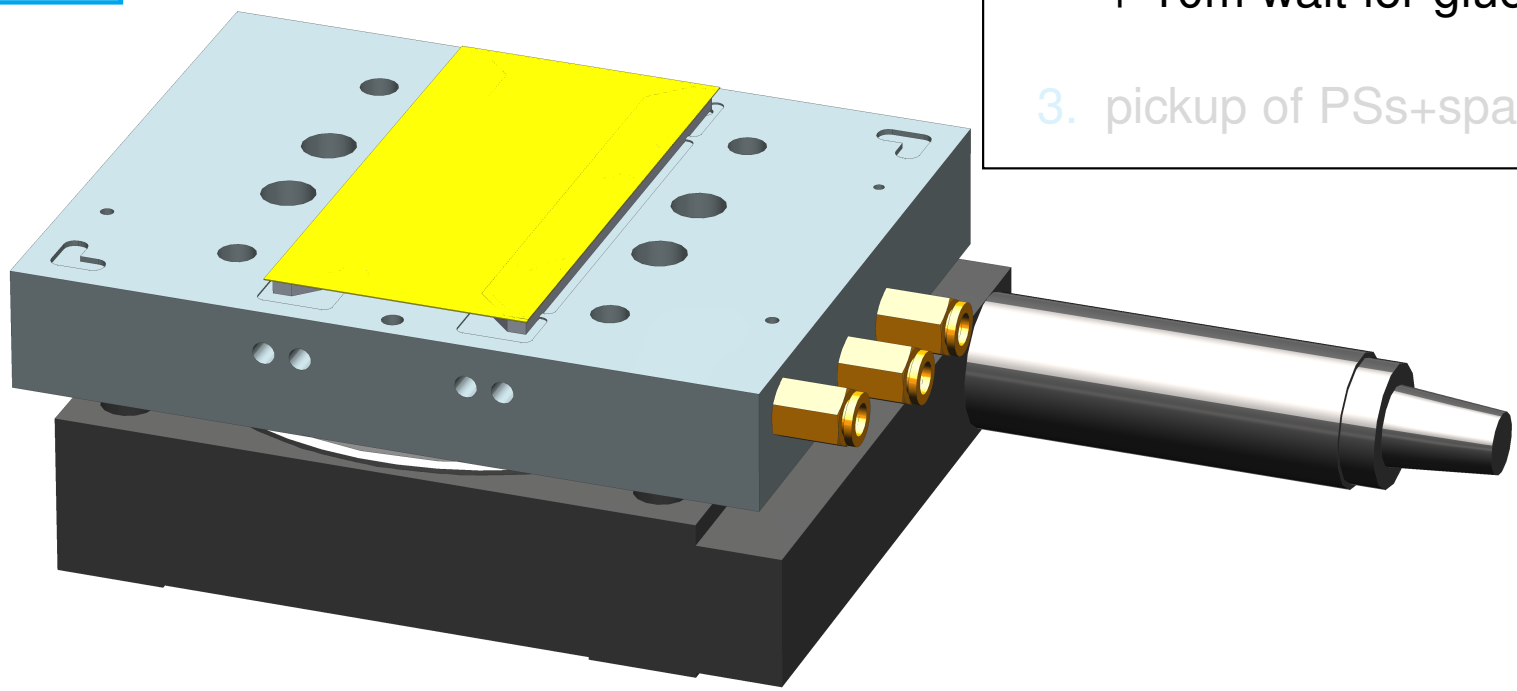
1. spacers w/ glue on stage (held in place by vacuum)
2. PSs lowered onto spacers + 10m wait for glue curing
3. pickup of PSs+spacers

Assembly procedure

Step #2 PSs + spacers assembly

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers

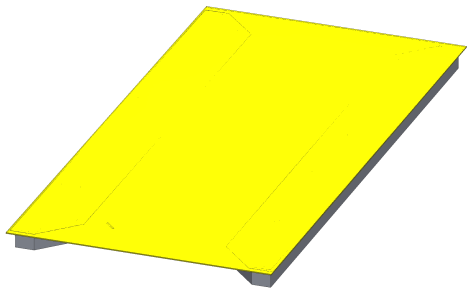
1. spacers w/ glue on stage (held in place by vacuum)
2. PSs lowered onto spacers + 10m wait for glue curing
3. pickup of PSs+spacers

