Pixel module assembly for ATLAS-ITk

Dimitris Varouchas (IJCLab-Orsay, CNRS/IN2P3),

on behalf of the ATLAS-ITk collaboration

Pixel2022

The Tenth International Workshop
on Semiconductor Pixel Detectors for Particles and Imaging

12–16 December 2022
La Fonda Hotel | Santa Fe, New Mexico, USA

TOPICS:
Pixel detectors in nuclear and particle physics, astrophysics, bioscience, and x-ray science, with emphasis on pixel sensor technology and device design, front-end readout electronics, radiation effects on devices, mechanics and integration, calibration, and data processing.

Stipends are available for partial support of students and postdocs attending this conference.
For information on how to apply for a stipend: physics.unm.edu/Pixel2022/stipends.php

Contributed abstracts for talks and posters are welcome.
Deadline for abstract submission: September 15, 2022.

Organizing Committee

TO REGISTER, AND FOR MORE INFO:
physics.unm.edu/Pixel2022

CONTACT:
pixel2022@unm.edu


Pixel2022

The Tenth International Workshop
on Semiconductor Pixel Detectors for Particles and Imaging

12–16 December 2022
La Fonda Hotel | Santa Fe, New Mexico, USA

Pixel module assembly for ATLAS-ITk

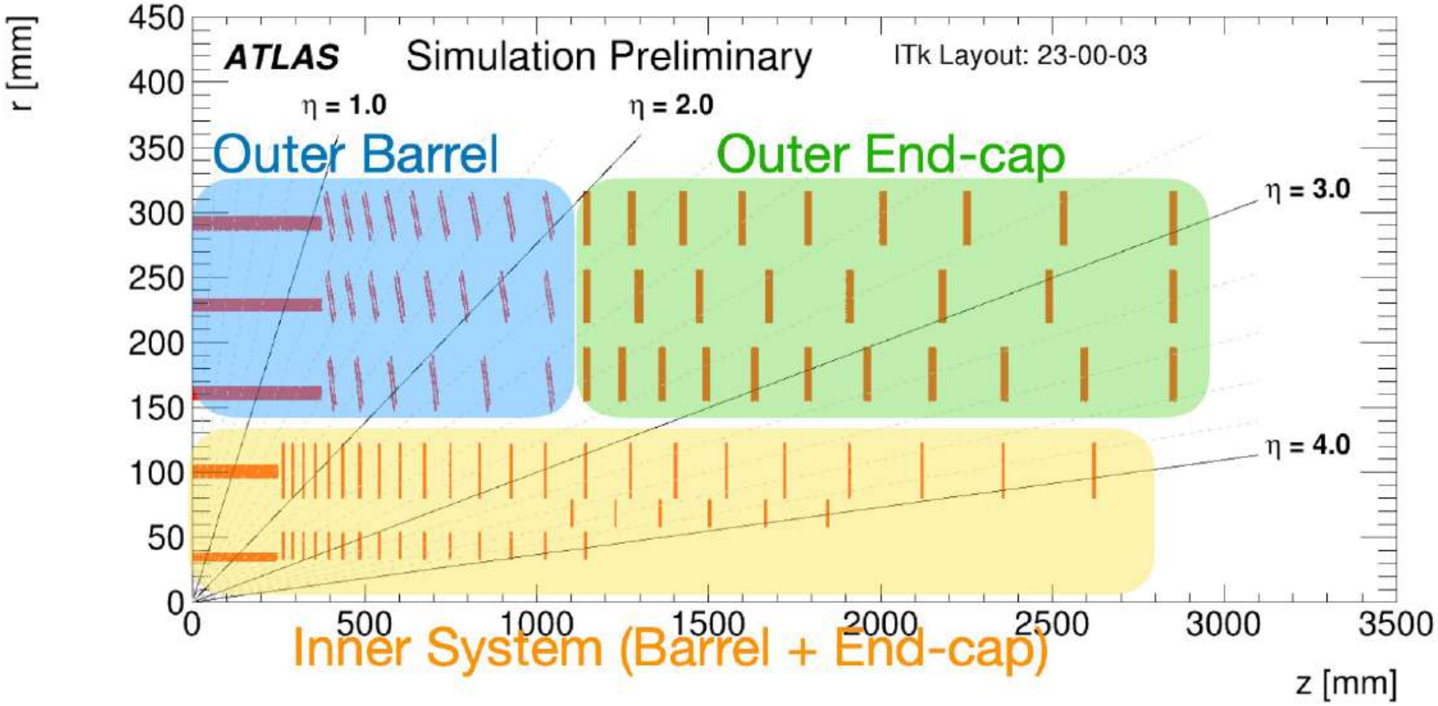
With a strong bias towards the production

Dimitris Varouchas (IJCLab-Orsay, CNRS/IN2P3),

on behalf of the ATLAS-ITk collaboration

ITk-Pixel layout

- **ITk-Pixel detector composed by 3 parts: outer barrel, outer end-cap, and inner system**



- **Outer barrel:** 3 barrel layers, 23 inclined rings
- **Outer endcap:** 28 vertical rings
- **Inner system:** 2 barrel layers and 44 vertical rings
  - Most innermost layer, L0: 34 mm from the beam pipe

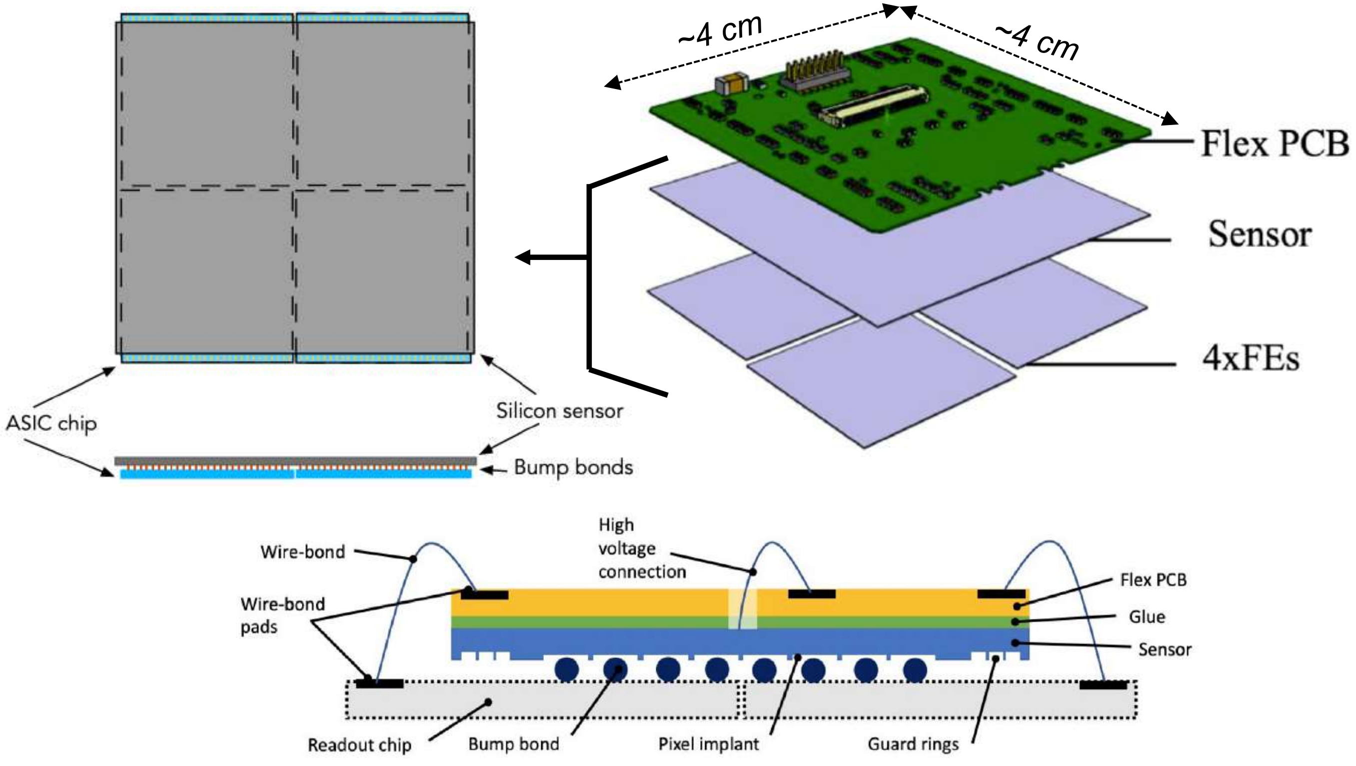
See also Craig's talk, last Tuesday

ITk-Pixel building blocks: modules

- **Bare module:** silicon sensor **bump bonded** to FE chips
  - **Chips** are thinned to 150 µm
  - **Sensors**
    - **L2, L3 and L4 sensors,** 150 µm thick
    - **L1 sensors,** 100 µm thick
    - **L0 sensors,** 250 µm thick

50x50 µm^2 pixel pitch

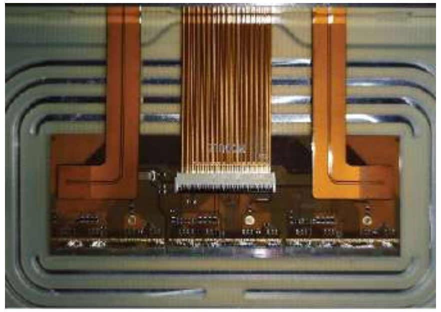
Pixel pitch: 25x100 µm^2 barrel, 50x50 µm^2 rings



Quad module

- **Flexible printed circuit board** (Flex PCB) glued on bare module, and then **wire bonded to ASIC**

- **Two** types of **modules**
  - **Quad** modules: **4 FEs** bump bonded to **one planar sensor**; Layer 1, 2, 3 and 4
  - **Triplet** modules: **3 single-FE** bare modules (**3D sensor**) **connected** to the **same flex**; Layer 0



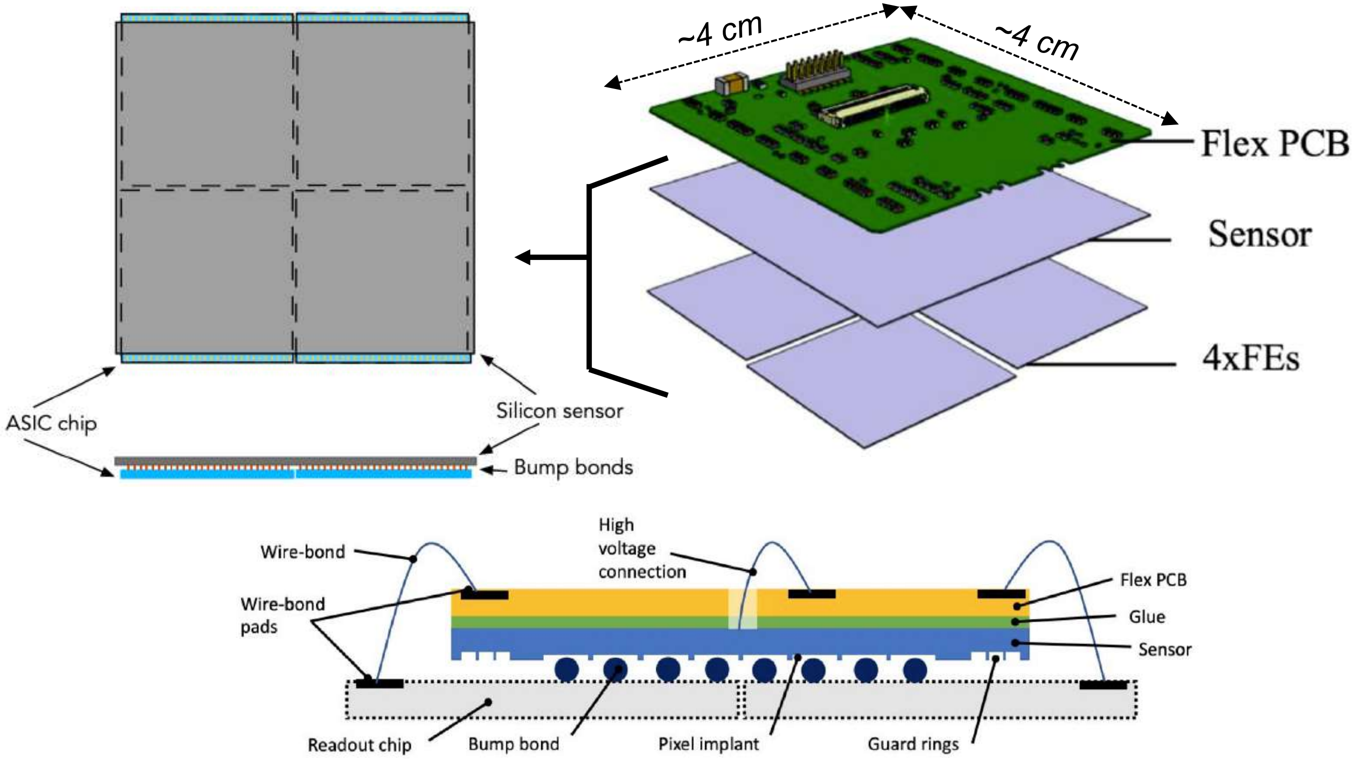
Triplet barrel module

ITk-Pixel building blocks: modules

- **Bare module:** silicon sensor **bump bonded** to FE chips
    - **Chips** are thinned to 150 μm
    - **Sensors**
        - **L2, L3 and L4 sensors,** 150 μm thick
        - **L1 sensors,** 100 μm thick
        - **L0 sensors,** 250 μm thick

50x50 μm^2
pixel pitch

Pixel pitch: 25x100 μm^2 barrel,
50x50 μm^2 rings



Quad module

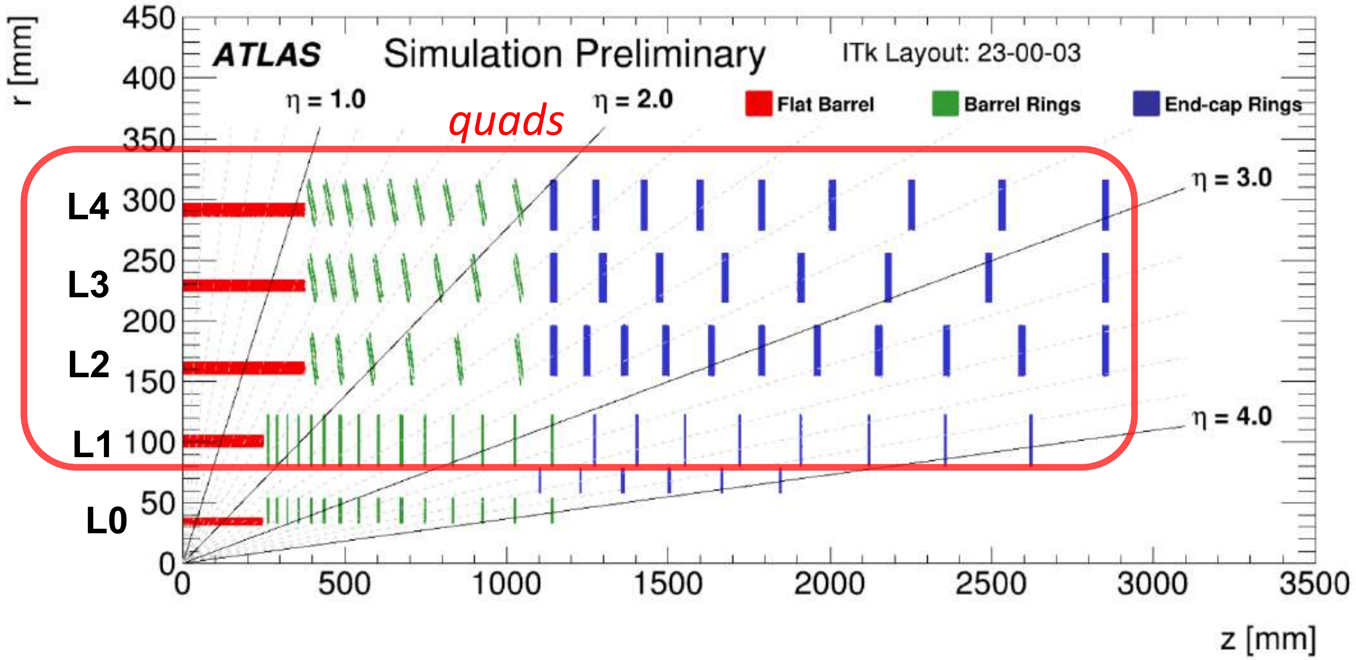
- **Flexible printed circuit board** (Flex PCB) glued on sensor, and then **wire bonded to ASIC**

- **Two** types of **modules** *Focus of this talk: the assembly of **quad modules***
    - **Quad** modules: **4 FEs** bump bonded to **one planar sensor**; Layer 1, 2, 3 and 4
    - **Triplet** modules: **3 single-FE** bare modules (**3D sensor**) **connected** to the **same flex**; Layer 0

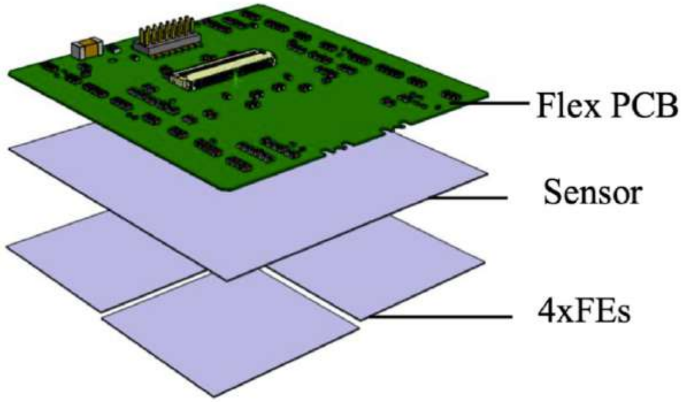
Triplet barrel module

Quad modules in Pixel-ITk

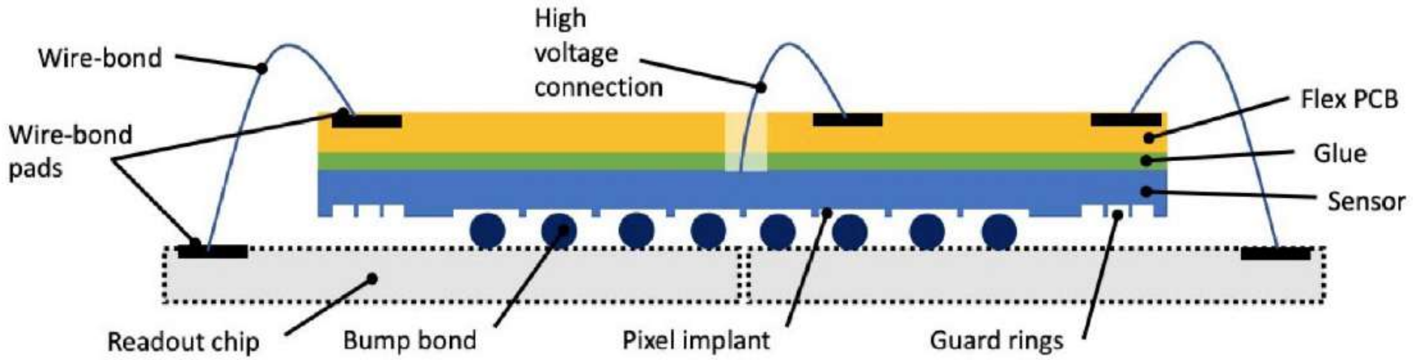
Modules in Pixel-ITk	
L0 – Barrel, triplets	96
L0 – Rings, triplets	300
Total triplets	**396**
L1, quads	1160
L2-L4, quads	6816
Total quad	**7976**
Total modules	**8372**