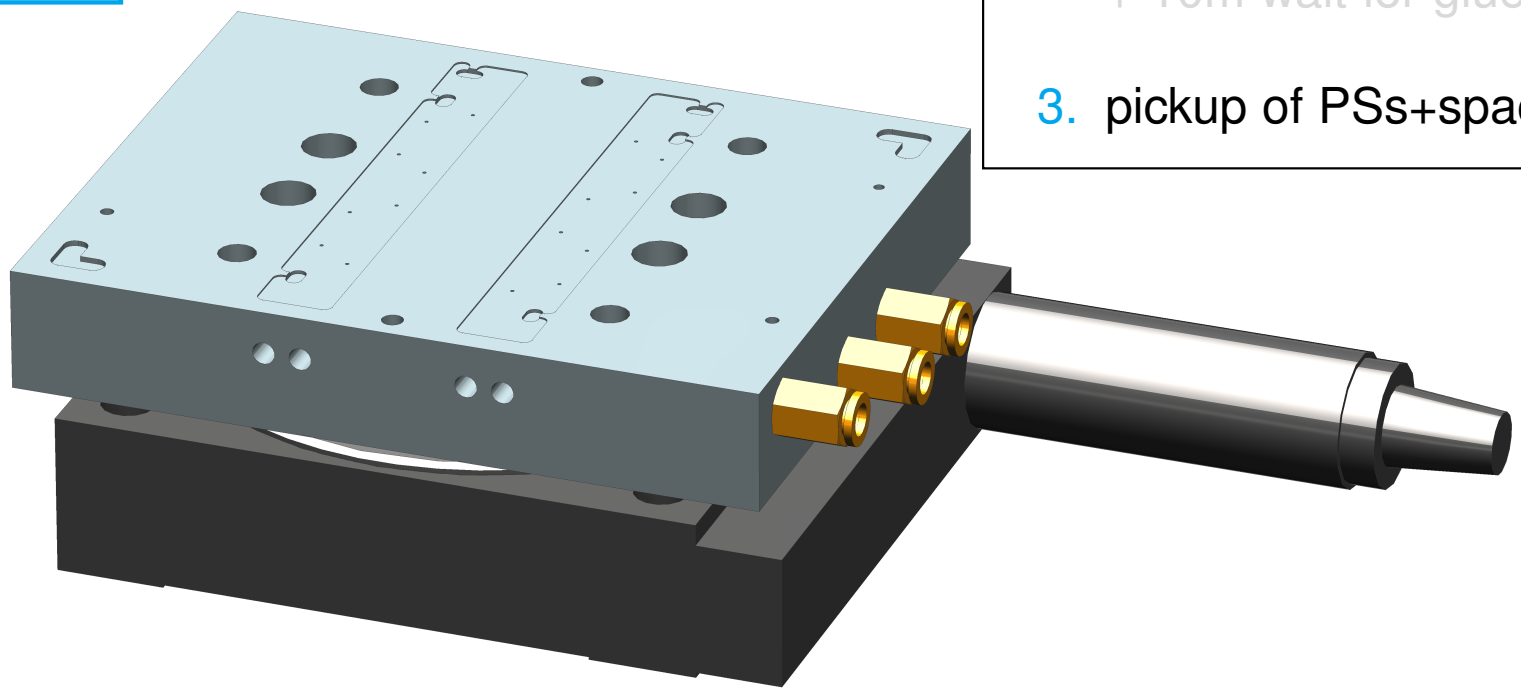


Assembly procedure

Step #2 PSs + spacers assembly

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers



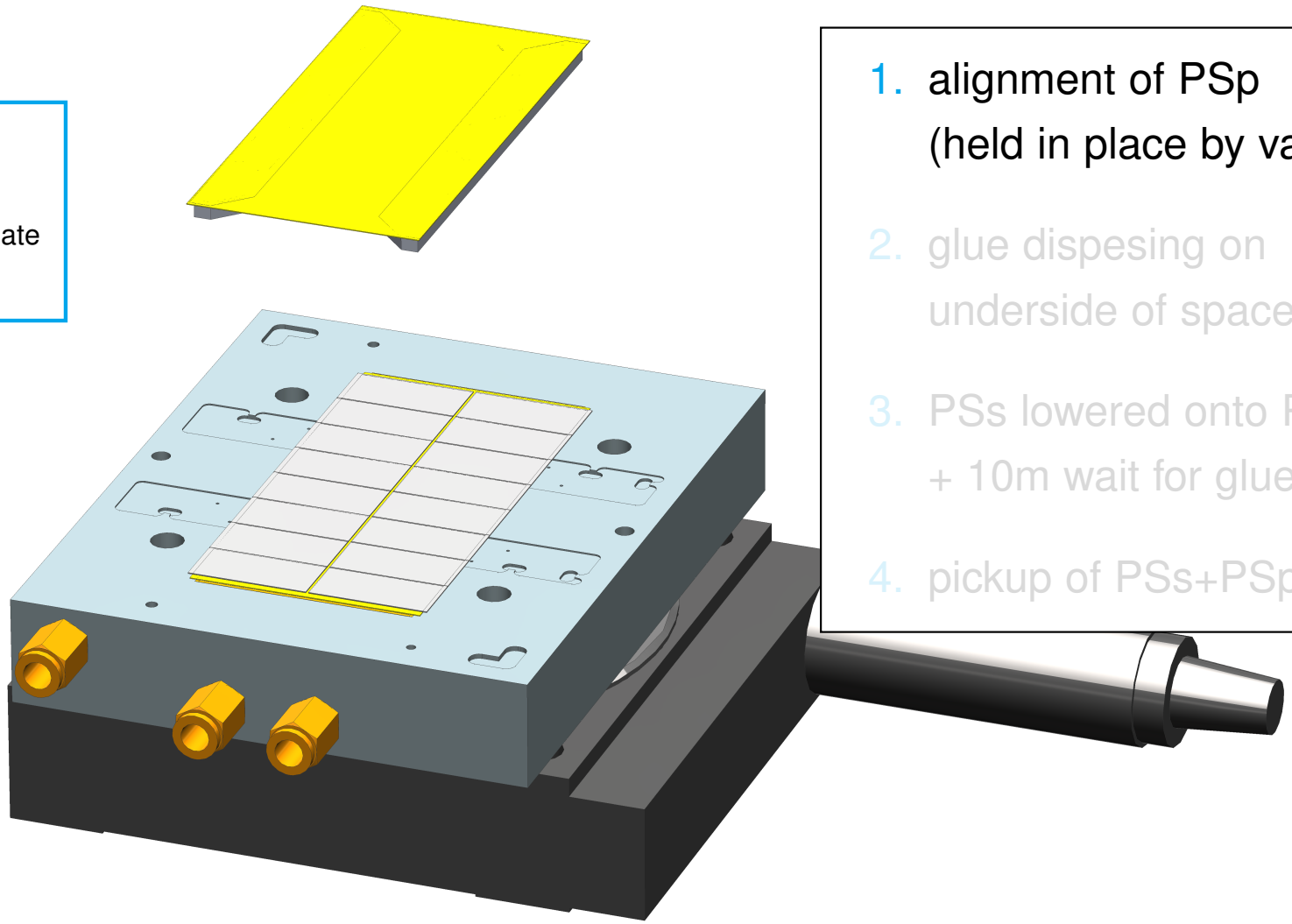


1. spacers w/ glue on stage (held in place by vacuum)
2. PSs lowered onto spacers + 10m wait for glue curing
3. pickup of PSs+spacers

Assembly procedure

Step #3 alignment of PSp, PSp+PSs assembly

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers

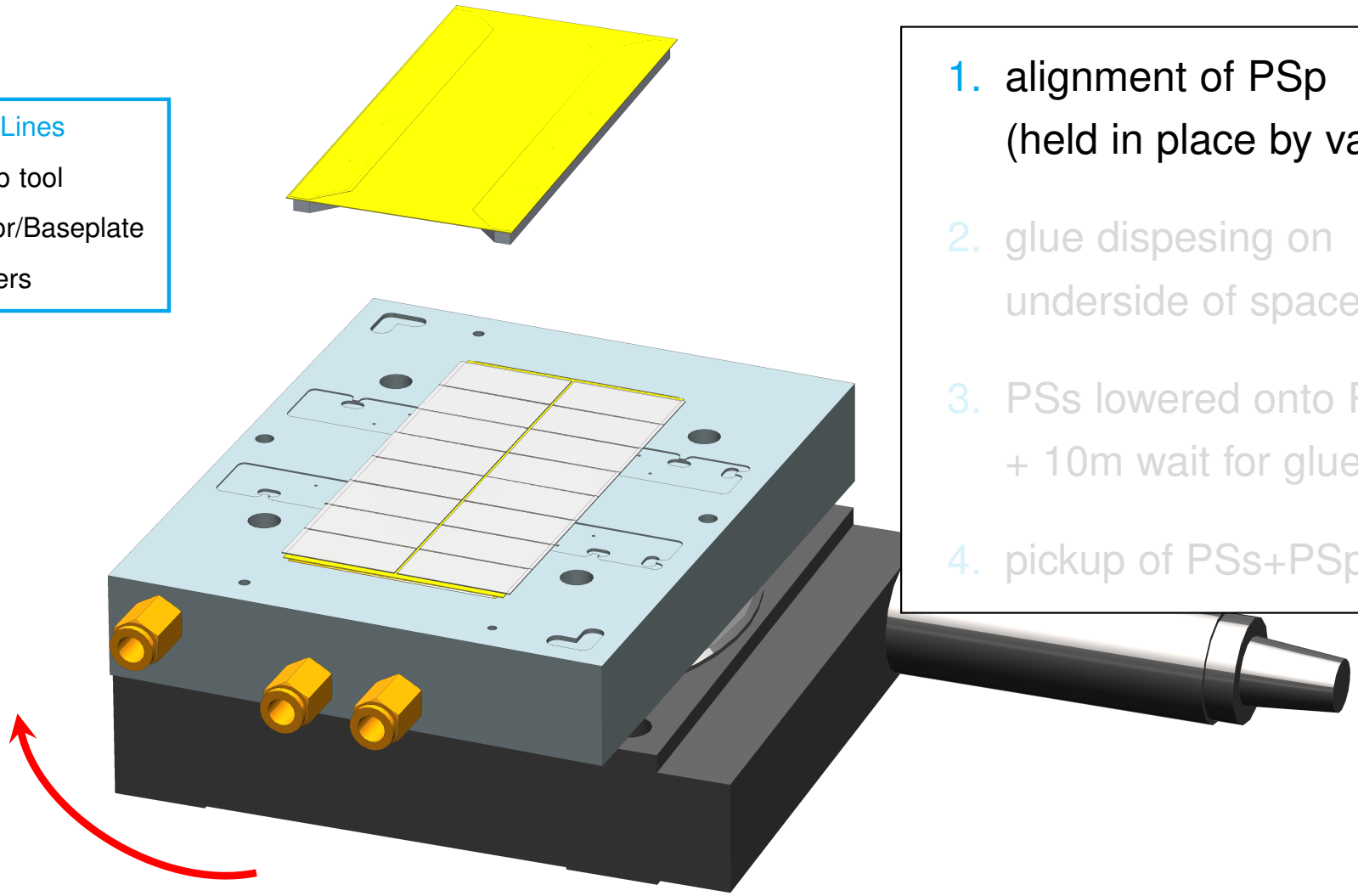


1. alignment of PSp
   (held in place by vacuum)
2. glue dispesing on
   underside of spacers
3. PSs lowered onto PSp
   + 10m wait for glue curing
4. pickup of PSs+PSp

Assembly procedure

Step #3 alignment of PSp, PSp+PSs assembly

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers

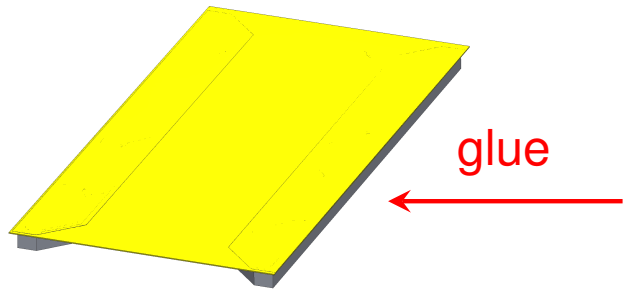


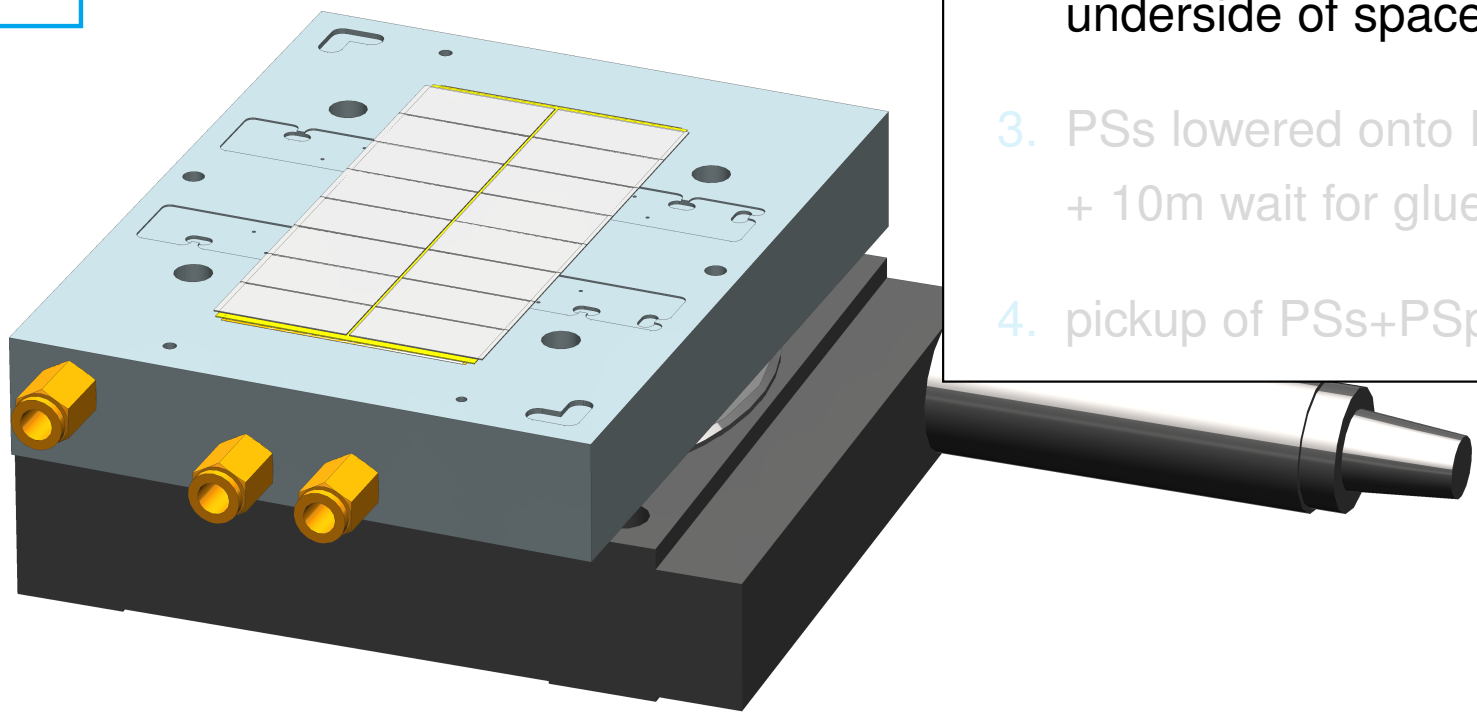
1. alignment of PSp
   (held in place by vacuum)
2. glue dispesing on
   underside of spacers
3. PSs lowered onto PSp
   + 10m wait for glue curing
4. pickup of PSs+PSp