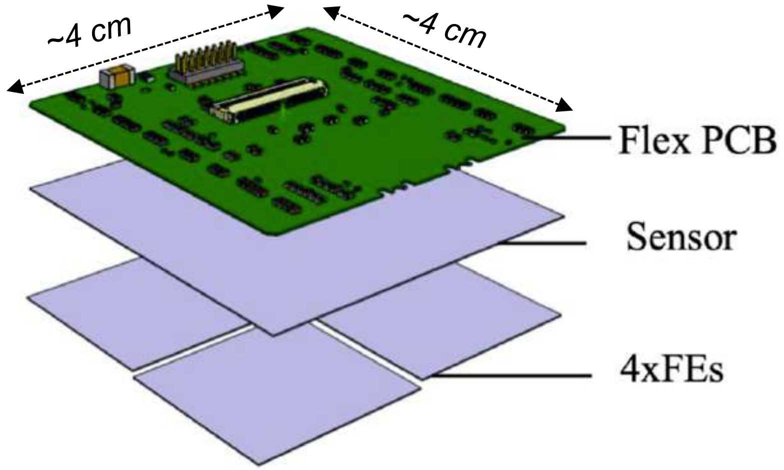


- L1, L2, L3 and L4: **quad modules**
- **~8k** installed **quad modules**, out of **~8.4k** modules in total: **95% quads modules**
- Module production yield: **~1.45** ⟹ need to produce **~11.4k** quad modules in total
- Huge assembly load, shared among **14 assembly institutes** (USA, UK, France, Germany, Italy, CERN, Japan) ⇒ important effort in ATLAS to **develop common procedures** as much as possible



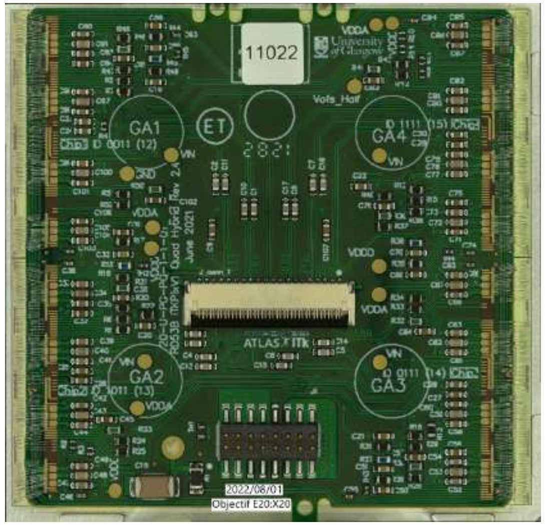
A quad module





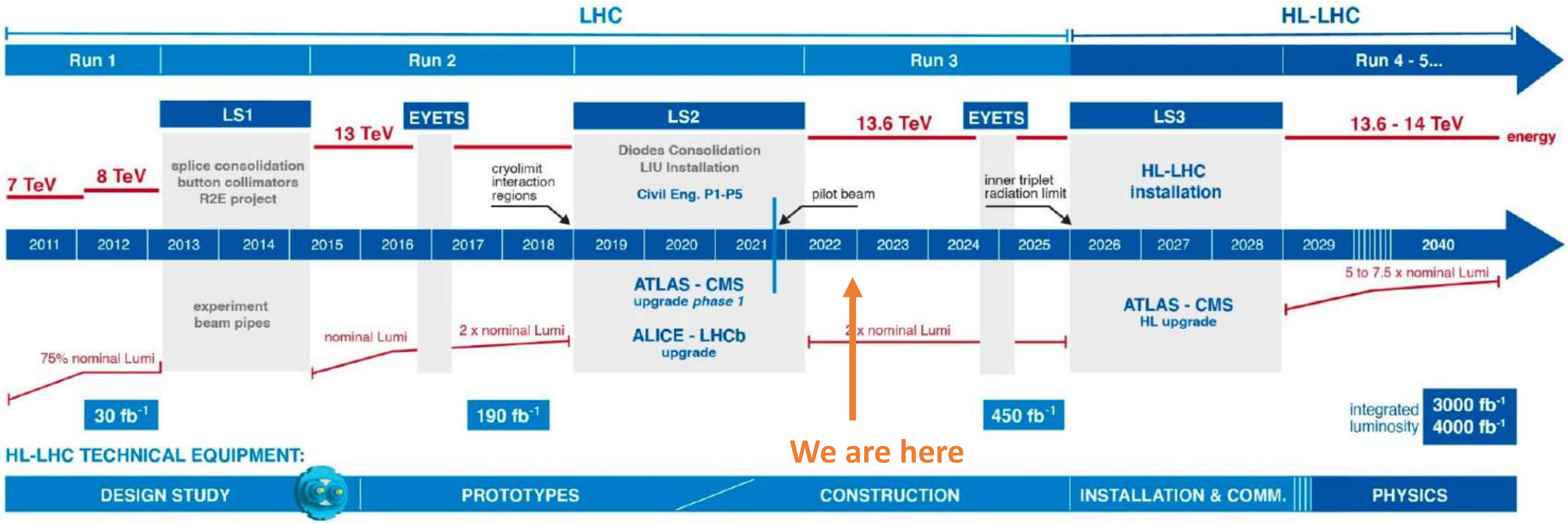
- Quad module: almost a **square** with a surface of ~**4x4 cm^2**
- **Thickness** (nominally)
  - FE chip: 150 µm; Bump bonds: 25 µm
  - Si sensor: 100 µm (L1), 150 um (L2-L4)
  - Adhesive: 40 µm
  - Flex PCB: 200 µm (without the components)
  - **Total: 515 µm (L1), 565 µm (L2-L4)**

- **Main challenges of assembly (flex-attach)**
  - Robust and rad-hard modules even after >10 years of operation (4000 fb^{-1})
  - **Ensure no delamination/failure** due to potential thermal stresses in case of power or cooling failures: modules have to **resist** over **large temperature range** ($\Delta T = 60\ ^0$C)
  - Respect **tight** module **envelope specifications**



Quad module

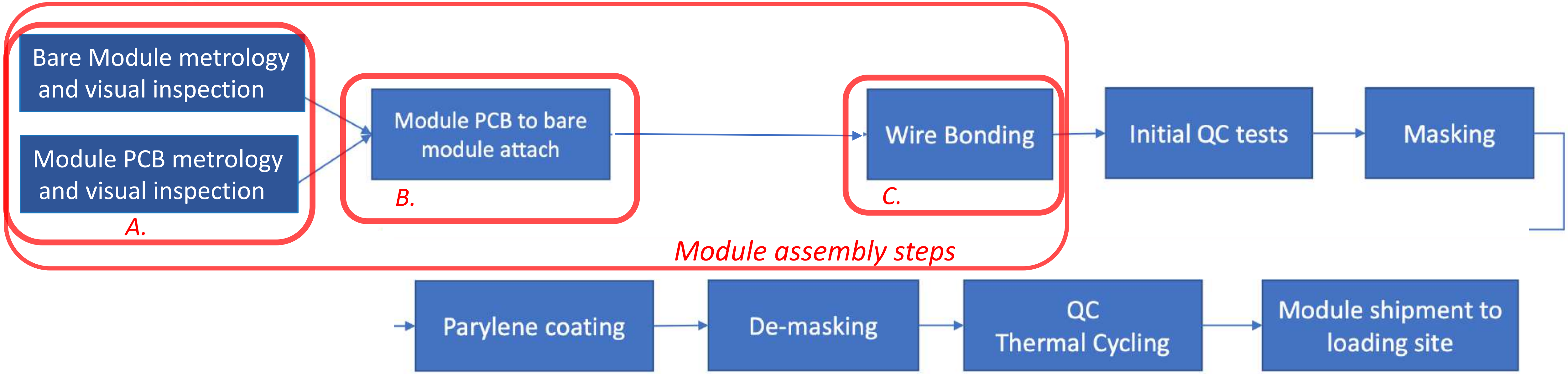
Module assembly timeline



See also Craig's talk, last Tuesday

- 2021-2022
  - End of R&D
  - Prototype small production, O(160) quad modules produced, using older chip version (RD53A)
  - Testing and finalisation of methods and procedures, extensive design validation
- 2023
  - Pre-production: ~10% of the modules produced
  - Assembly sites ramp-up and prepare for the production rates
- End of 2023
  - Start of module production

Module assembly



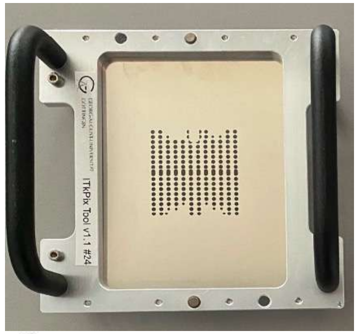
- **Module assembly** includes the **first steps** of the **module production flow:**
  - A. **Bare module** and **PCB (flex) reception**
    - And then: **visual inspection** and **metrology**
  - B. **Bare module** to **PCB (flex) attach** using an epoxy adhesive
    - And then: **visual inspection** and **metrology**
  - C. **Wire bonding**
    - And then: **visual inspection** and **wire bonds quality control**

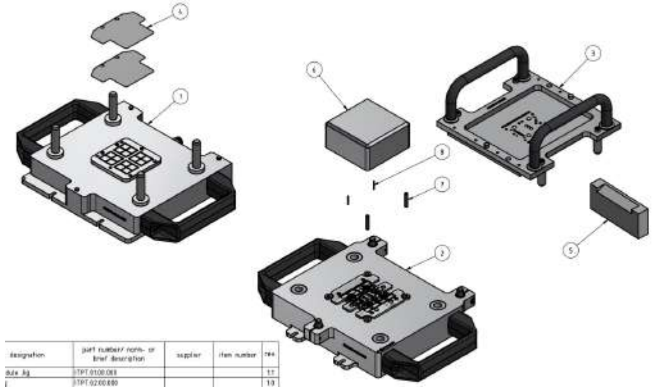
Quad flex-attach tooling overview

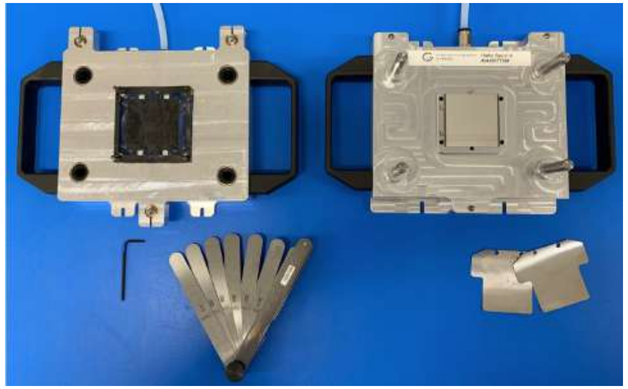
- Several R&D studies over the last years, different flex-attach tooling and techniques were proposed and tested

- A **common baseline flex-attach method** was chosen among the majority of assembly sites towards the production
  - Keep the cost reasonable
  - Target for precision and repeatability of results across assembly sites
  - Choose a relatively non-time consuming technique: <1h per module (w/o curing time)
  - ➢ **Flex and bare module mating jigs; manual glue application using a stencil**

- Two alternative approaches maintained as well
  - **Modified jigs** using **same stencil**
    - Combine flex-attach and cell loading; tooling design in collaboration with an external company that will perform the gluing
  - **Robotic assembly system** with a glue pattern similar to the stencil one
    - Allows that group to make use of a significant previous investment







Prototype version of common tooling

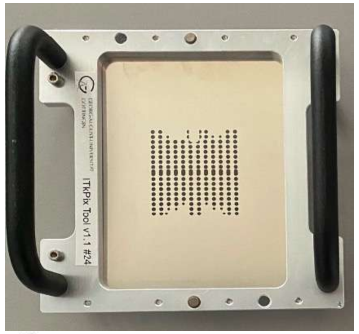
Quad flex-attach tooling overview

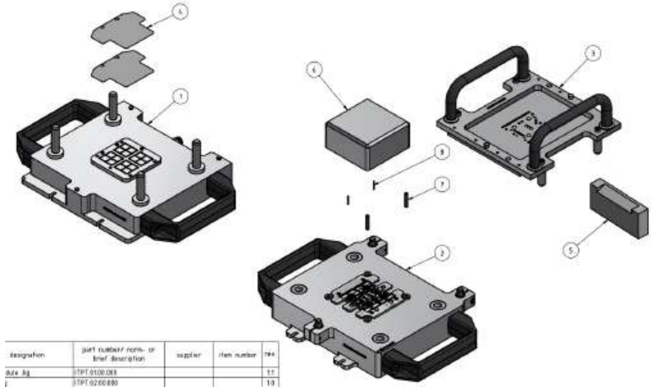
- Several R&D studies over the last years, different flex-attach tooling and techniques were proposed and tested

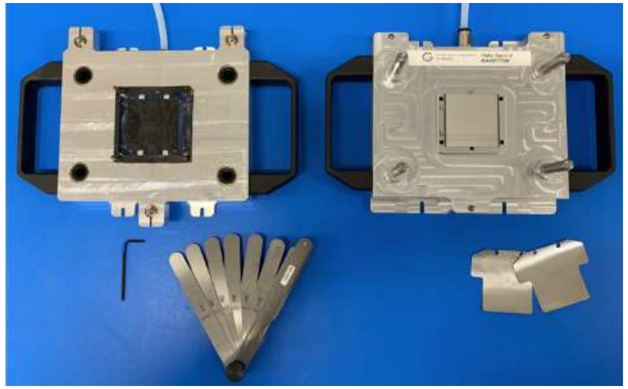
- A **common baseline flex-attach method** was chosen among the majority of assembly sites towards the production
  - Keep the cost reasonable
  - Target for precision and repeatability of results across assembly sites
  - Choose a relatively non-time consuming technique: <1h per module (w/o curing time)
  - ➢ **Flex and bare module mating jigs; manual glue application using a stencil**

Focus today

- Two alternative approaches maintained as well
  - **Modified jigs** using **same stencil**
    - Combine flex-attach and cell loading; tooling design in collaboration with an external company that will perform the gluing
  - **Robotic assembly system** with a glue pattern similar to the stencil one
    - Allows that group to make use of a significant previous investment

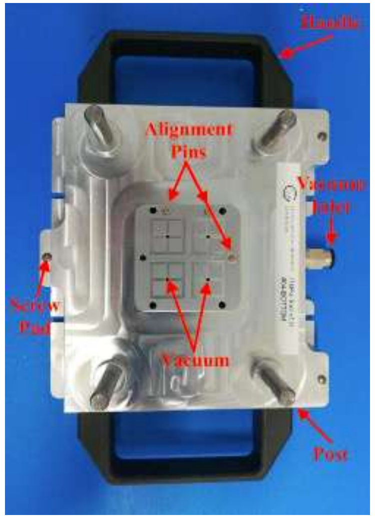




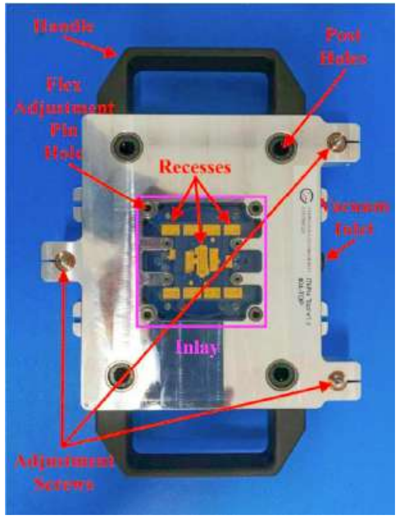


Prototype version of common tooling

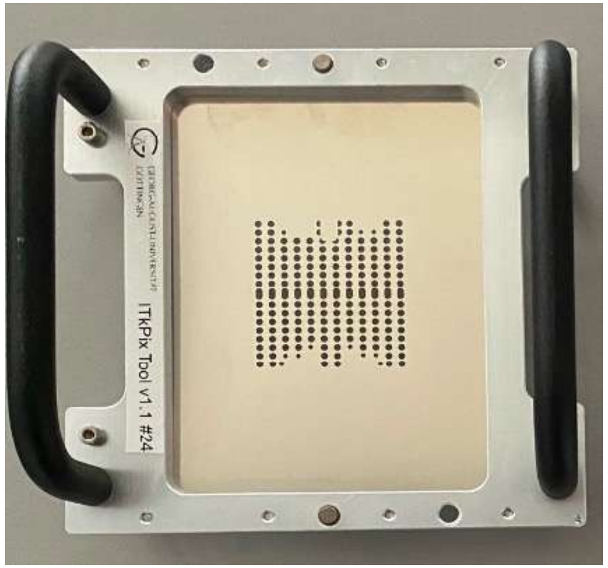
Photostory of module assembly



Bare module jig



Flex jig



Stencil tool with stencil

- Manual and simple assembly tooling based on mechanical **jigs** and a **stencil** to control the glue pattern
- Araldite 2011 **epoxy adhesive** used, proved radiation hard, used extensively in HEP experiments
- **8 hours** of **curing time** at room temperature

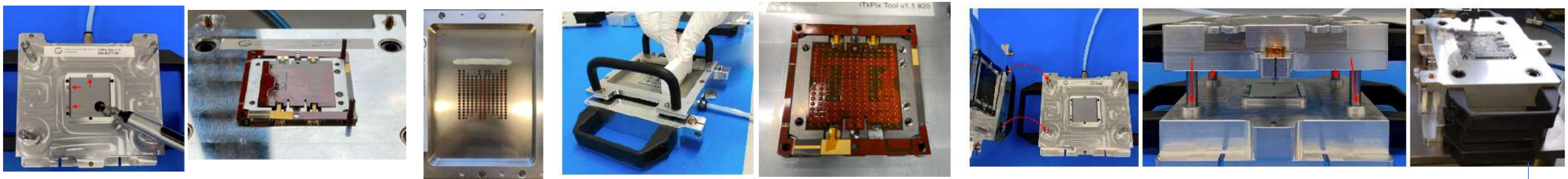
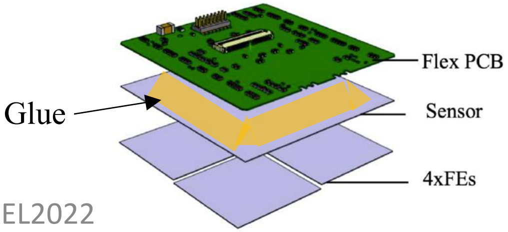


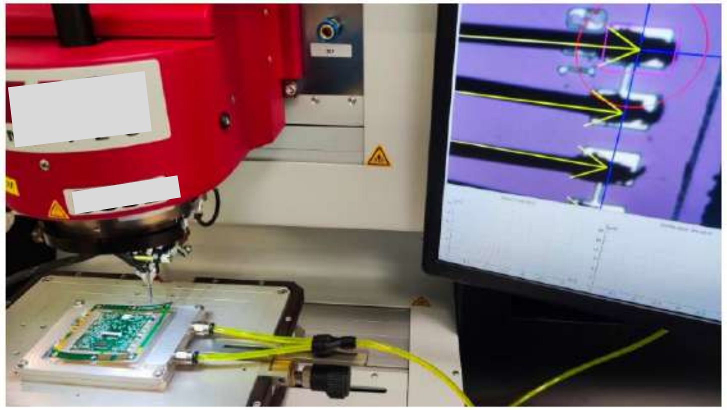
Photo story of gluing an ITk-pixel module