Assembly procedure

Step #3 alignment of PSp, PSp+PSs assembly

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers



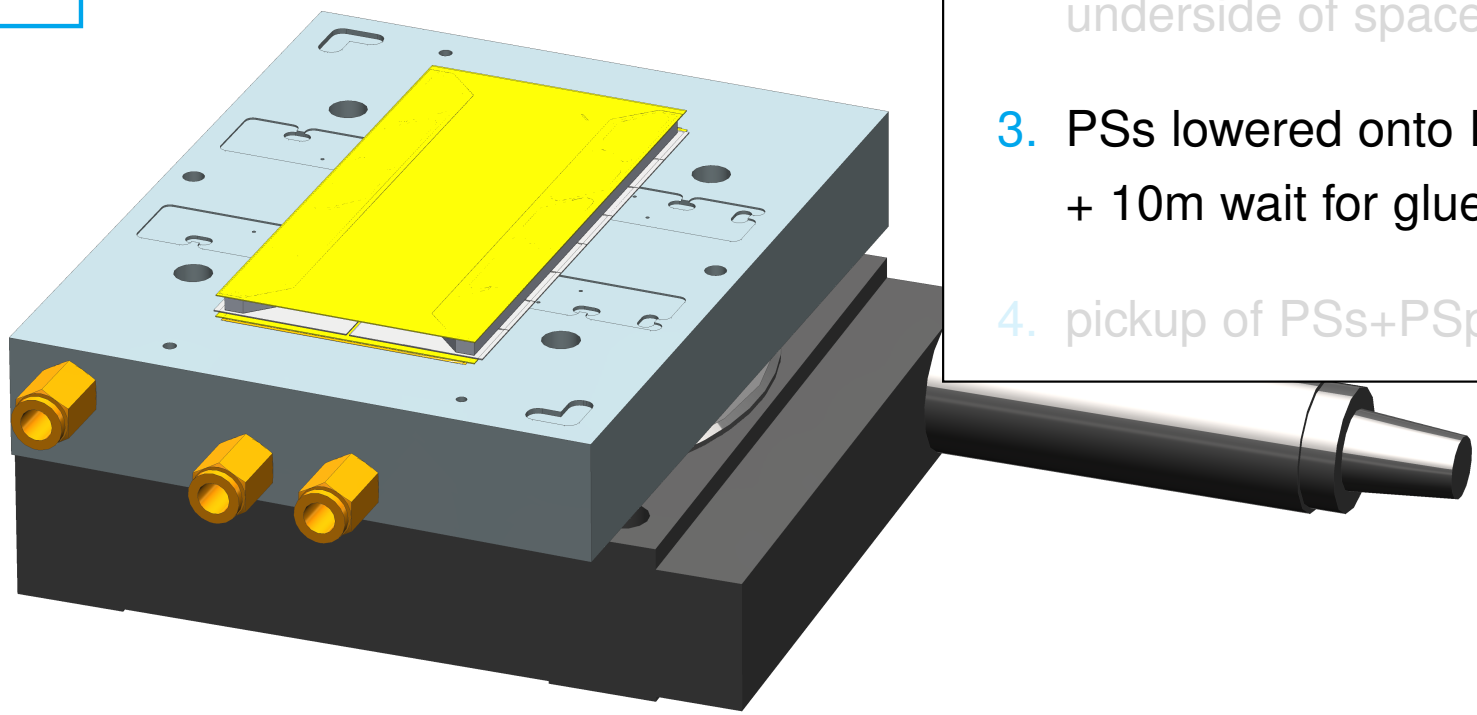


1. alignment of PSp
   (held in place by vacuum)
2. glue dispesing on
   underside of spacers
3. PSs lowered onto PSp
   + 10m wait for glue curing
4. pickup of PSs+PSp

Assembly procedure

Step #3 alignment of PSp, PSp+PSs assembly

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers

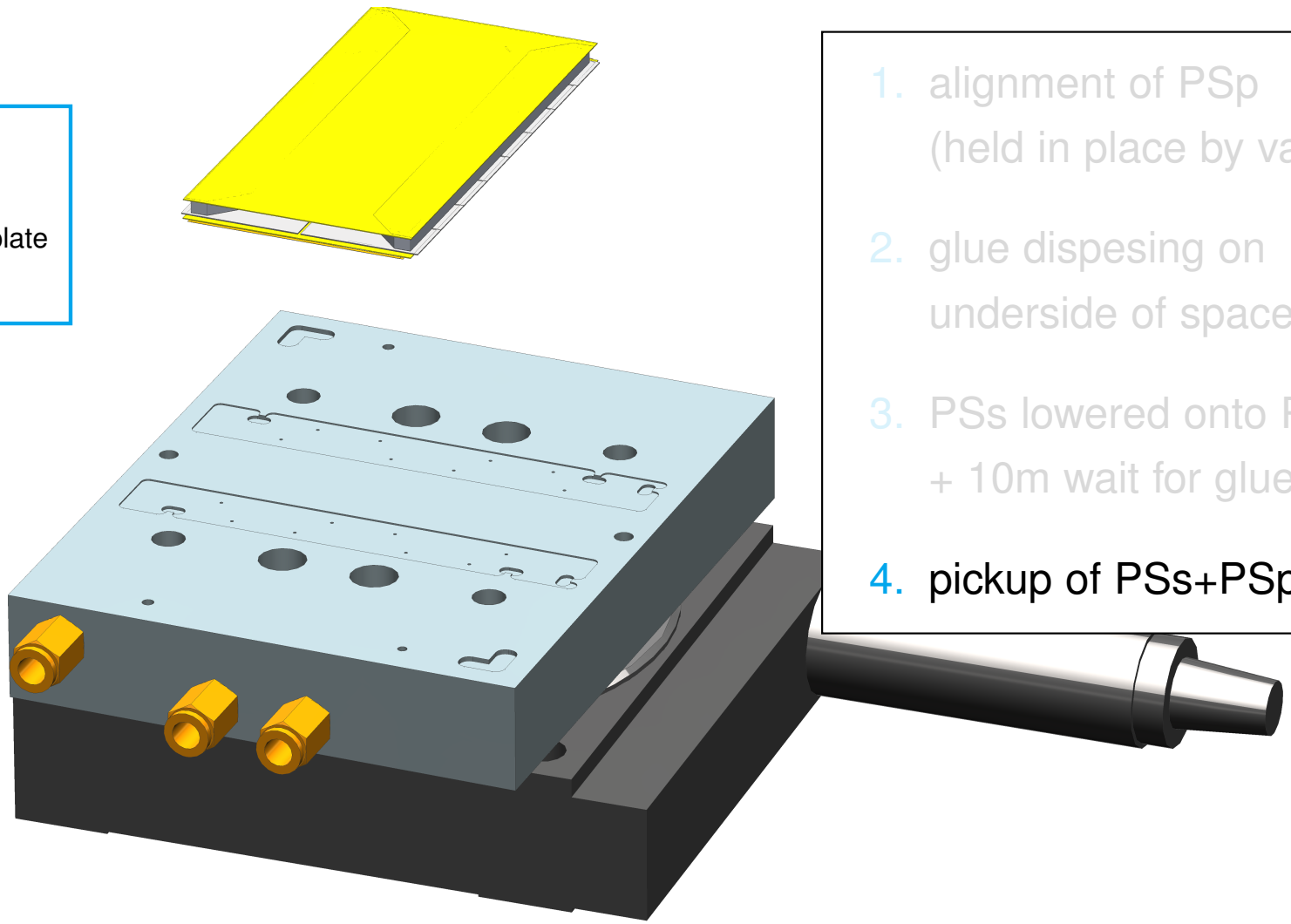


1. alignment of PSp
   (held in place by vacuum)
2. glue dispesing on
   underside of spacers
3. PSs lowered onto PSp
   + 10m wait for glue curing
4. pickup of PSs+PSp

Assembly procedure

Step #3 alignment of PSp, PSp+PSs assembly

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers

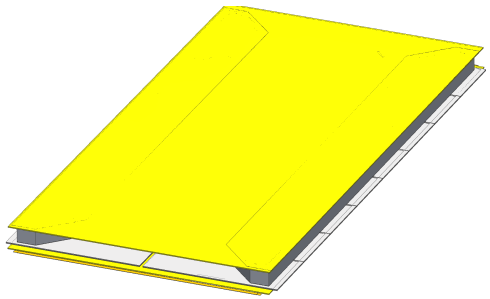


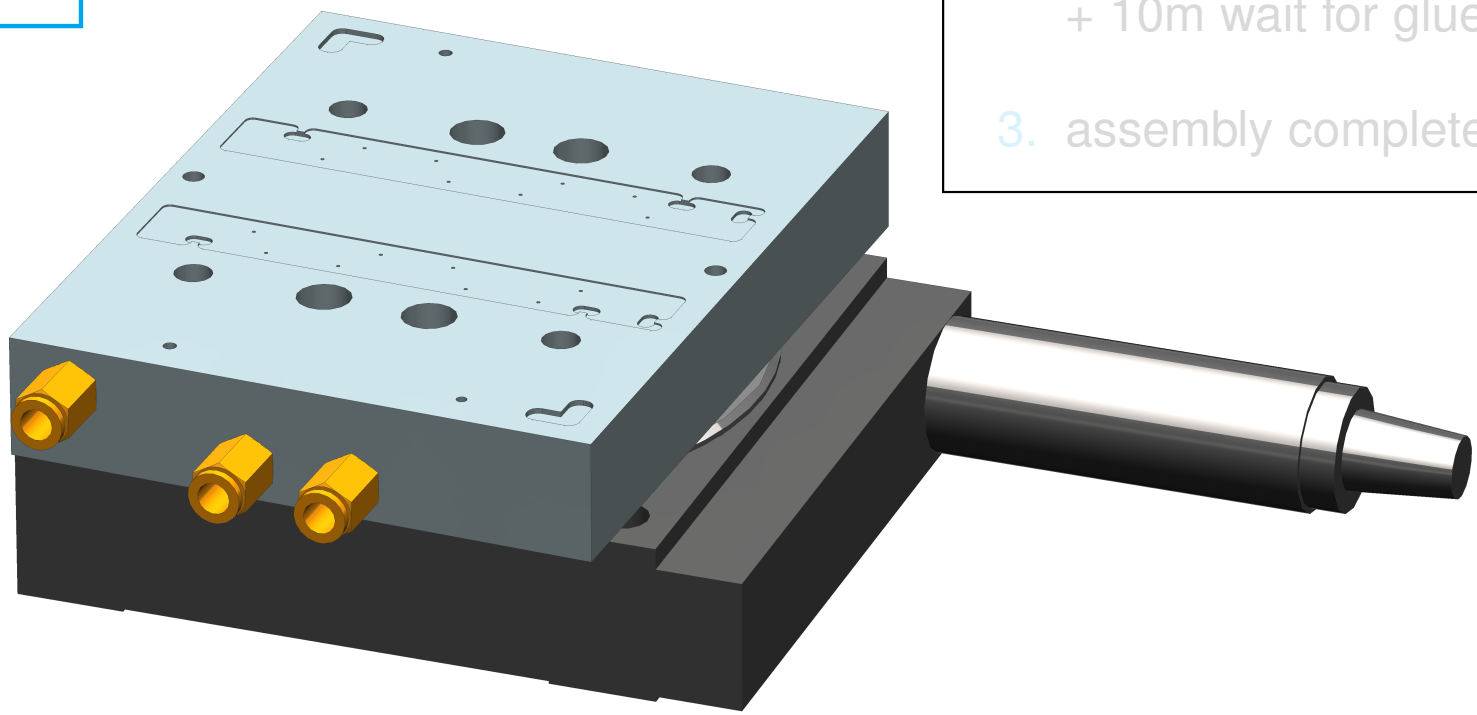
1. alignment of PSp
   (held in place by vacuum)
2. glue dispesing on
   underside of spacers
3. PSs lowered onto PSp
   + 10m wait for glue curing
4. pickup of PSs+PSp