8h later

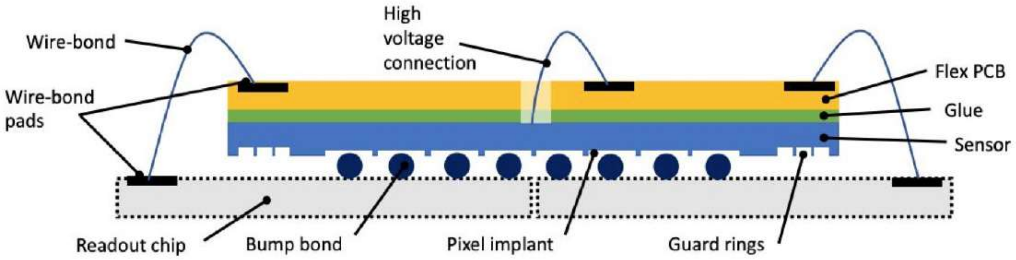
Glued module

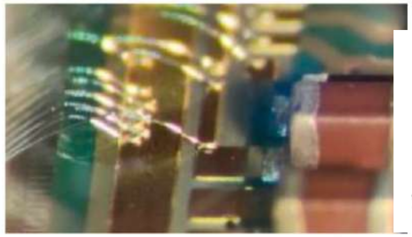
Wire bonding



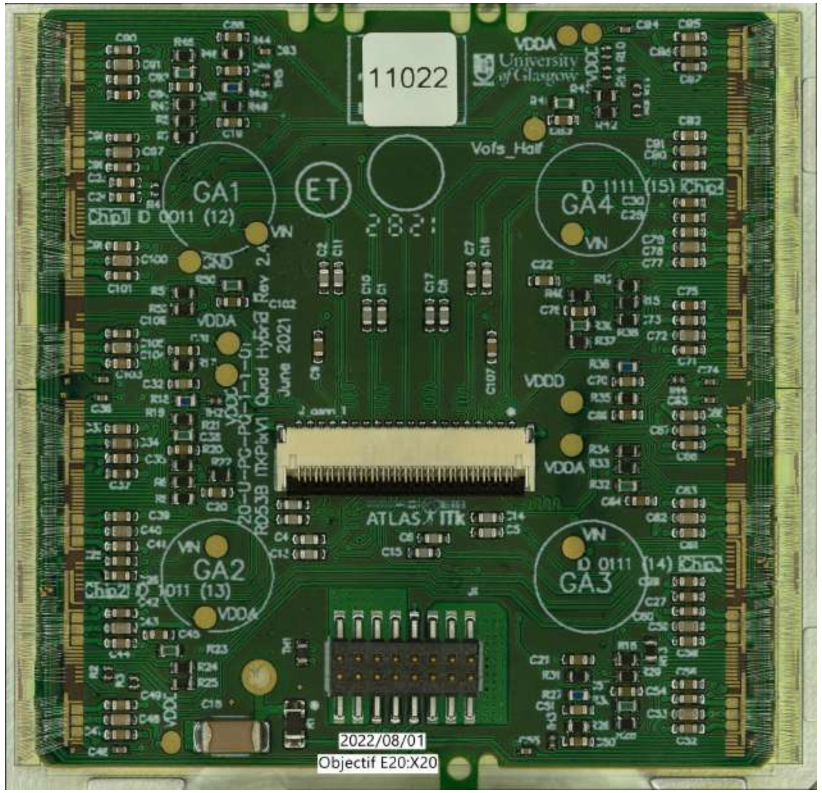
[redacted]

[redacted]



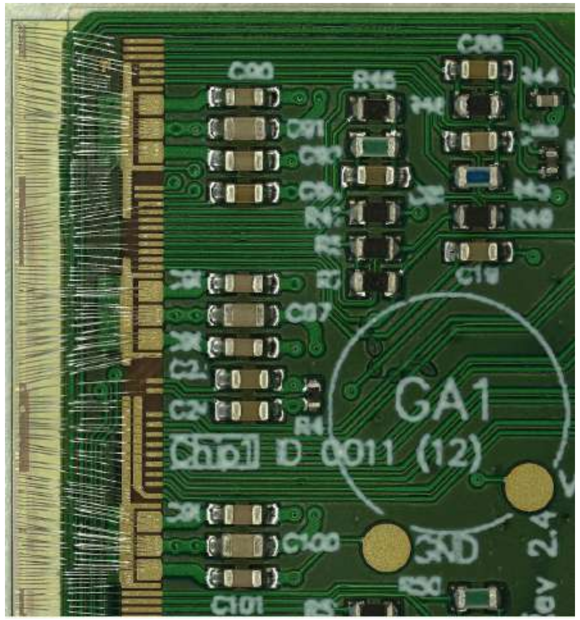


Wirebonding Aluminium Diam. 25µm

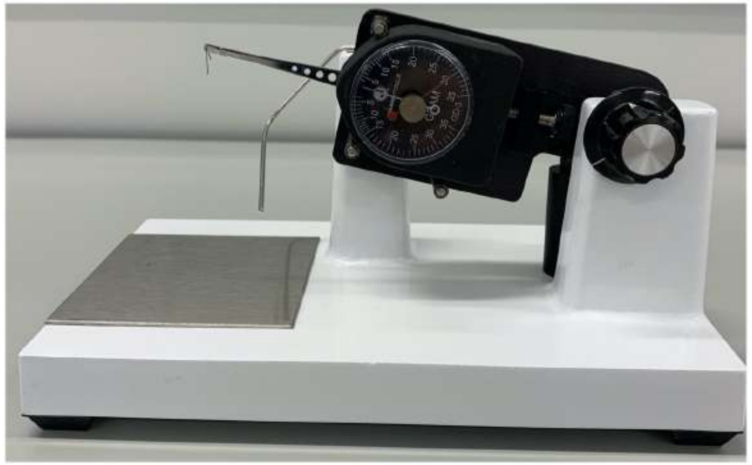


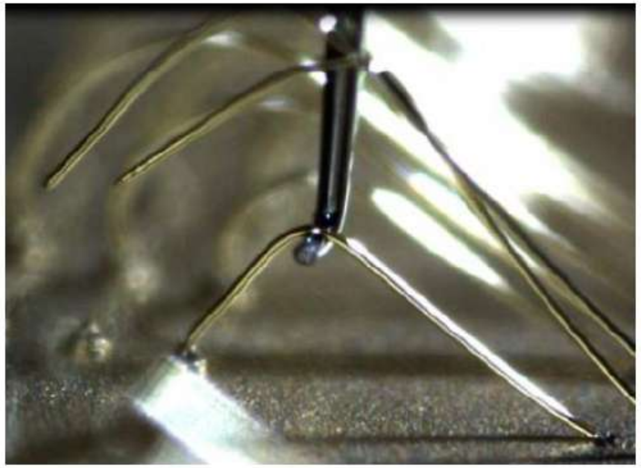
- **Aluminium wire**, **25µm** of diameter
- **~700 wire bonds** per **quad module**, complex layout resulting in non trivial wire bonding: **density**, **length** and **angle** of bonds
- Several parameters need to be under control
  - **Robust** and **uniform gluing** across the whole module surface; **avoid flex bouncing** at the **edges** due to lack of glue
  - **Flex to bare module alignment**, and **glue thickness** have to be **within specs**
  - Wire bond **pads surface quality** of **paramount importance**

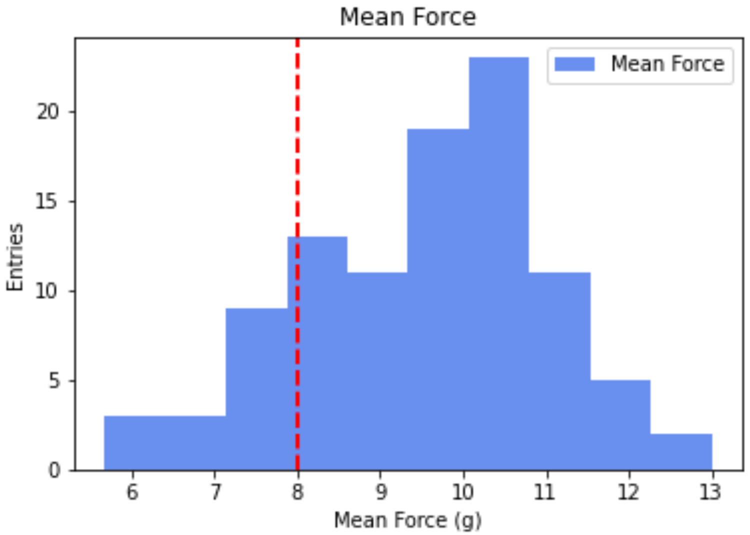
Wire bonding quality control



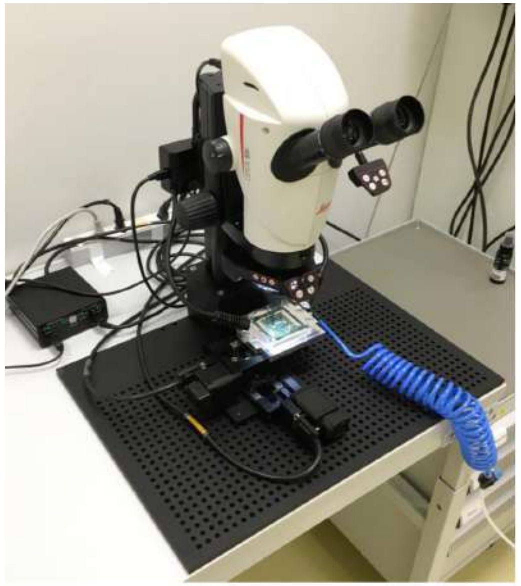
- **Visual inspection** make sure all bonds are put correctly, no bonds touching, no shorts
- **Pull tests**: pull a few unnecessary wires until destruction
  - Specification: minimum force 5g; average force ≥ 8g; ≥ 90% of pulls must be heel breaks
- Ultimate check: **power up the module** using a power supply, pigtails/cables and a a readout DAQ card, and make sure **communication** is **established** with **all 4 chips**

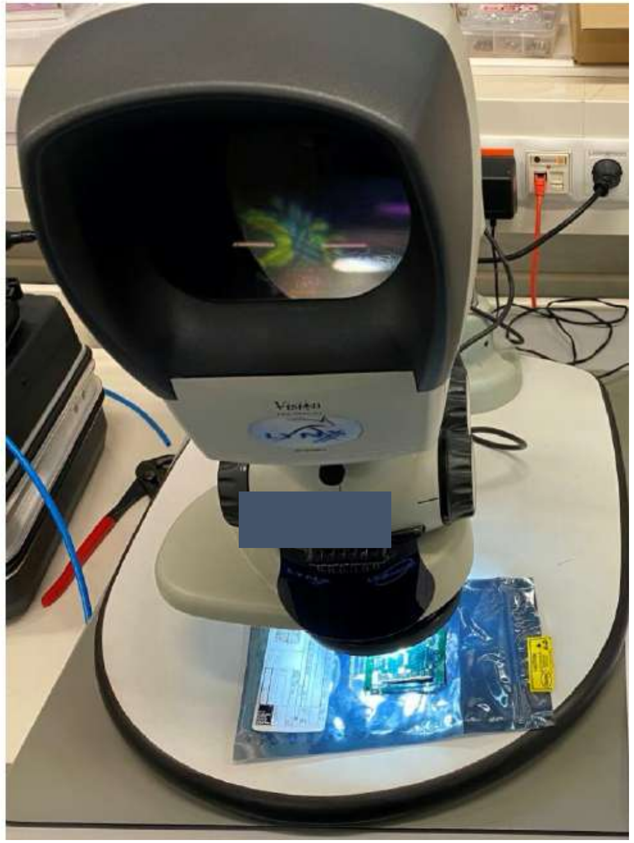






A lot of visual inspection…





[redacted]

[redacted]

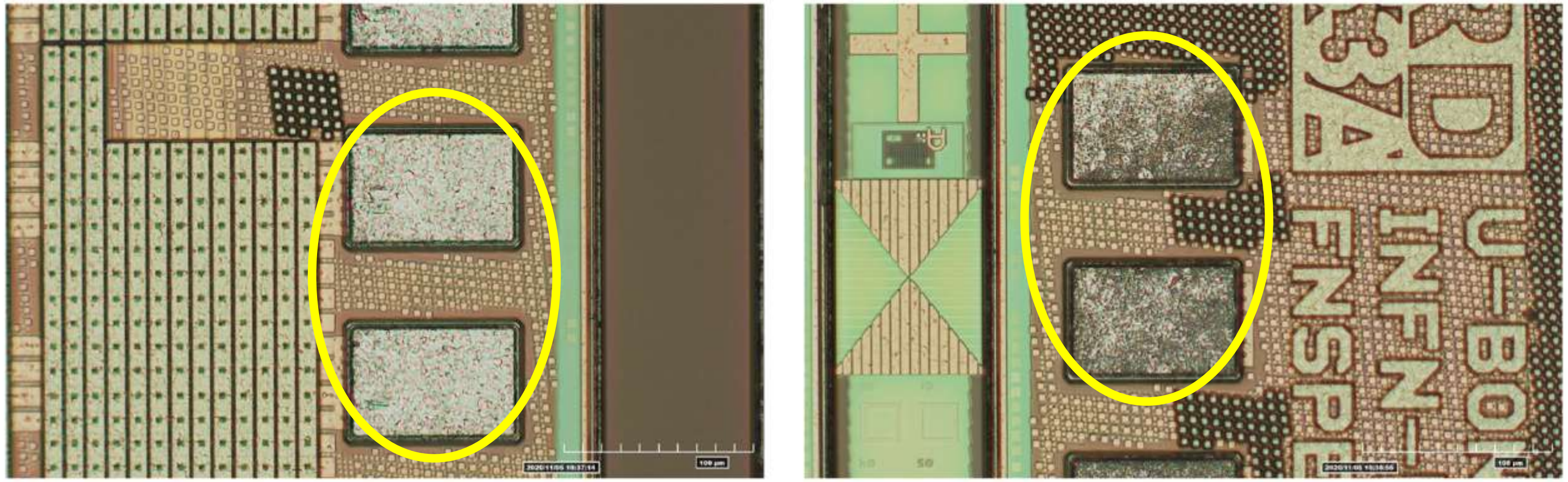
[redacted]

[redacted]

[redacted]

- A variety of visual inspection instruments at the assembly sites
  - HD photographic **cameras**
  - Optical and digital **microscopes**

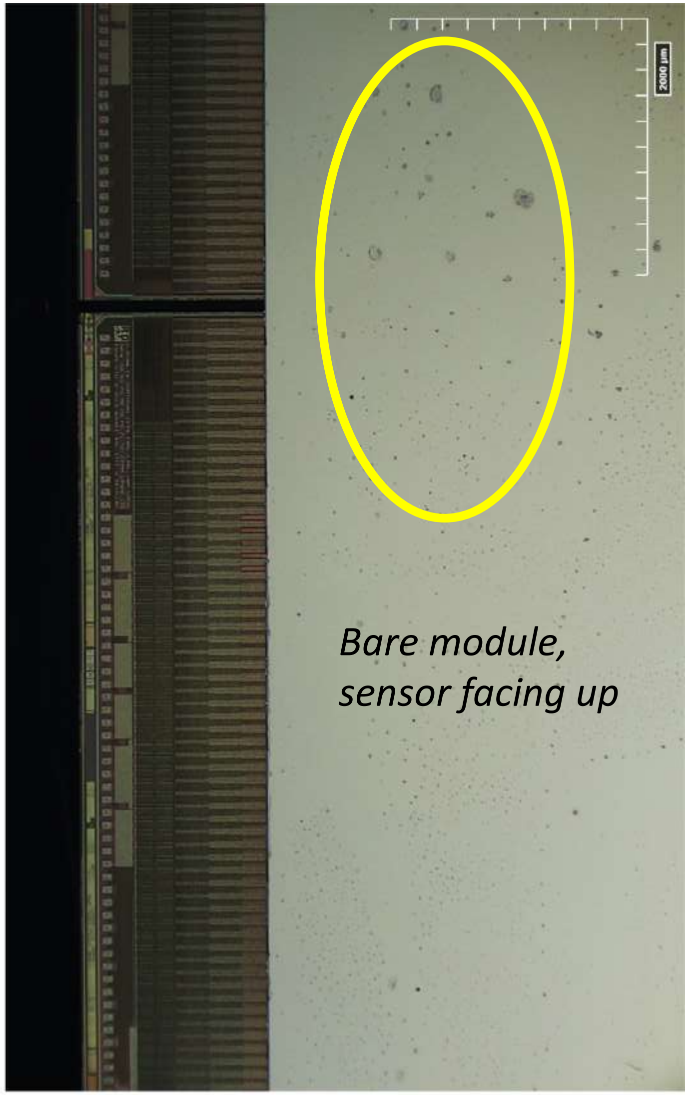
A lot of visual inspection…



Clean

Contaminated

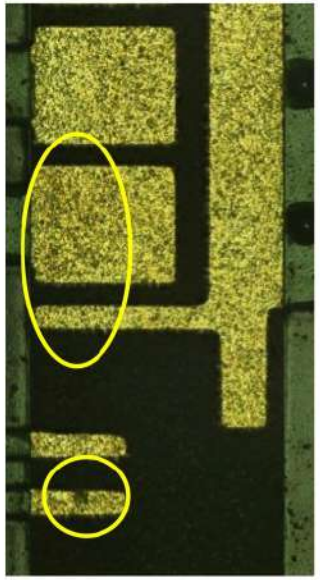
FE chip wire bonding pads

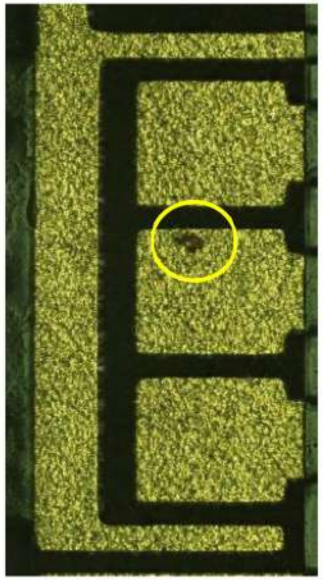


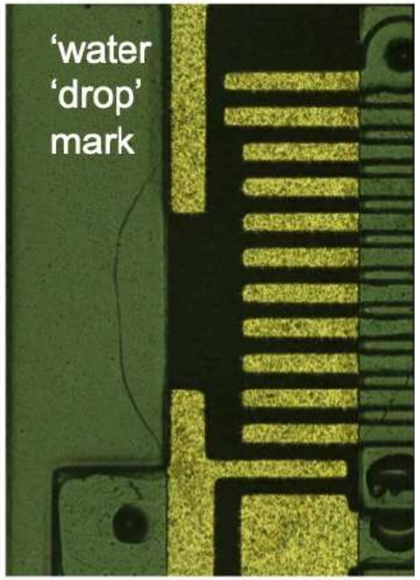
Bare module, sensor facing up

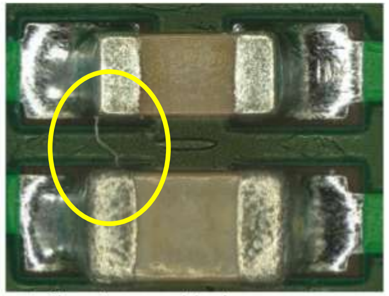
Back side of FE chips

A lot of visual inspection…

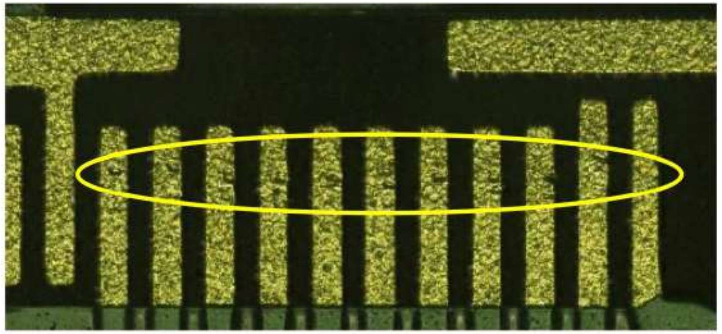


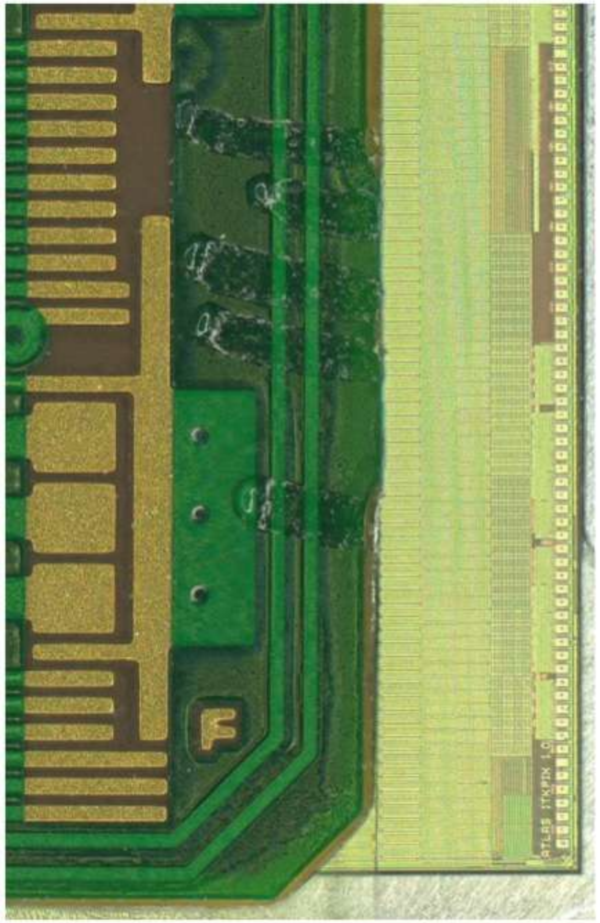




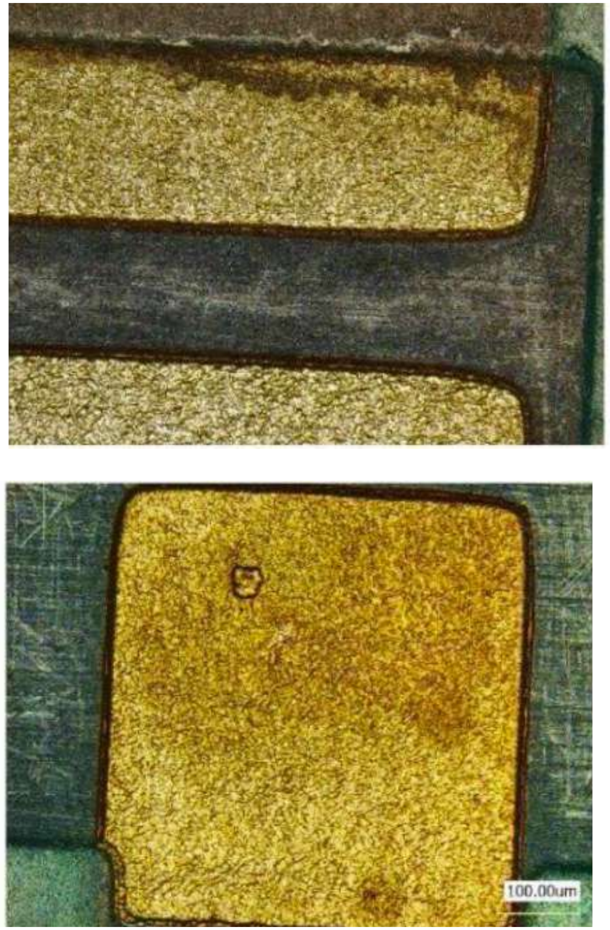


Fiber trapped below e-comp





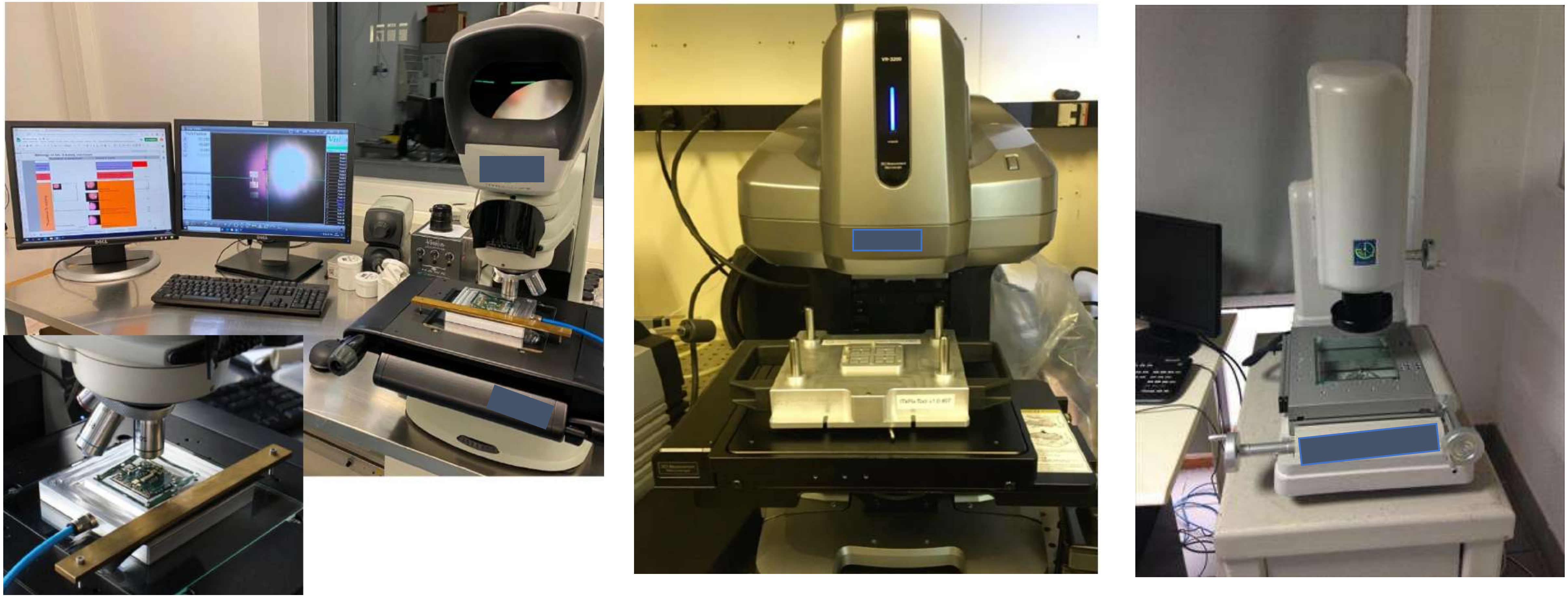
Glue seepage



Poor flex pad quality

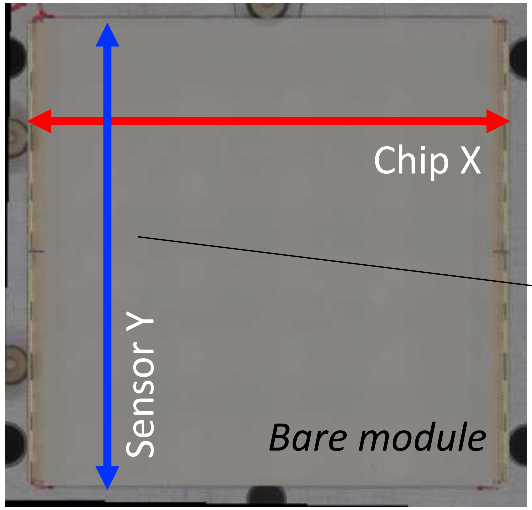
- A lot of effort on visual inspecting flex pad surfaces
- Important aspect with respect to a smooth and successful wire bonding

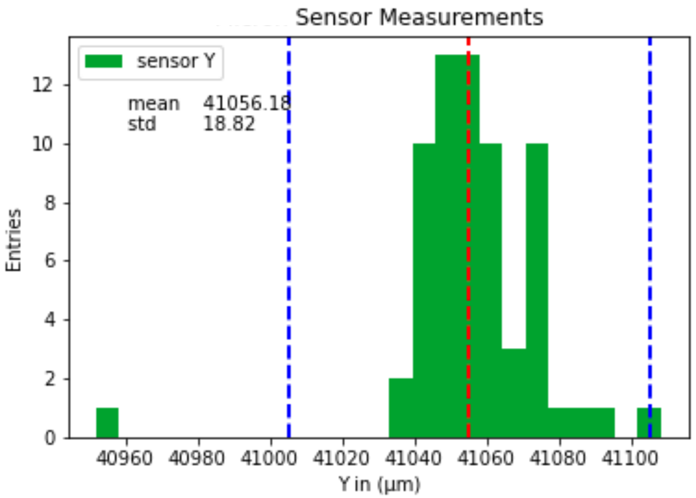
Metrology

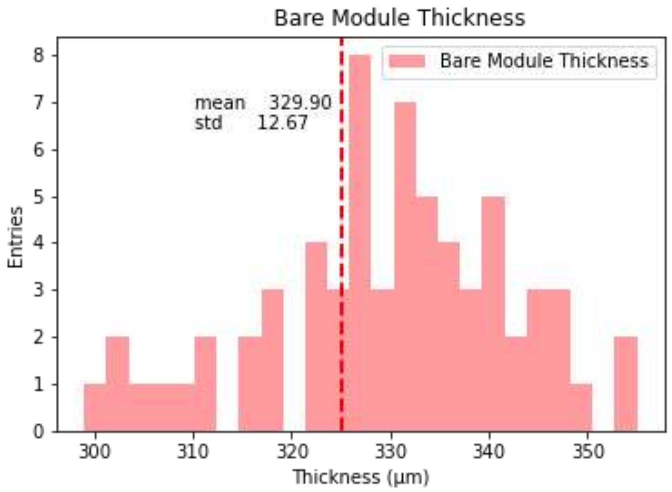


- Similar to visual inspection, a plethora of metrology instruments at the assembly sites, capable of measuring **dimensions**, **angles**, **thickness**, **flatness** at a **precision** of a **few microns**
  - Profilometers, smart scopes, CMM, digital microscopes, ….

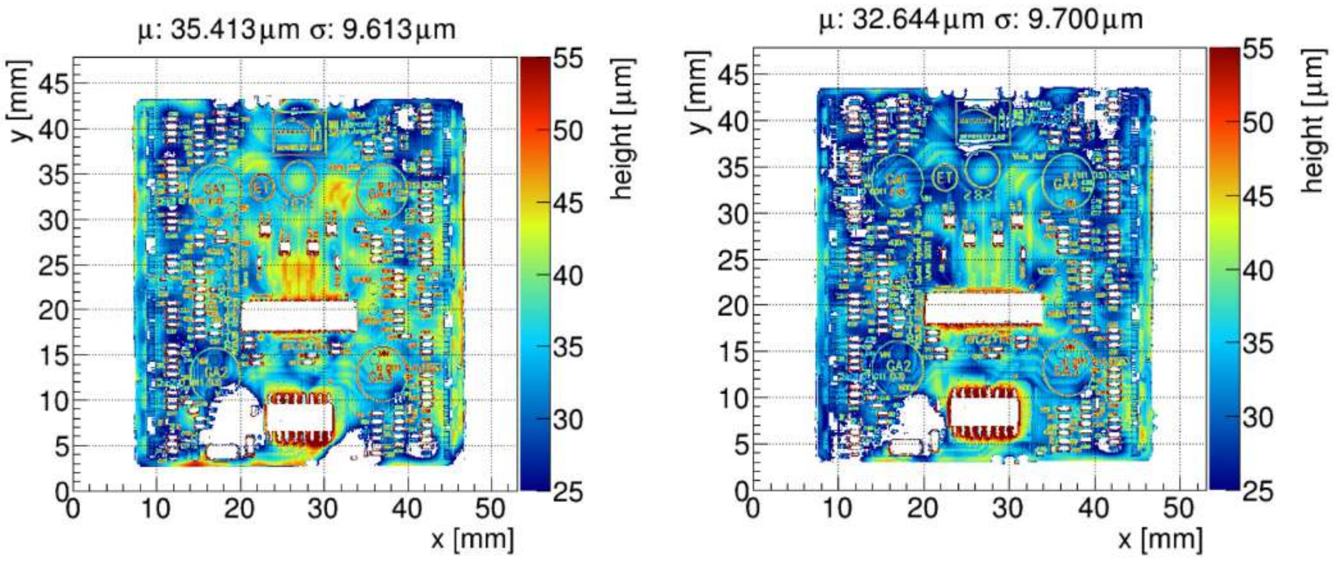
Metrology







- **Metrology** of **assembled module**
  - Flex to bare module **alignment**
  - Total **module thickness**: module envelope check
  - Derive **glue layer thickness**: important element of tooling performance

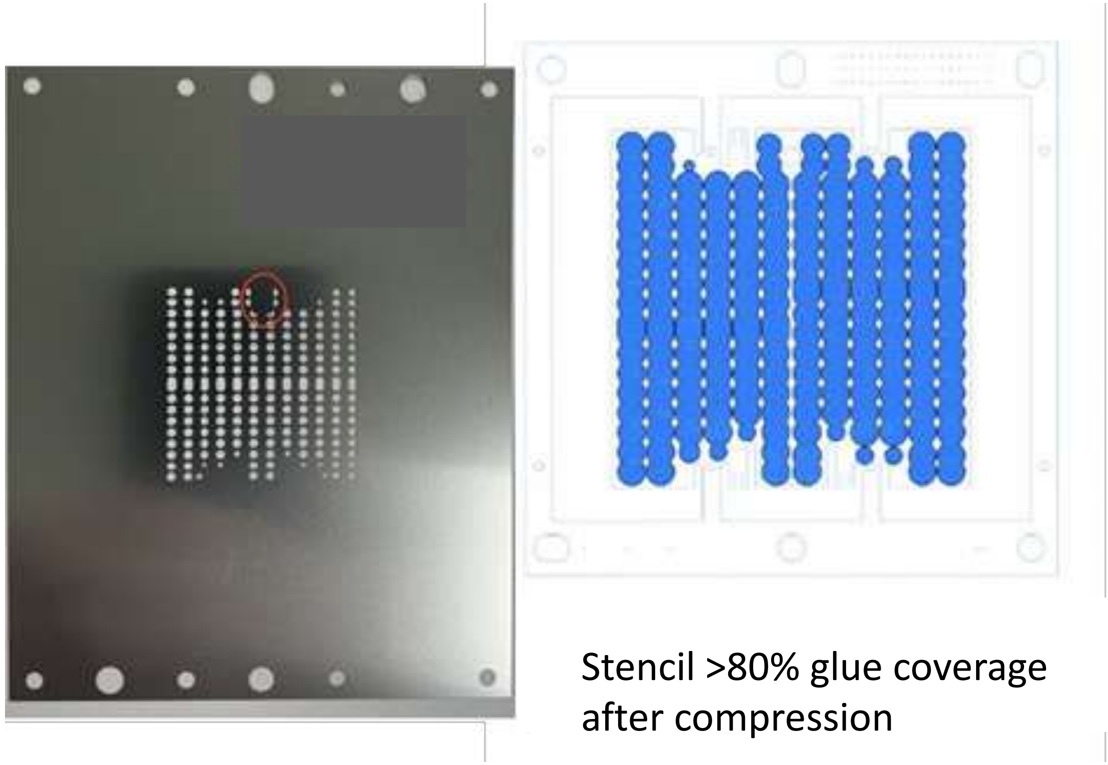


Glue layer thickness across the module within 40 um ± 15 um

Glue pattern validation

- Stencil glue dots to allow continuous glue layer over the surfaces, with a coverage > 80% ⇒ Reduce the risk of delamination because of thermal stresses

Glue pattern after using the final prototype stencil: continuous glue layer



[redacted]

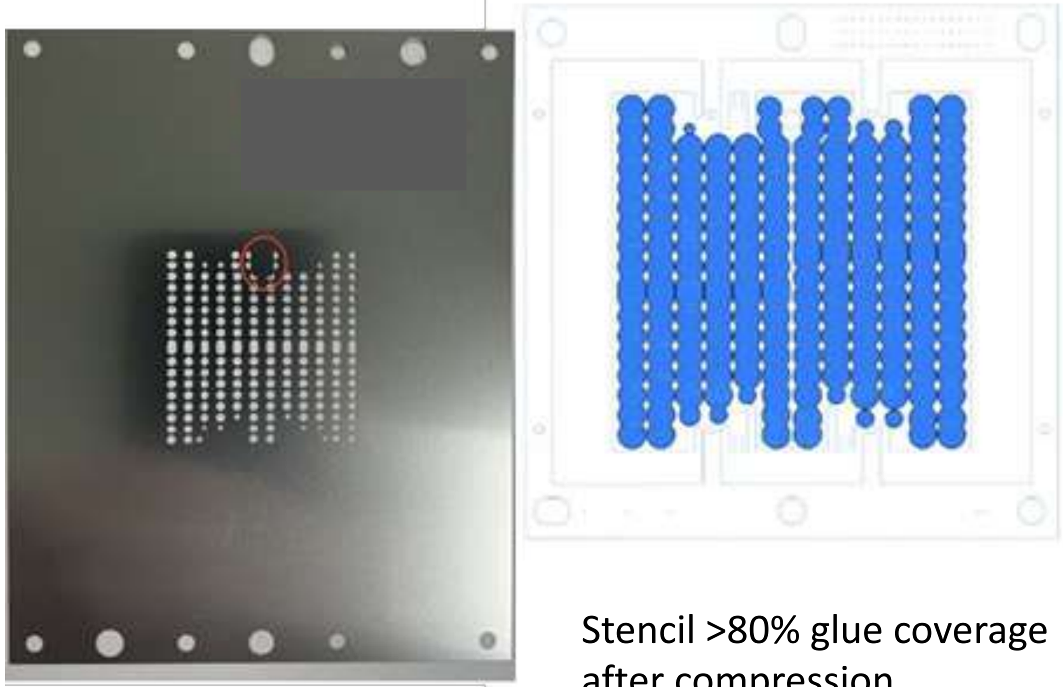
Stencil >80% glue coverage after compression

- Numerous **glass dummies** produced to check
  - No glue seepage into HV connection hole
  - Continuous glue layer is achieved

Glue pattern validation

- Stencil glue dots to allow continuous glue layer over the surfaces, with a coverage > 80% ⇒ Reduce the risk of delamination because of thermal stresses

Glue pattern after using the final prototype stencil: continuous glue layer



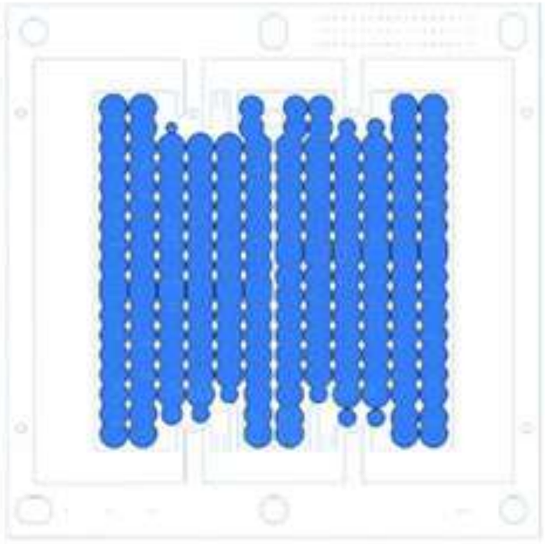
Stencil >80% glue coverage after compression