Assembly procedure

Step #4 PSp+PSs glued to baseplate

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers



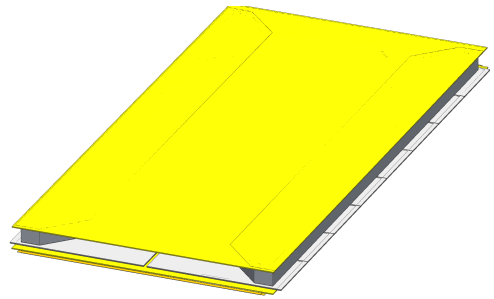


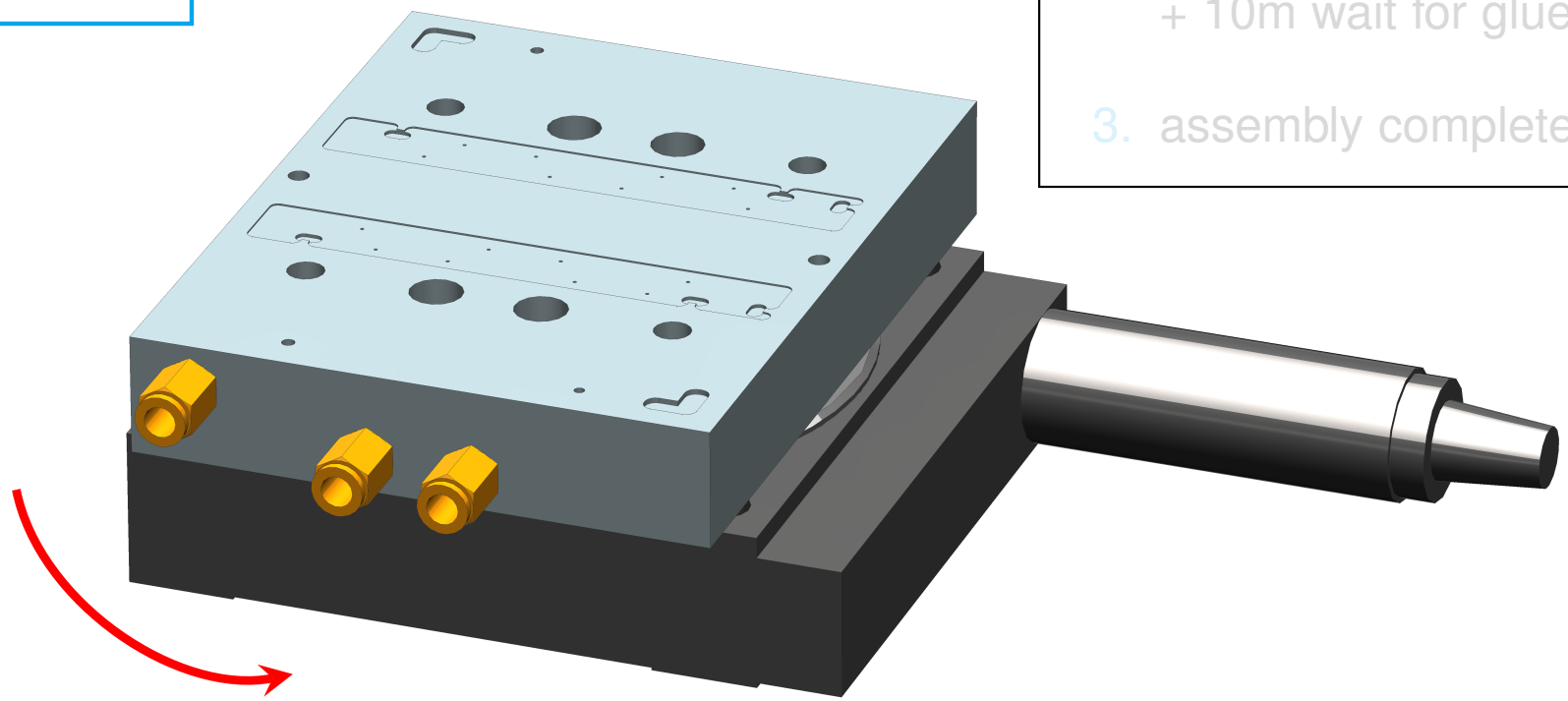
1. baseplate with glue
   (held by vacuum and pins)
2. PSs+PSp onto baseplate
   + 10m wait for glue curing
3. assembly completed

Assembly procedure

Step #4 PSp+PSs glued to baseplate

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers



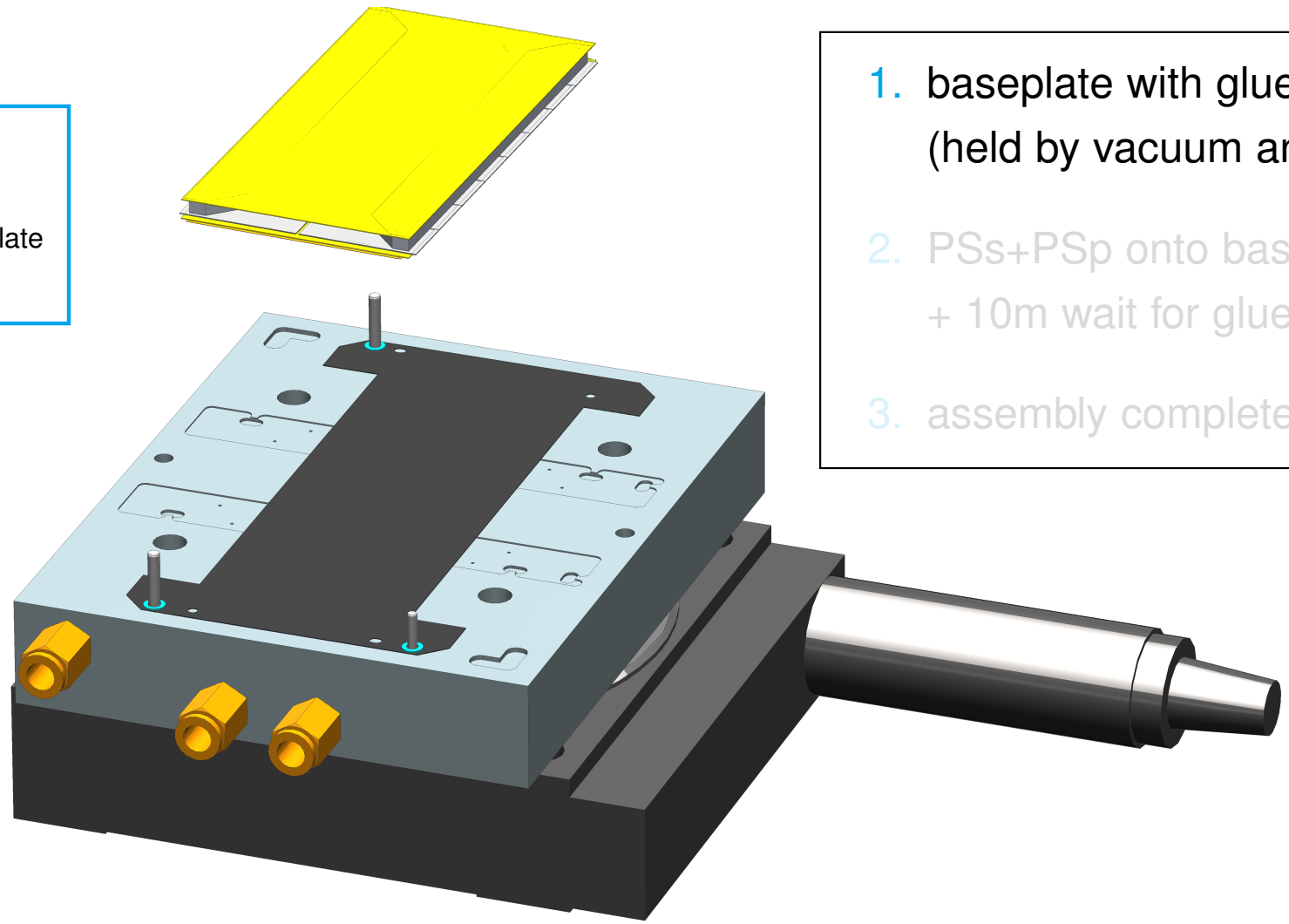


1. baseplate with glue
   (held by vacuum and pins)
2. PSs+PSp onto baseplate
   + 10m wait for glue curing
3. assembly completed