- **16 Si dummies** and thermally cycled them
  - On these Si dummies, we looked for delamination after 1, 5 and 10 cycles (sometimes going to even higher number of cycles)
  - **No detachment, nor** any other **failure** of the adhesive was observed after module probed at the corners
- **O(160) real RD53A prototype quads**
  - Thermal cycles test passed successfully, **no delamination seen**

Glue pattern validation

- Stencil glue dots to allow continuous glue layer over the surfaces, with a coverage > 80% ⇒ Reduce the risk of delamination because of thermal stresses

Glue pattern after using the final prototype stencil: continuous glue layer



Stencil >80% glue coverage after compression

- 1 Si dummy went over extreme thermal cycling conditions
  - +60 ^{0}C to -55 ^{0}C inspected at 0, 20, 50, 100, 200, 300, 500 & 1000 cycles : **no sign of delamination**
  - -40 ^{0}C (in a freezer) for 10 months : **no delamination observed after this time**

- 10 irradiated tested quads until now
  - **No flex delamination, no adhesive failure**

From prototype tooling to production tooling

- Lots of lessons learnt during the prototype modules assembly

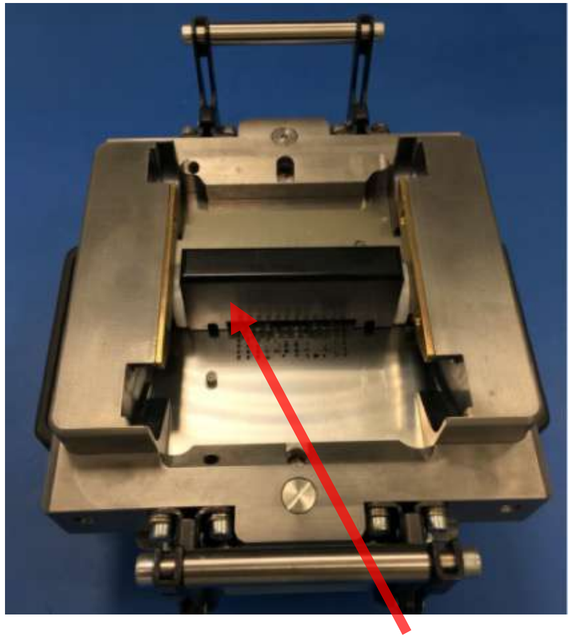
- We took the opportunity to improve the flex-attach common tooling towards (pre-)production

- Goal: produce an updated tooling **as less as possible operator-dependant**, ensuring consistent and precise results across all the assembly sites, respecting the specifications
  - **Reduce variation** in **glue layer thickness** and **glue mass** across assembly sites: operator dependant
  - **Improving mating of jigs** affecting reproducibility of results among different sites: operator dependant
  - ➢ Enhance **strength of tooling components** by choosing more **appropriate raw material** (Al alloy, steel)

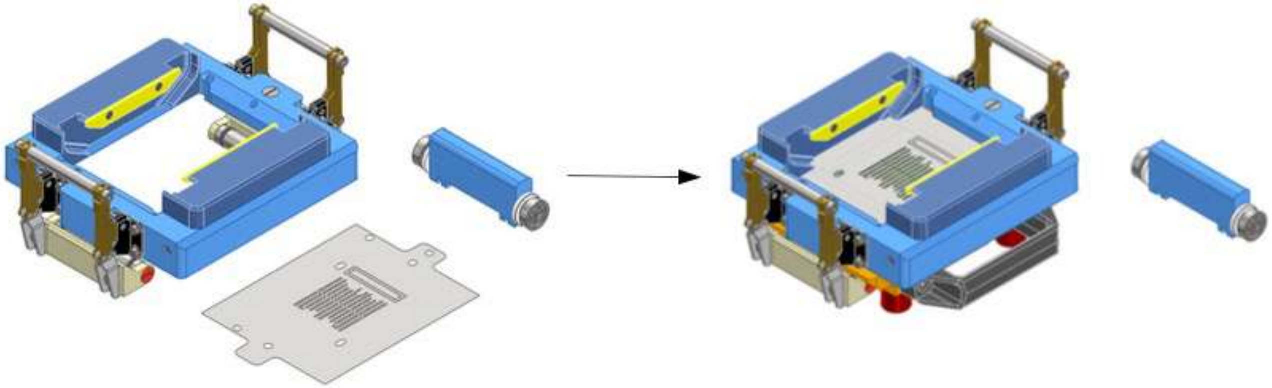
From prototype tooling to production tooling

- **Controlled glue application by newly designed stencil frame**
  - **Clamping lever** to ensure **tightening** of **stencil** on the frame
  - **Change design of spatula**
    - **Spatula inserted** into the frame taking advantage of **special rails** at the **two edges** of the **frame**
    - When spatula slides along the rails, **spatula side rings** are **squeezed** and the **spatula pushes firmly on the stencil**

➢ Resulting **amount of glue** does **not depend** on the **force applied** to the spatula **by the operator**



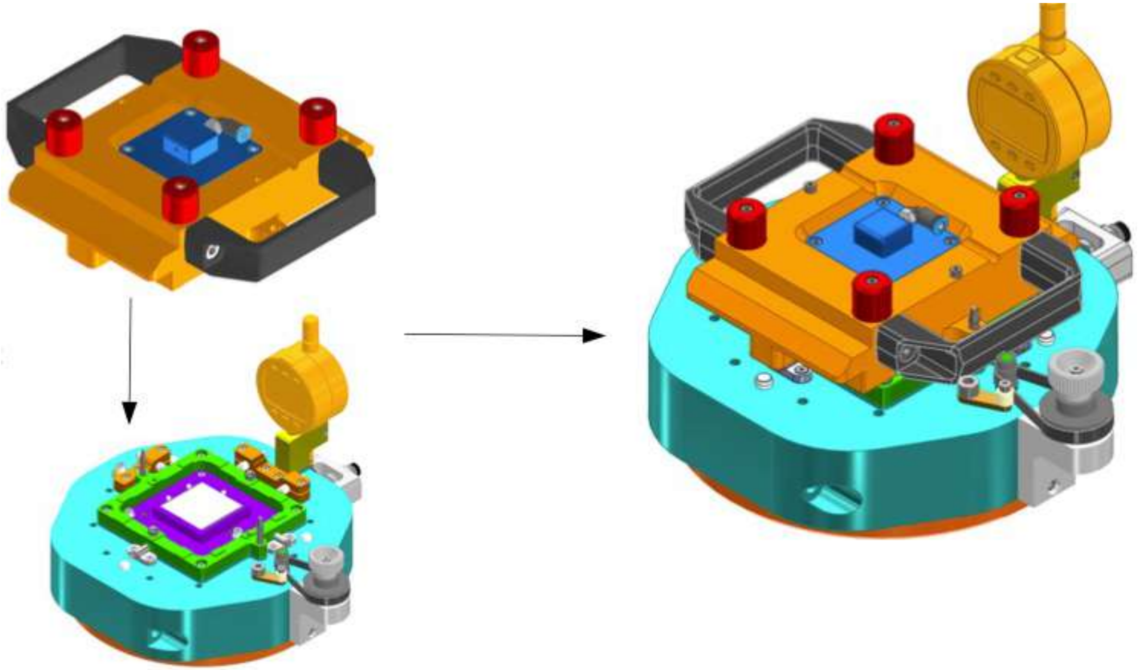
Spatula



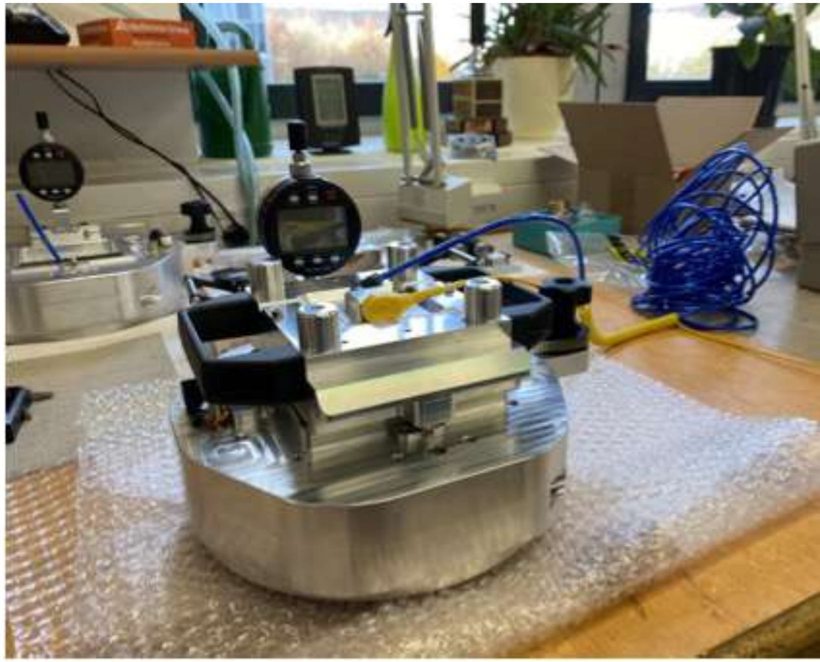
Stencil frame

Spatula side

From prototype tooling to production tooling



- **Dial gauge** for **fixing** the **glue thickness**, extremely easy and fast!
- Very nice concept of tooling: **adjustment** of **glue thickness compensates** for **thickness variation** of **components**
  - Super interesting feature given the tolerances of bare components

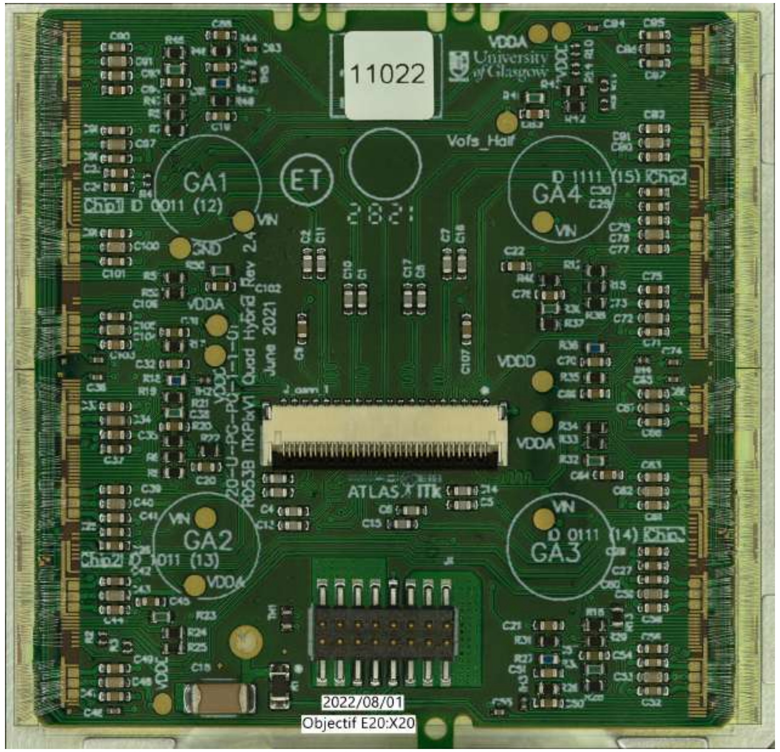


Average gluing duration (without curing)

- Module assembly (bare components placing, stencil attachment, glue height calibration, glue application with spatula): **~10 minutes**
- Cleaning, reset of tooling: ~**5 minutes**
- ➢ **Total: ~15 minutes**

Summary

- **Modules** are the **building blocks** of **Pixel ITk detector**
- Their **assembly** is the **first step** in the modules **production**
- A lot of **tests** at the **reception** of **the bare components**: first institute tests after the vendors
- Over the last years, extensive R&D and design validation to **ensure** the production of **robust modules** that will last (for some cases) for **more than 10 years** of HL-LHC operation
- **Procedures**, **toolings** and **methods** are now **finalized**, we are ready for **exciting time ahead** with the **(pre-)production**

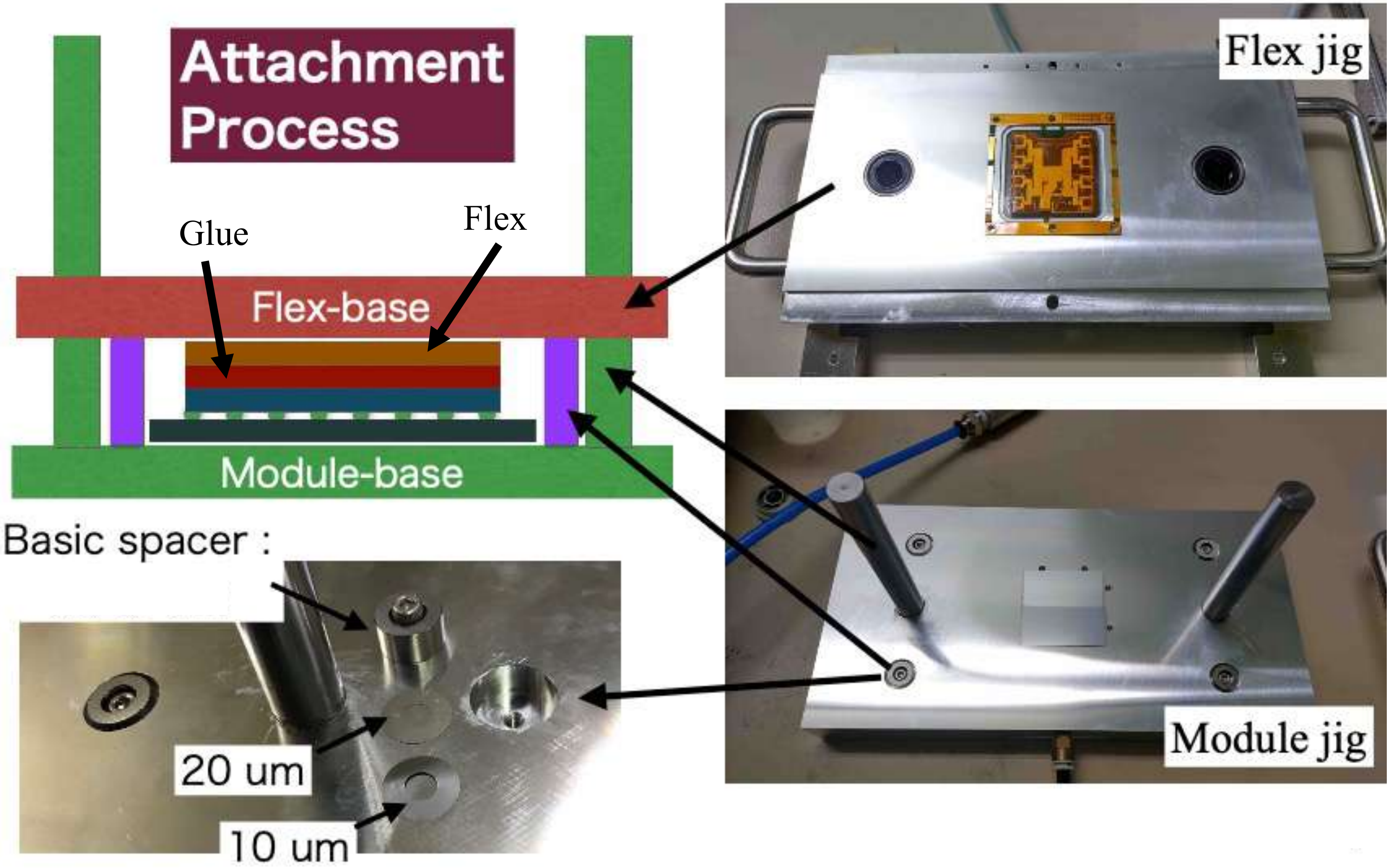


Bonus slides

Alternative gluing methods 1/2

Credits to M. Togawa

- Glue thickness is adjusted by spacer.
  - No force on sensor and ASIC

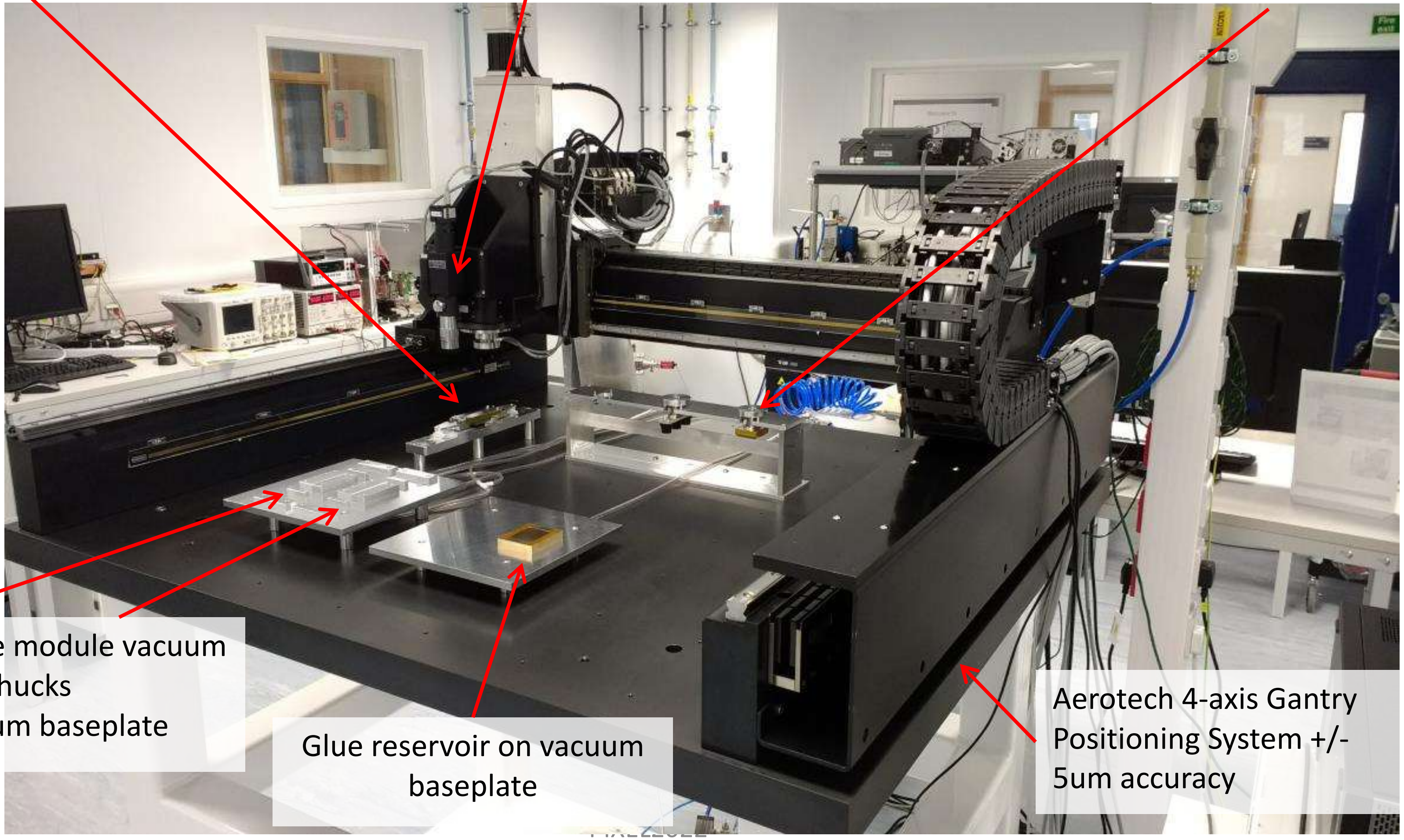


- **Modified jigs** using **same stencil**
- Very **similar** to the **common** baseline **tooling**
- One **conceptual difference:** **glue thickness** is fixed with the use of **spacers**
- **Bare module** and **flex thicknesses** have to be measured necessarily before every assembly

Alternative gluing methods 2/2

Credits to R. Plackett

- **Robotic assembly system** with a glue pattern similar to the stencil one



Vacuum pick-up ‘Bridge tool’ in docking station

Camera w/ microscope lens and lighting & laser rangefinder

Glue stamp tool in tool rack

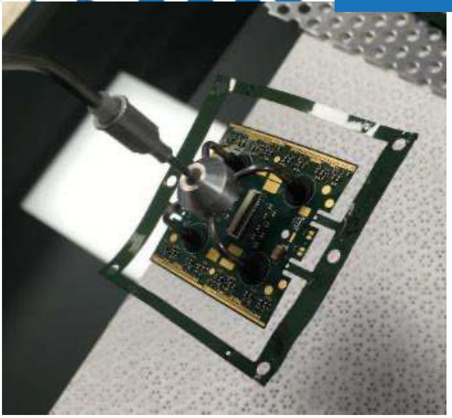
Flex and bare module vacuum chucks on vacuum baseplate

Glue reservoir on vacuum baseplate

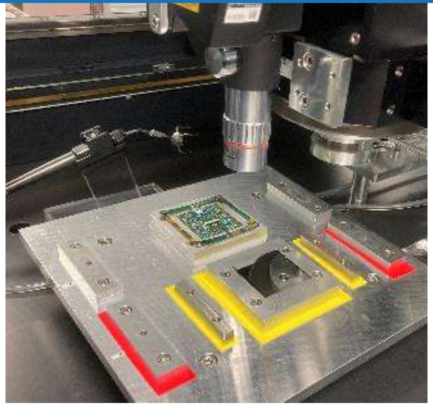
Aerotech 4-axis Gantry Positioning System +/- 5um accuracy

Alternative gluing methods 2/2

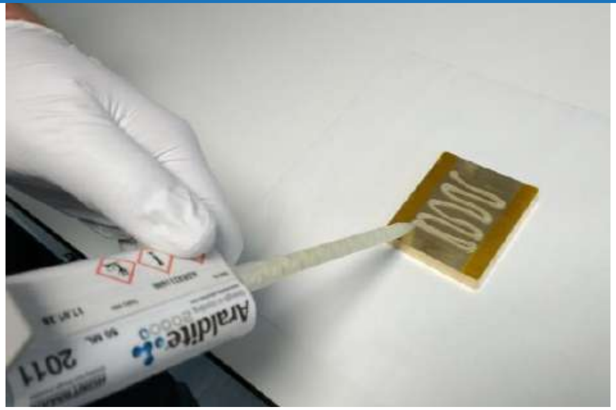
Credits to R. Plackett



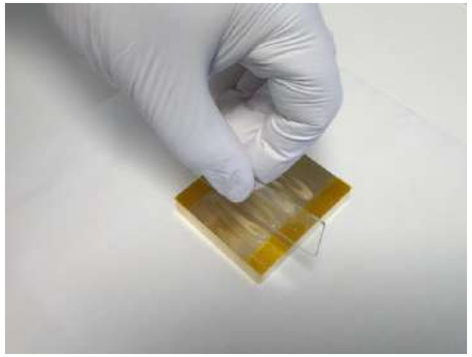
1) Flex and bare module placed on robot vacuum chucks manually with custom vacuum tools. Vacuum clamped down.



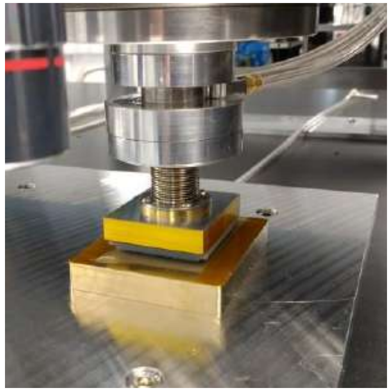
2) Robot microscope surveys position of vacuum clamped components to +/-5um (can use pattern recognition)



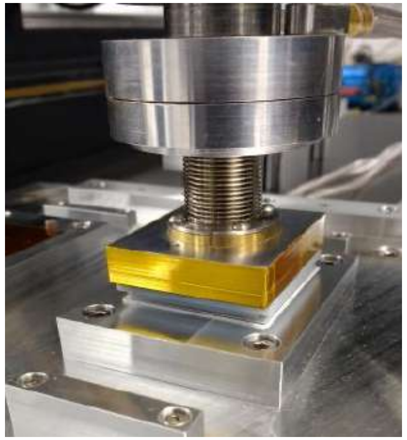
3) Araldite 2011 is loaded into the reservoir with a mixing nozzle



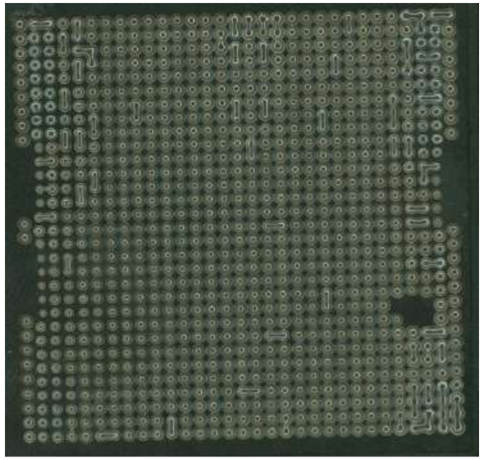
4) Glue is scraped flat with a straight edge to give a well defined surface to dip the stamp into



5) Glue reservoir is vac clamped to the robot and the stamp tool is dipped with precisely controlled parameters (time and force)



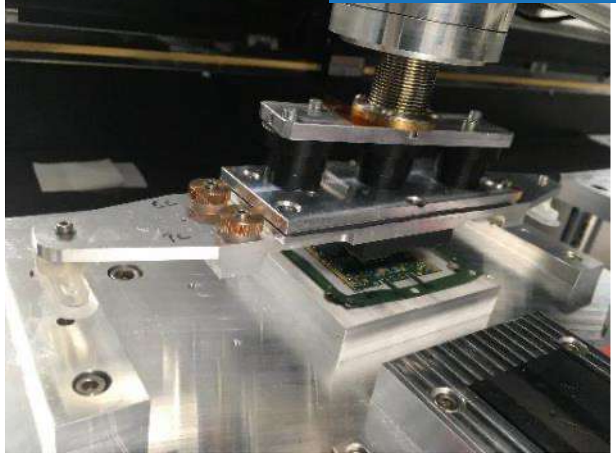
6) The robot stamps the glue pattern onto the sensor surface with a reputability of +-2mg



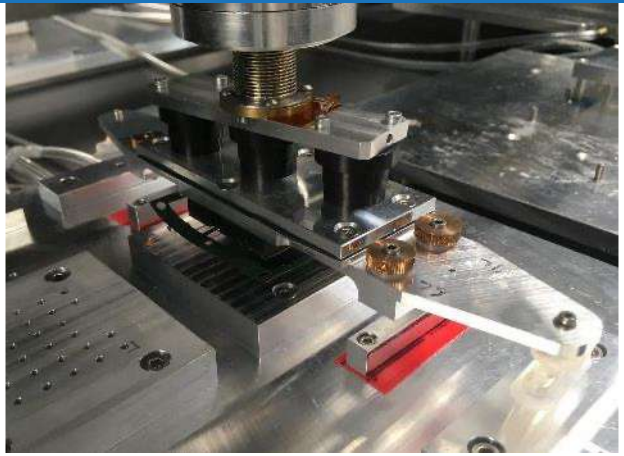
(aside) The ITKpix glue dot pattern on a sensor.

Alternative gluing methods 2/2

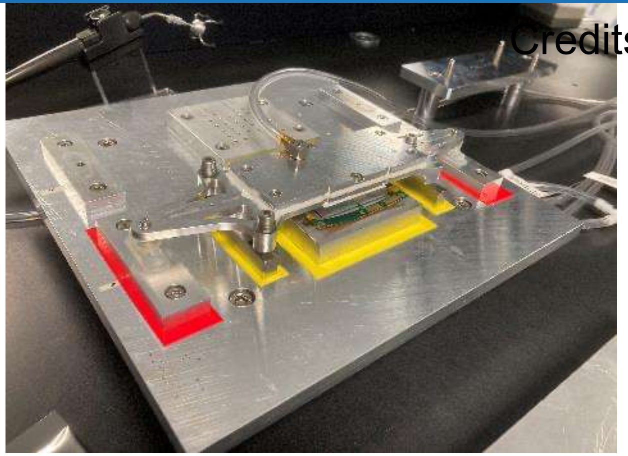
Credits to R. Plackett



7) The robot picks up the ‘bridge tool’ and places it over the flex using the previously surveyed position and **The flex is picked by the bridge tool** with a double clamping sequence to avoid bouncing during the pickup transfer.



9) The robot places the flex onto the bare module using the previously surveyed position. Precision feet set the glue thickness to +/- 10um



10) The robot leaves the bridge tool in place overnight for the glue to cure. Vacuum remains on.

- In full production, four modules will be built in parallel using 4 ‘stations’ on the robot and 4 bridge tools.
- This process achieves a **±20µm placement accuracy of the flex on the module alignment**, and a **±10 µm accuracy on the glue thickness**.
- The glue deposited is programmatically selectable from **50mg to 80mg and stable to ±2 mg**

Triplets assembly method

Credits to E. Pianori

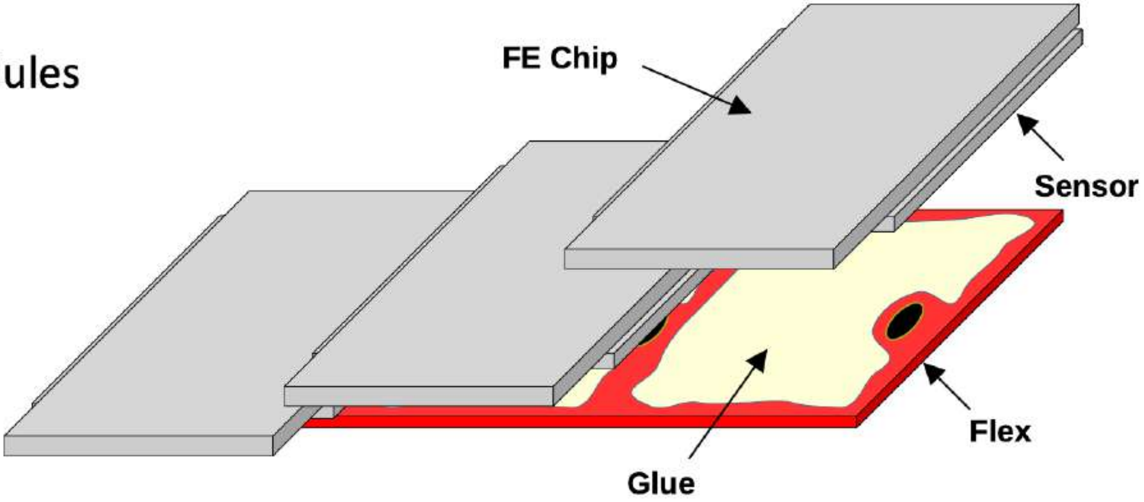
Barcelona/Oslo/Milano uses similar approach: Pick and place machine + stamp

- Hybrid kept in place with vacuum, with SDM components down
- Glue deposited on back-side of the hybrid using pick-and-place machine
  - Glue deposition different for each group – optimised together with other parameters of the assembly
- Single modules placed on the back side of the hybrid using pick-and-place machine
  - Different alignment methods used by different groups
  - Aim at same specs
- Milan recently received their machine, will adapt the method developed by Barcelona for the R0.5 triplets

Genova use a different approach:

- placing the flex on top of positioned bare modules

Pick and place machine + jigs (base plate)

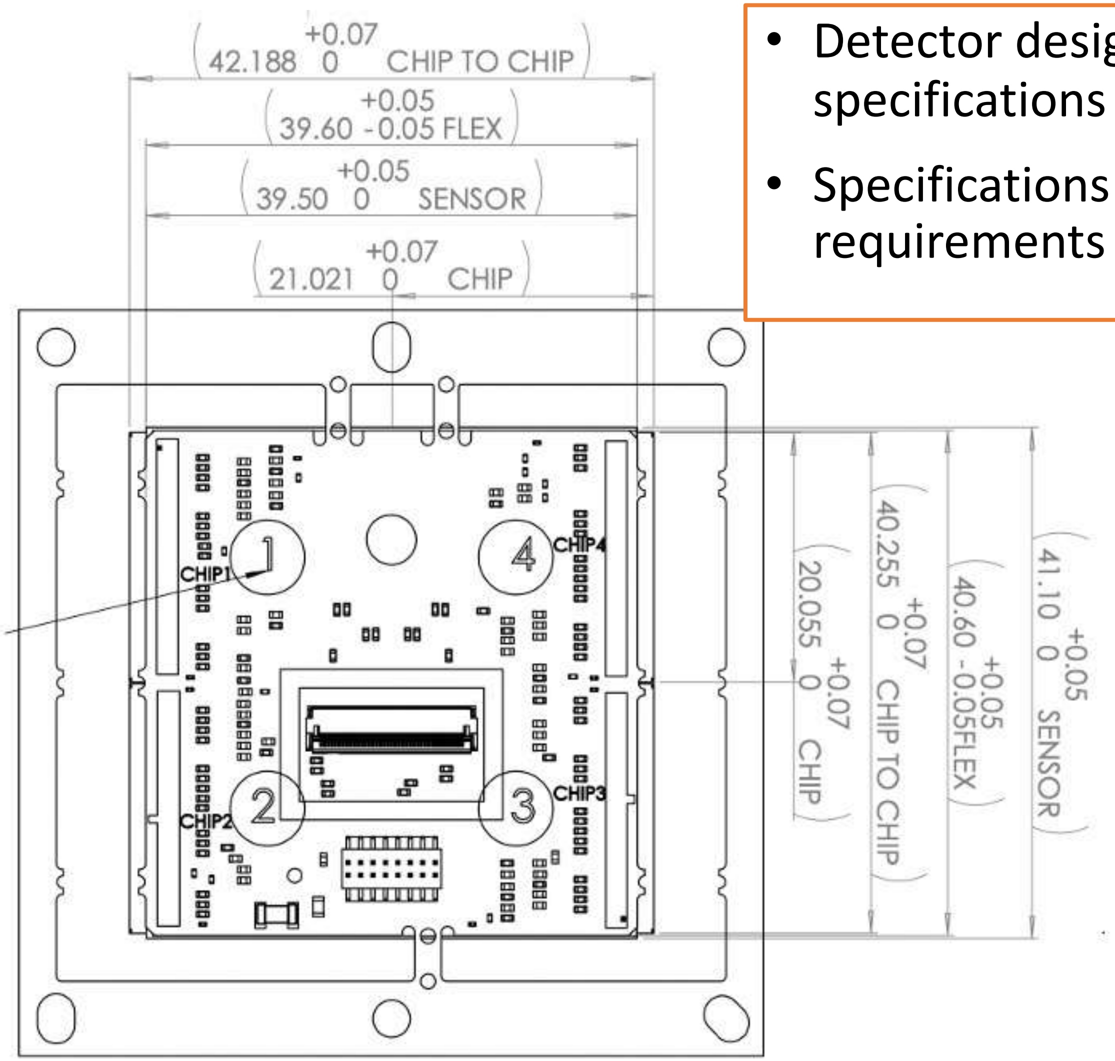


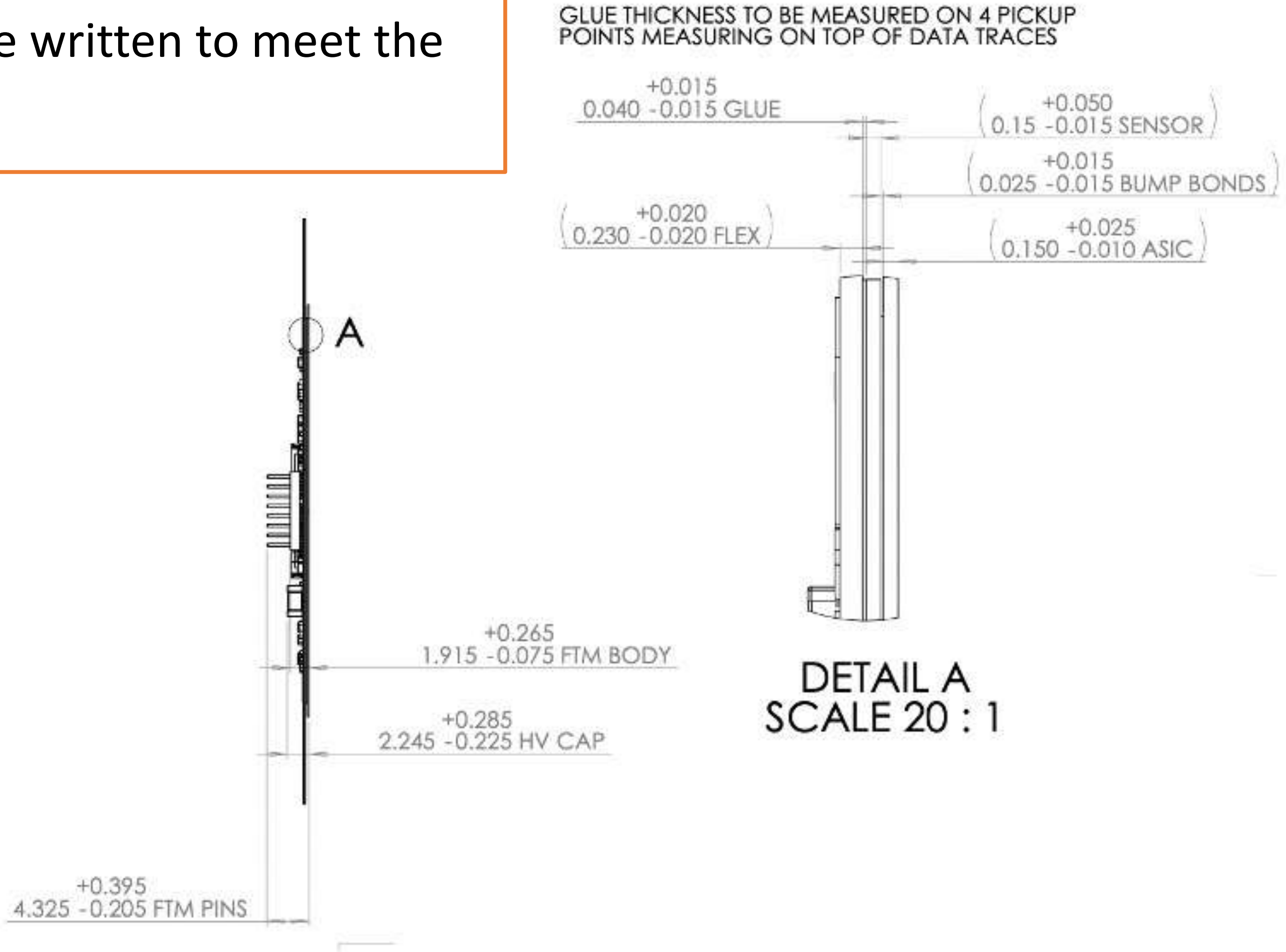
Backup

- Quad assembly specifications

Quad module assembly drawings

- Detector design is created to meet the specifications
- Specifications are written to meet the requirements





Specifications related to assembly

- Adhesive
  - Coverage of at least 80% on the glued surfaces (PCB – Sensor side of bare module)
  - Enough glue under PCB wire bond pads and under the pick-up areas
  - Continuous glue perimeter to minimise stress in the glue layer
  - No adhesive seepage beyond the PCB that will cover the wire bond pads, including HV hole
  - Adhesive thickness larger than 10 um to ensure sufficient bond strength
  - No delamination seen after thermal cycling and irradiation