Assembly procedure

Step #4 PSp+PSs glued to baseplate

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers



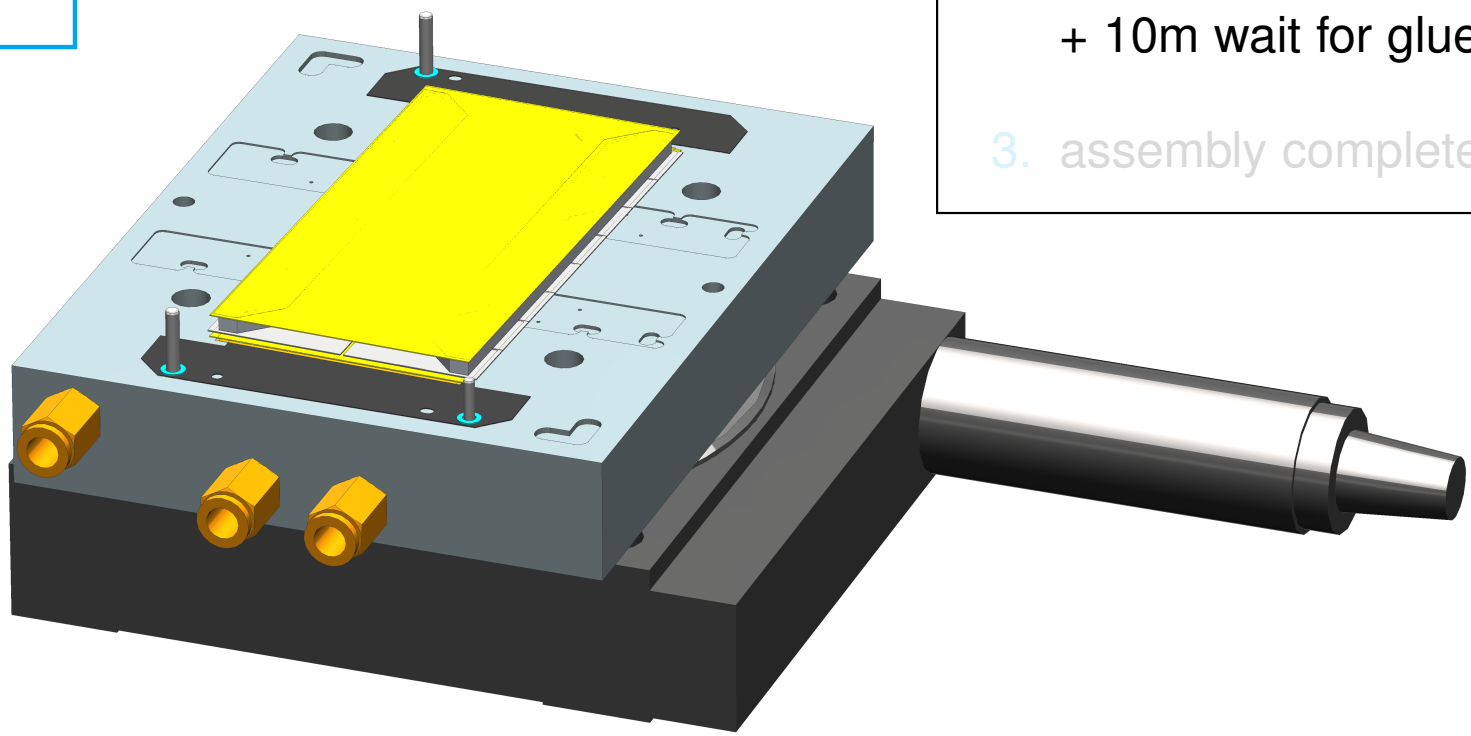
1. baseplate with glue (held by vacuum and pins)
2. PSs+PSp onto baseplate + 10m wait for glue curing
3. assembly completed

Assembly procedure

Step #4 PSp+PSs glued to baseplate

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers

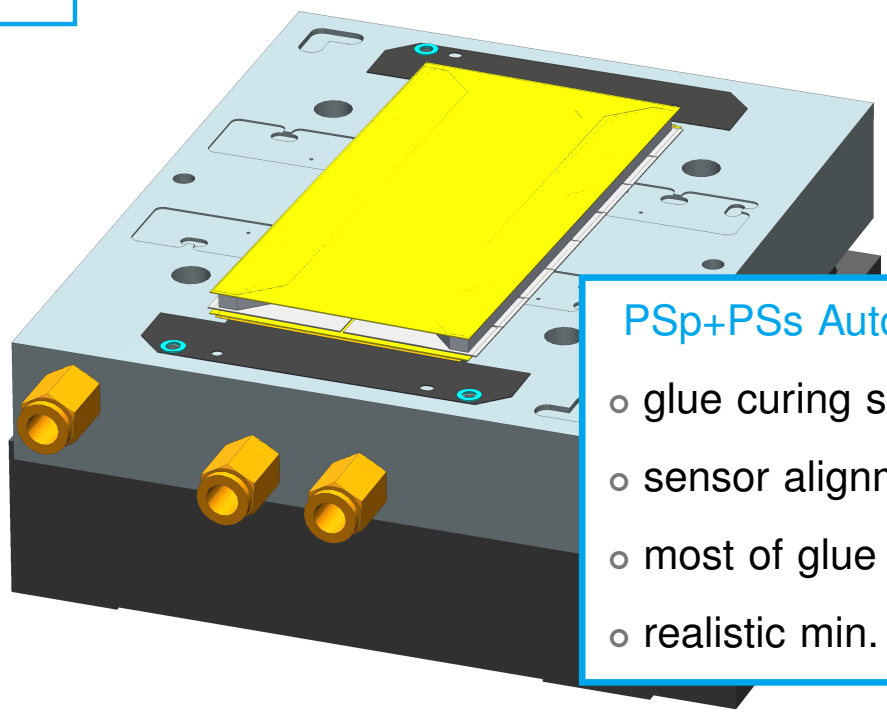
1. baseplate with glue
   (held by vacuum and pins)
2. PSs+PSp onto baseplate
   + 10m wait for glue curing
3. assembly completed



Assembly procedure

Step #4 PSp+PSs glued to baseplate

Vacuum Lines
- Pickup tool
- Sensor/Baseplate
- Spacers



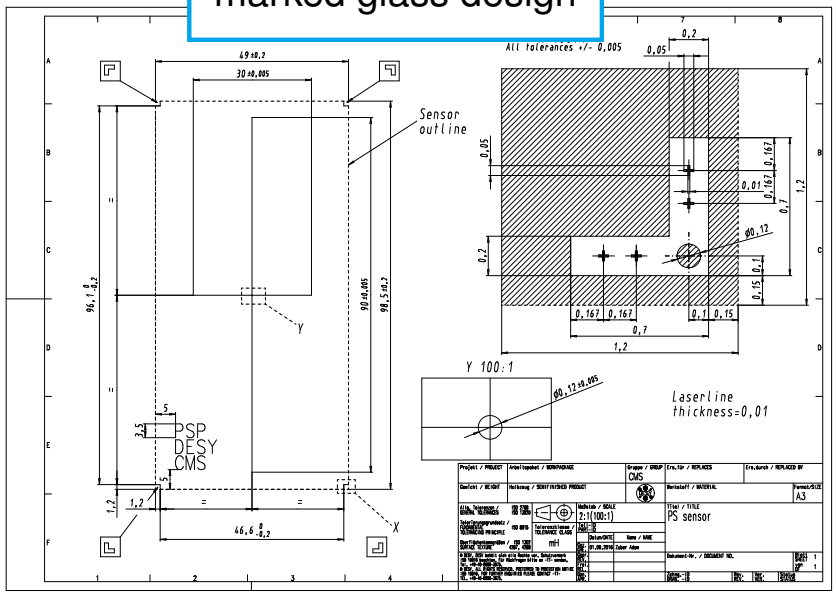
1. baseplate with glue (held by vacuum and pins)
2. PSs+PSp onto baseplate + 10m wait for glue curing
3. assembly completed

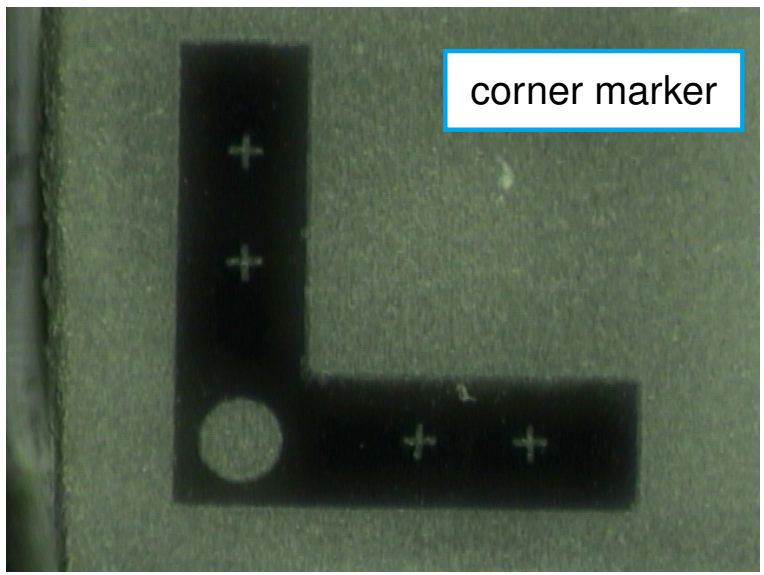
PSp+PSs Auto-Assembly:
- glue curing steps: tot. ∼**30m**
- sensor alignment (x2): tot. ∼**10m**
- most of glue dispensing can be done in parallel
- realistic min. time for 1 assembly: **1 hour** (1-2 people)

First mechanical prototypes

Components for first dummy modules

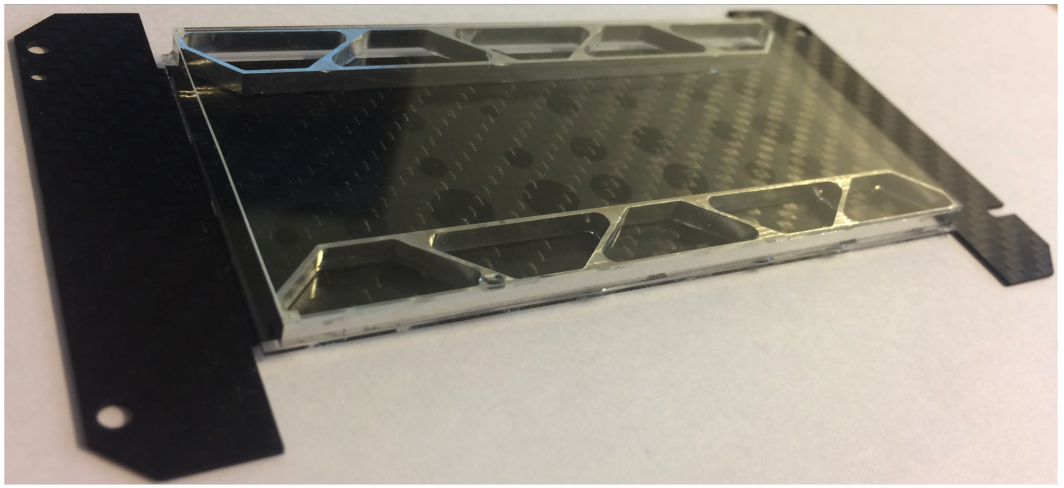
- first assemblies using marked glasses with PSs/PSp XY dimensions
  - designed in house and produced by external company
  - precision of laser-etched fiducial markings within specs ($\delta_\theta \lesssim 60\ \mu\mathrm{rad}$)
- Al spacers produced in house and by external vendor
- CFRP baseplates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





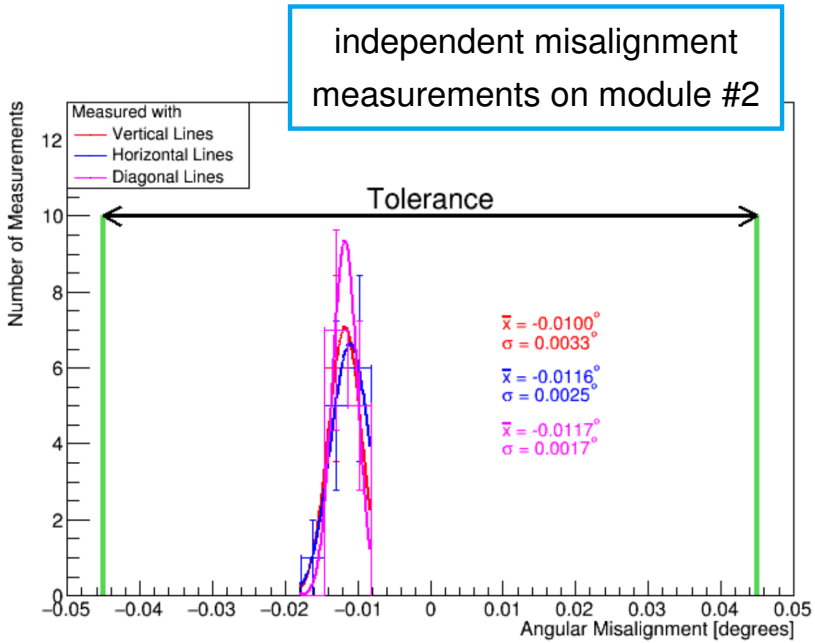
Metrology on first dummy modules

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



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

assembly #	glue	spacers	alignment (μrad)
1	Loxeal	Al (DESY)	**279**
2	Loxeal	Al (external)	**175**
3	Loxeal+Polytec	Al (external)	**523**



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