- Module mass
  - A variation of +10% - 6% (inheriting from the bare components specifications); expected to be around 3 g

- Wire bonding
  - 25 um Aluminium wire
  - Wire bond pull tests: minimum force 5g; average force ≥ 8g; STD force ≤ 15% ; ≥ 90% of pulls must be heel breaks
  - Wires to be pulled straight after wire bonding and before any coating applied

Specifications related to assembly

- Flex to bare module centre to centre alignment
  - ± 100um in X, ± 100um in Y to ensure module envelope, maintain wire bonding angle, connector position for the outer barrel modules

- Module flatness
  - Measured at the backside of the FE chips, 50 um or better, to guarantee proper thermal contact with the local support ⇐ in particular relevant for the OB modules
  - Measurement to be done at the end of the QC (after thermal cycling)

- Module thickness
  - Thickness variation at the 4 pick-up areas not larger than ± 15 um

- Module envelope
  - Respecting the module envelope within tolerances in all 3 dimensions X, Y, and Z

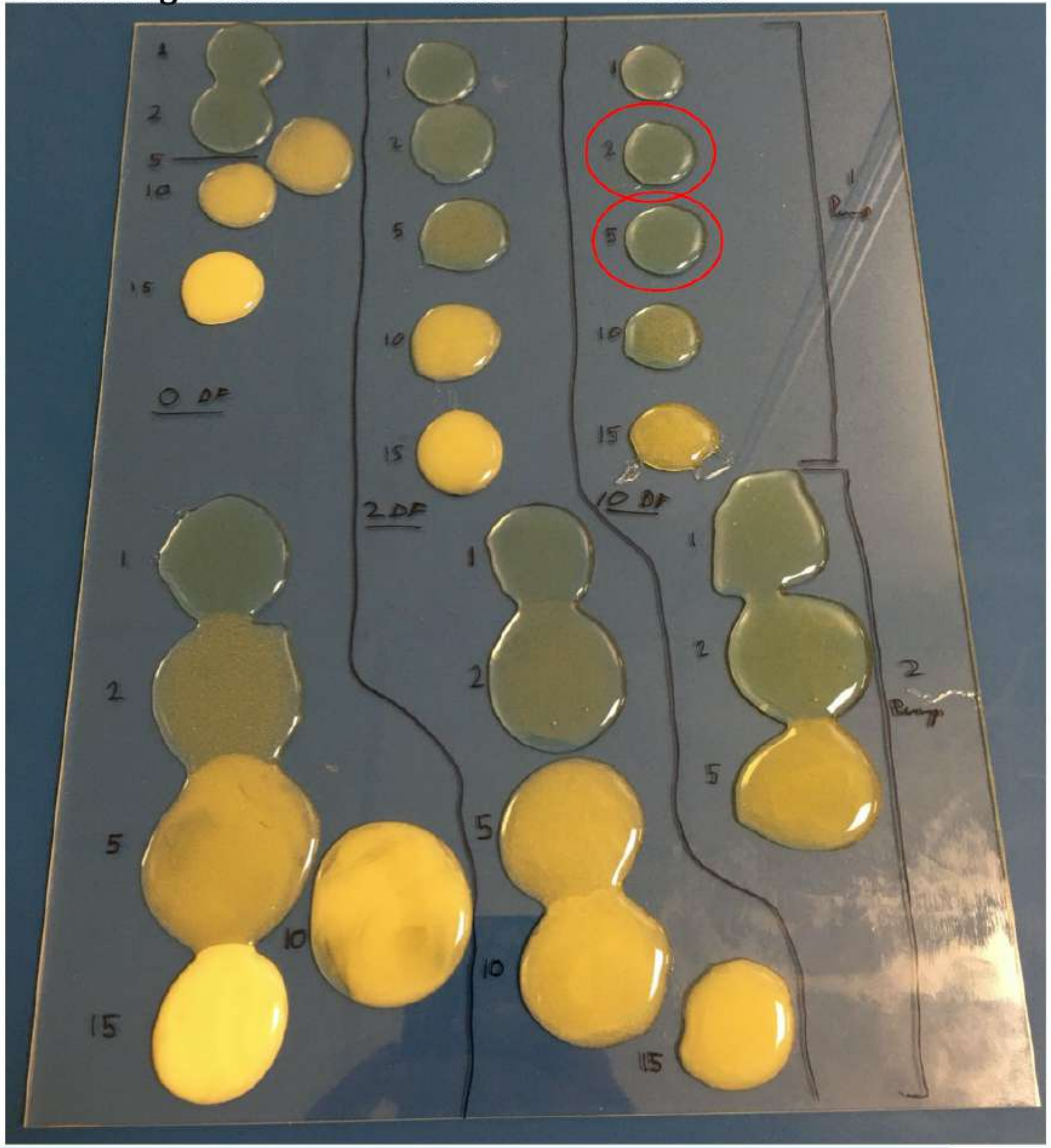
Araldite 2011 Mixing Study

Key observations:

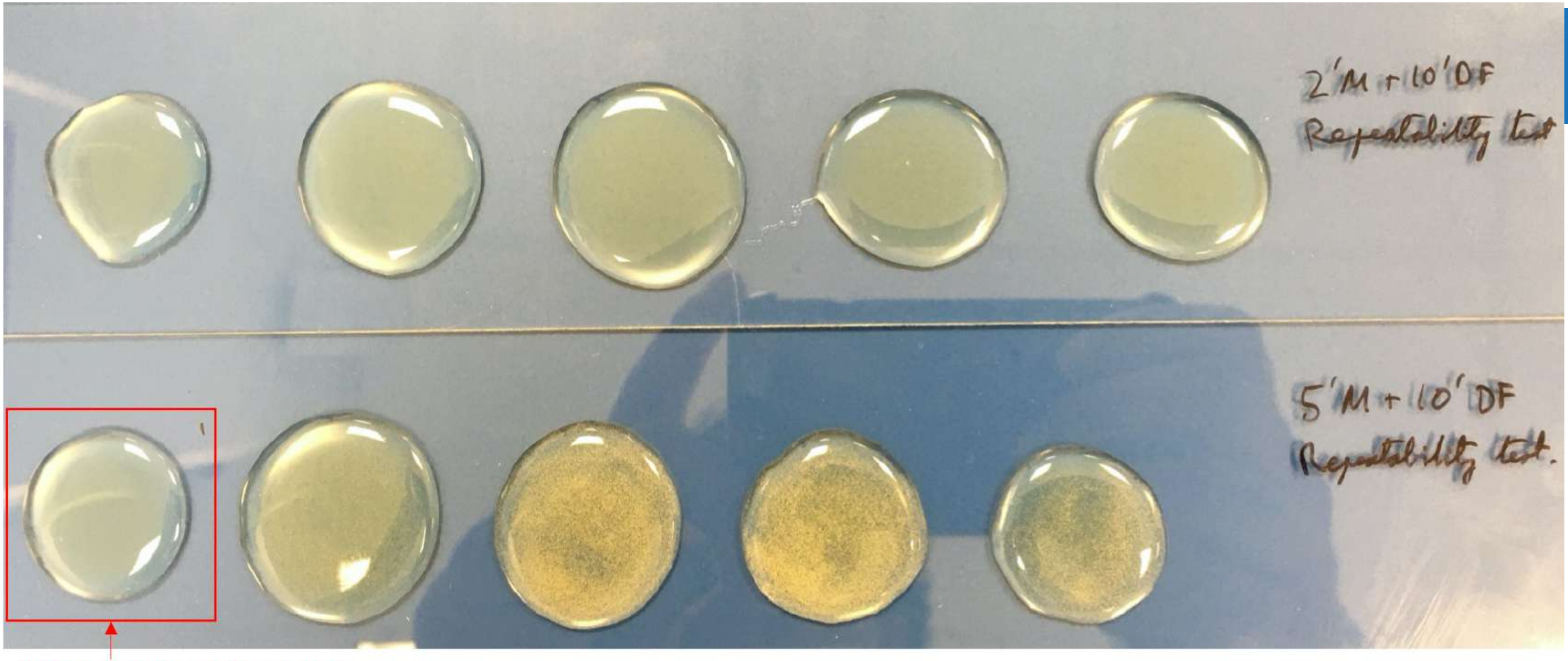
- **Excess mixing leads to increased bubble presence (whitening).**
- Longer defoaming counters this effect successfully.
- Visually best outcomes (colour&bubbles) were:
  - 2 min mixing and 10 min defoaming (DF).
  - 5 min mixing and 10 min defoaming.

1 pump (3 g)					
Minutes		Minutes		Minutes	
Mix	DF	Mix	DF	Mix	DF
1	0	1	2	1	10
2	0	2	2	2	10
5	0	5	2	5	10
10	0	10	2	10	10
15	0	15	2	15	10
2 pumps (6 g)					
Minutes		Minutes		Minutes	
Mix	DF	Mix	DF	Mix	DF
1	0	1	2	1	10
2	0	2	2	2	10
5	0	5	2	5	10
10	0	10	2	-	-
15	0	15	2	-	-

Defoaming: 0min 2mins 10mins



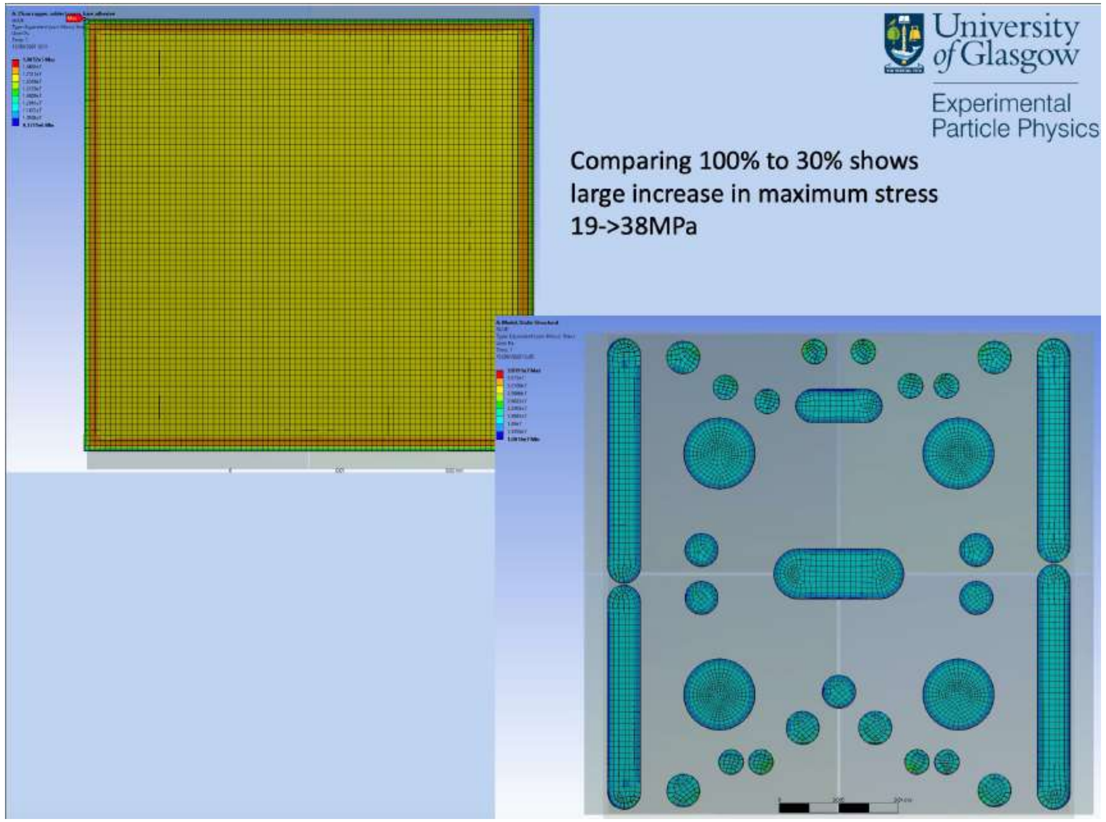
Study
Speed: 2000rpm



1/5 sample had no microbubbles.

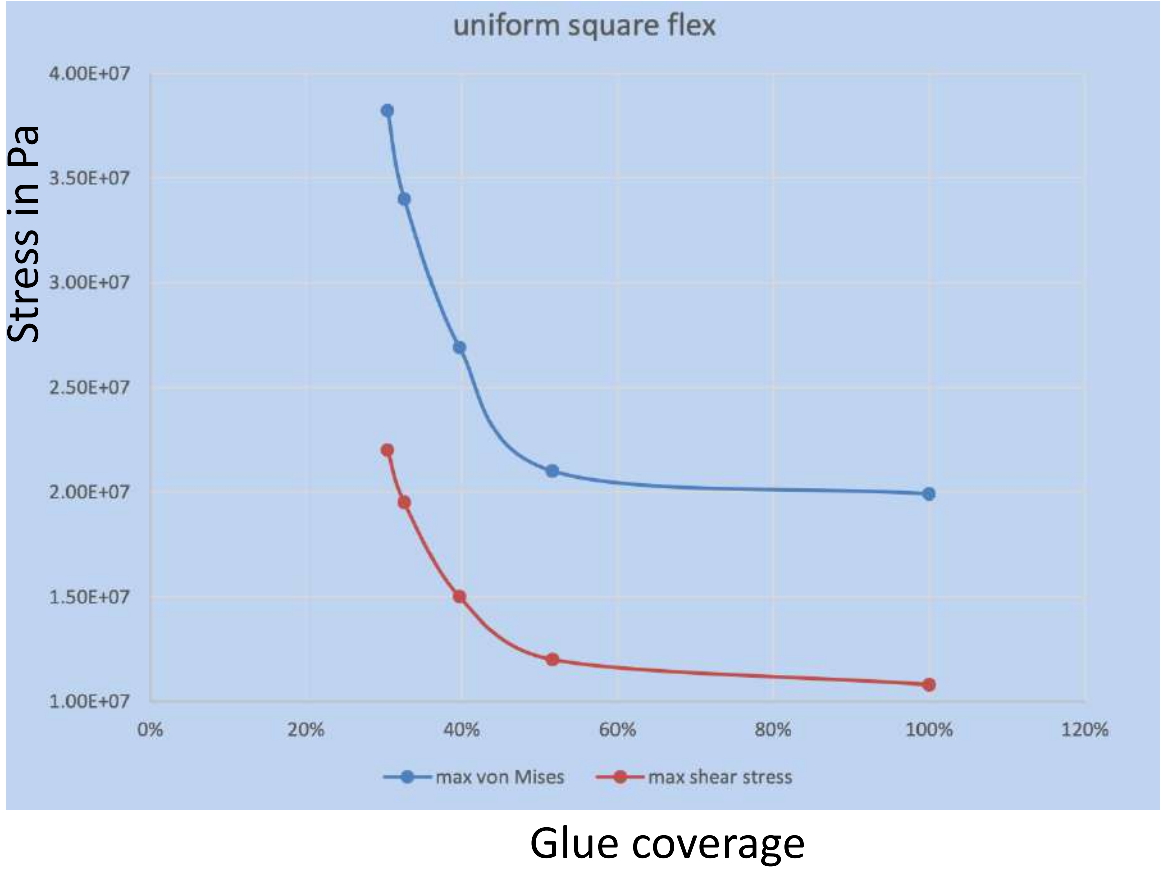
- Not all groups have this type of planetary glue mixers and defoamers, it’s not a requirement
- Some groups having been using the mixing nozzle and the assemblies have been validated under extreme conditions: up to 1000 +60C to -55C cycles, -40 C freezer for 10 months, no flex delamination nor adhesion failure

Glue layer thermal expansion



University of Glasgow
Experimental Particle Physics

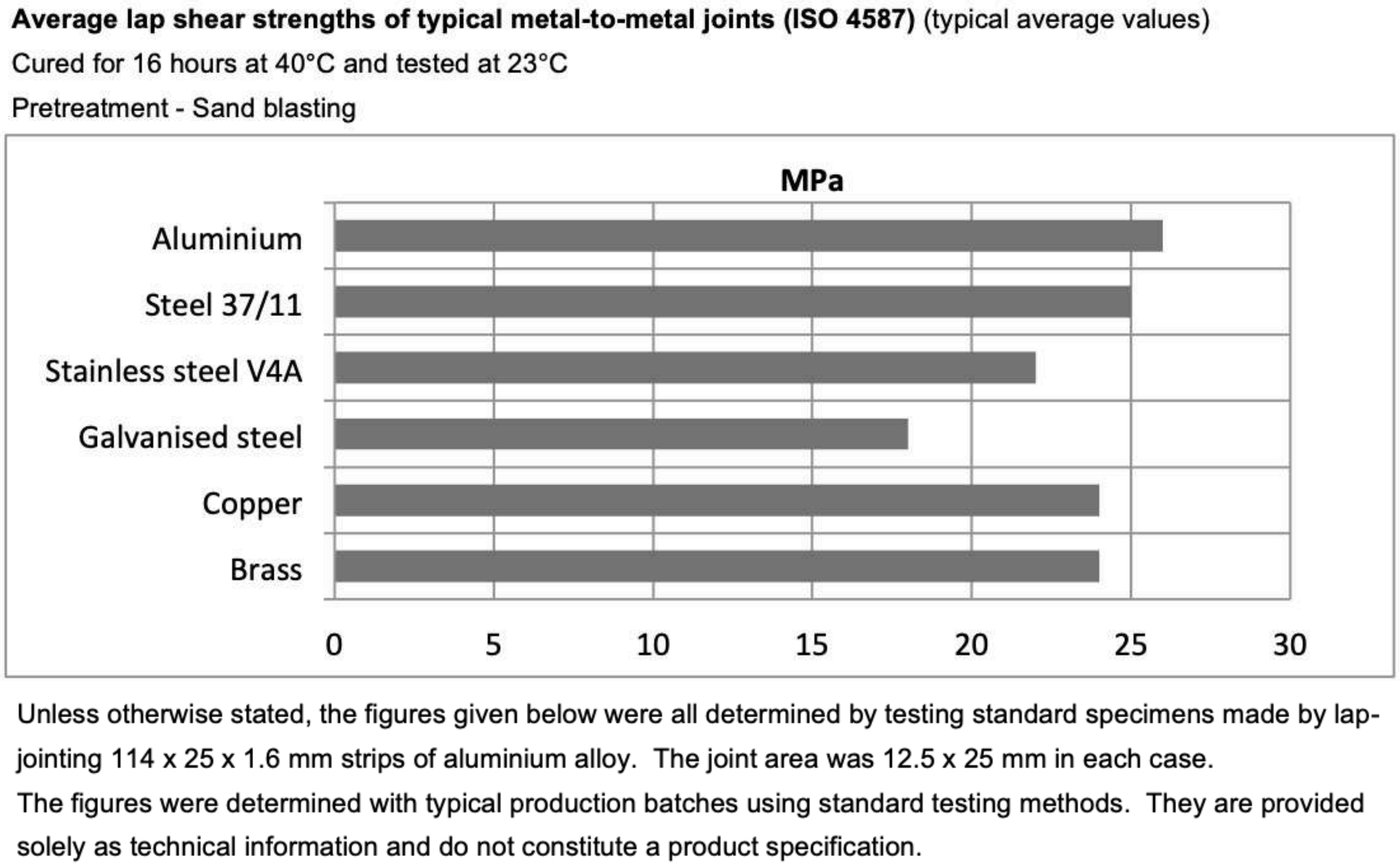
Comparing 100% to 30% shows large increase in maximum stress 19->38MPa



Glue thermal expansion

Need to know what is the threshold where the flex may start peeling off on its own

From manufacturer:



Average lap shear strengths of typical metal-to-metal joints (ISO 4587) (typical average values)

Cured for 16 hours at 40°C and tested at 23°C

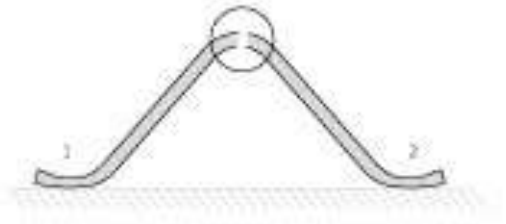
Pretreatment - Sand blasting

Unless otherwise stated, the figures given below were all determined by testing standard specimens made by lap-jointing 114 x 25 x 1.6 mm strips of aluminium alloy. The joint area was 12.5 x 25 mm in each case.

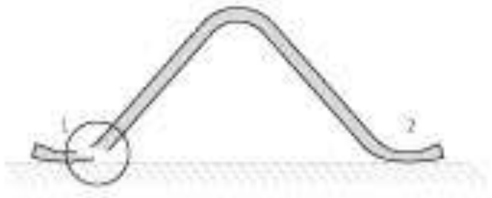
The figures were determined with typical production batches using standard testing methods. They are provided solely as technical information and do not constitute a product specification.

Wire bonding failures

Mid span break



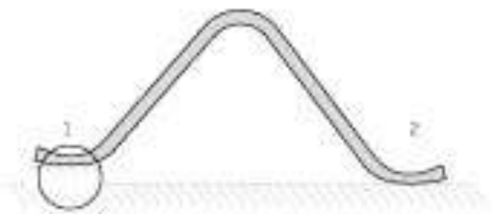
Heel break



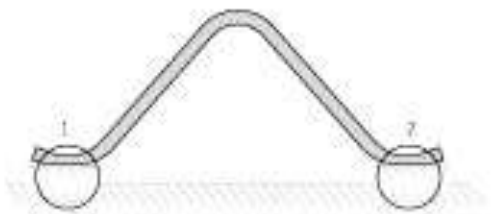
Wedge break

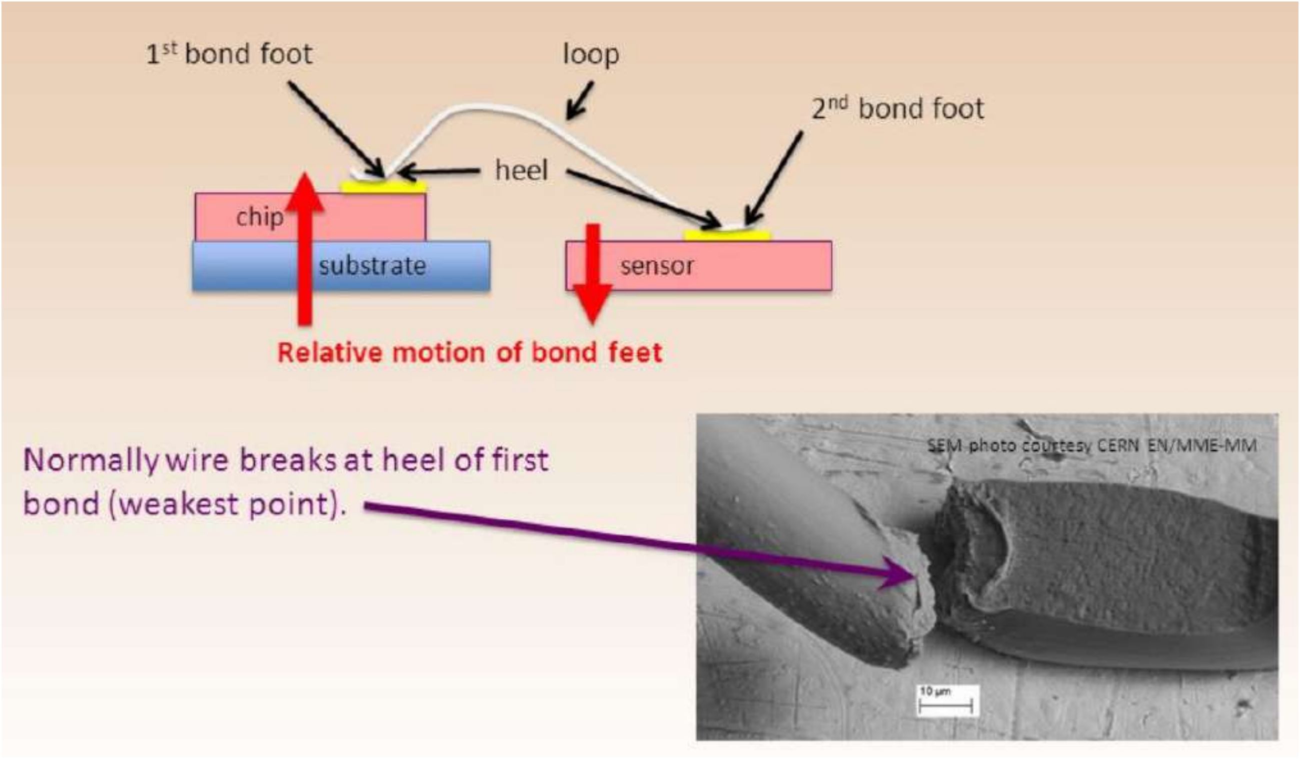
Both wedge bonds break

Wedge crater



Both wedge craters





Relative motion of bond feet

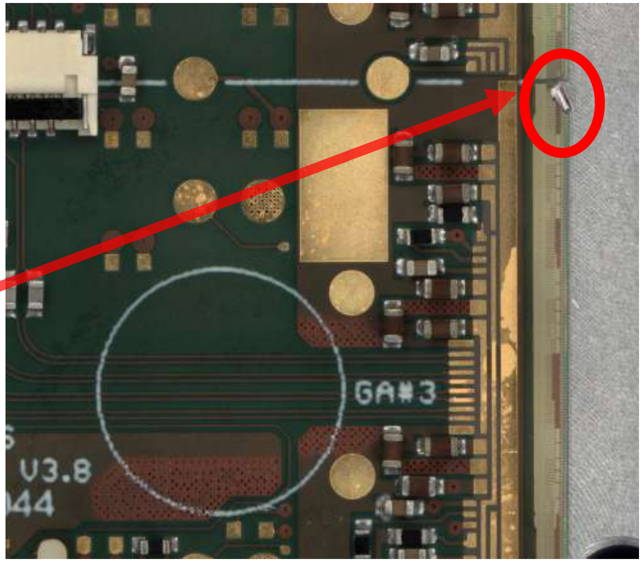
Normally wire breaks at heel of first bond (weakest point).

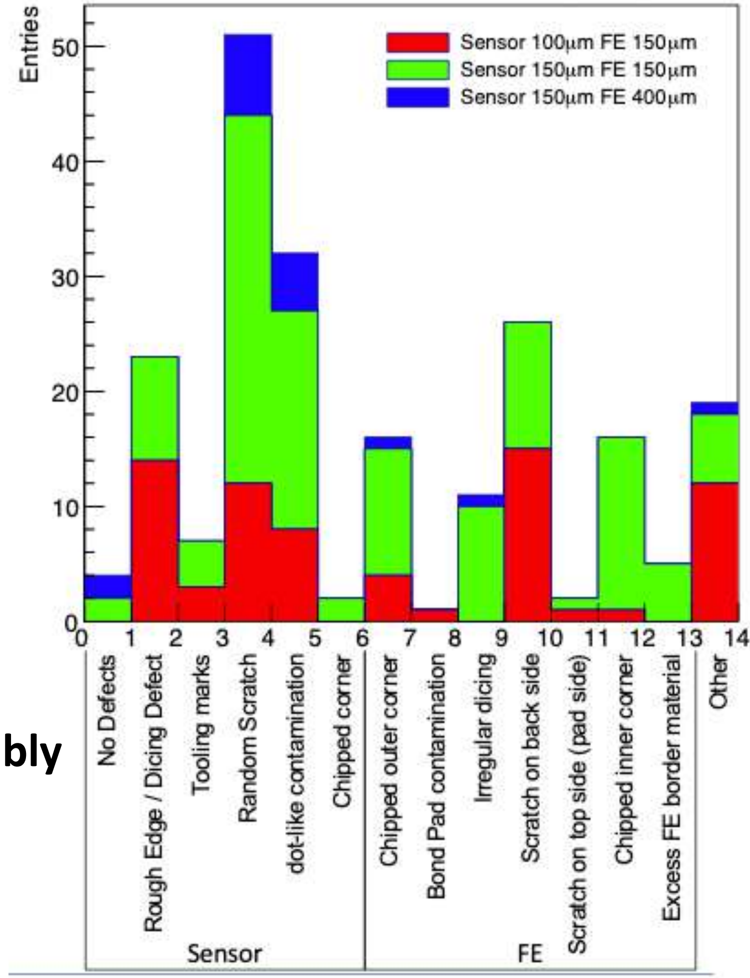
SEM photo courtesy CERN EN/MME-MM

RD53A assembly yield and visual inspection

- Out of **163 RD53A quad modules**, **we lost 4 because** during metrology and assembly (handling, error during gluing): **yield 97.5%**
- Visual inspection
  - We have identified 13 defects
  - Overwhelming defects identified to be irregular (random) scratches
  - Contribution nevertheless from tooling marks
  - White dot-like contaminants present on large fraction of sensors
  - Fairly low instances of chipped corners at sensor level, FE chipping though significant

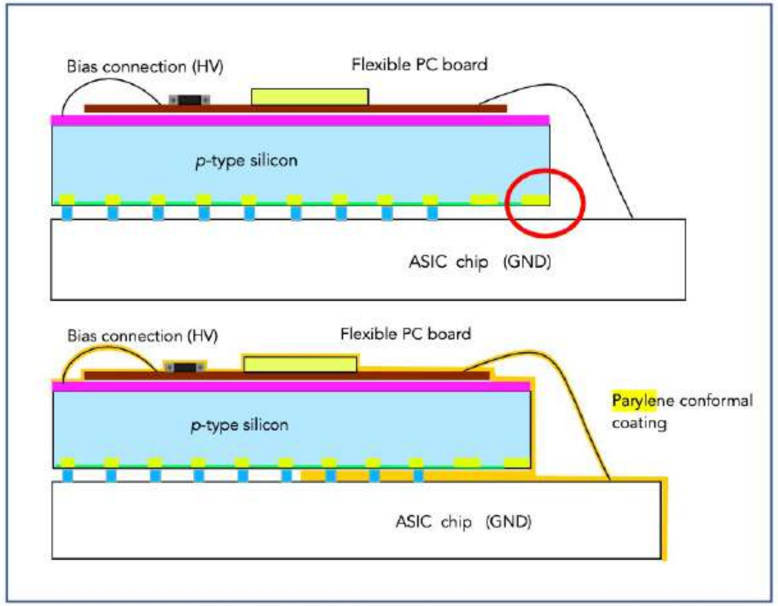
➢ Assumption is that majority of these defects are introduced during hybridisation stage

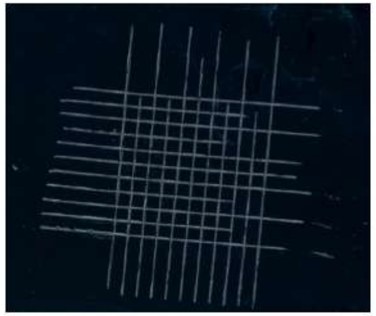




➢ **Besides the 4 lost modules, no other damage or defect during the metrology/assembly**

Parylene

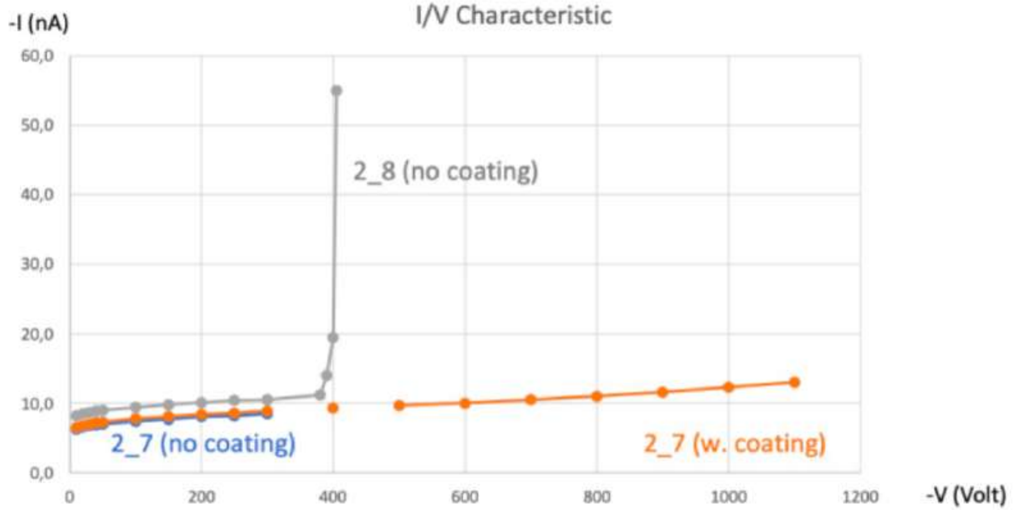




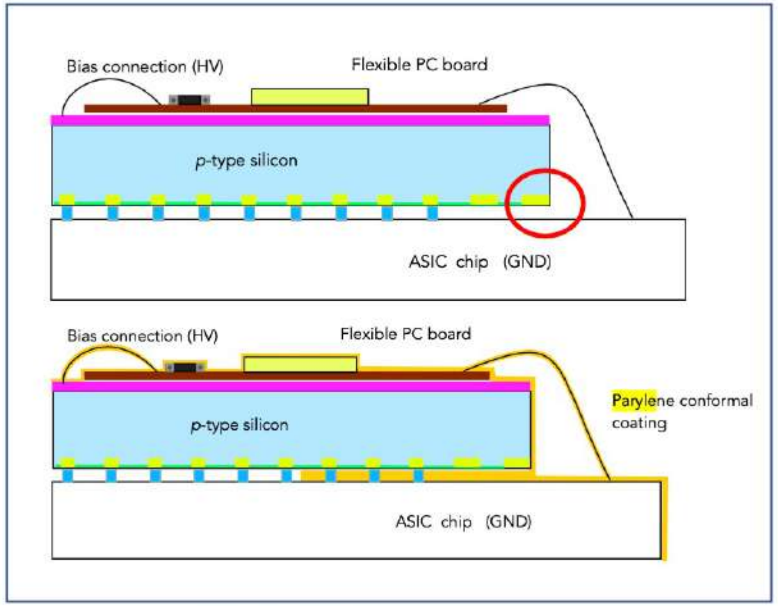
Adhesion tests of Parylene on Silicon after 1 10^{16} neutron eq. cm^{-2} (nucl. reactor irradiation)

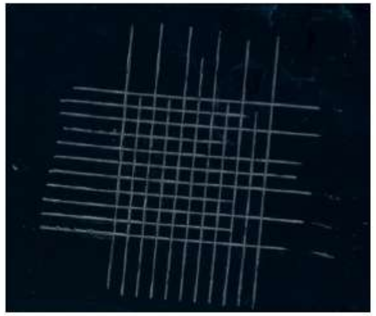
- Large Bias voltage across thin air gap (10µm) : parylene coating (electrical insulator)
  - 54 quad modules (RD53a) coated with parylene N
  - Excellent reproducibility and adhesion
  - Both commercial and in-house lab coating
  - Tested after irradiation and thermal cycles
  - Protection of wire bonds too

- Spark tests on diodes sent from Liverpool (DSTV2_7 & DSTV2_8 with improved design)
- 1 used without coating for baseline (DSTV2_8)
- 1 used after coating in batch 3 (DSTV2_7), stopped at -300V before coating
- Compliance set on HV to 1 μA



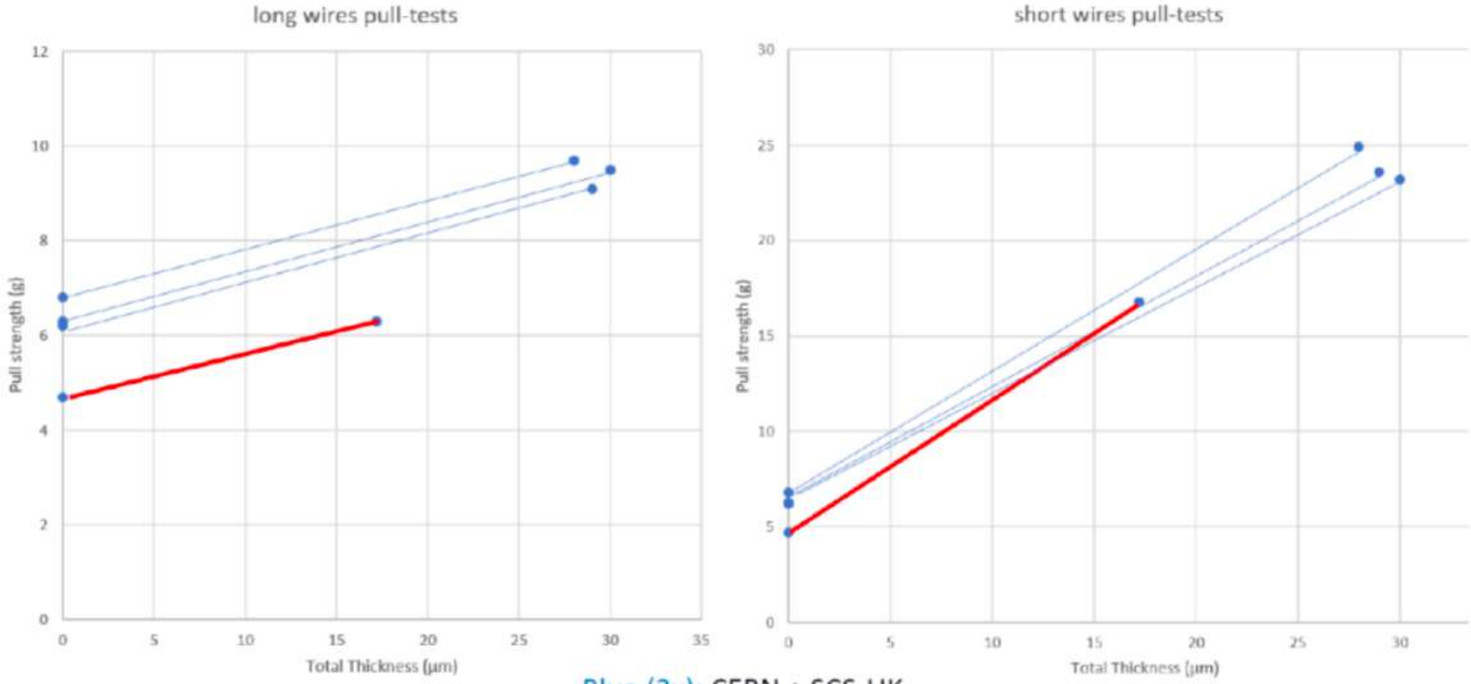
Parylene





Adhesion tests of Parylene on Silicon after 1 10^{16} neutron eq. cm^{-2} (nucl. reactor irradiation)

- Large Bias voltage across thin air gap (10µm) : parylene coating (electrical insulator)
  - 54 quad modules (RD53a) coated with parylene N
  - Excellent reproducibility and adhesion
  - Both commercial and in-house lab coating
  - Tested after irradiation and thermal cycles
  - Protection of wire bonds too



Blue (3x): CERN + SCS-UK

Red (1x): Paris-Cluster + APS

Pixel sensors

Saverio D’Auria, ICHEP2022

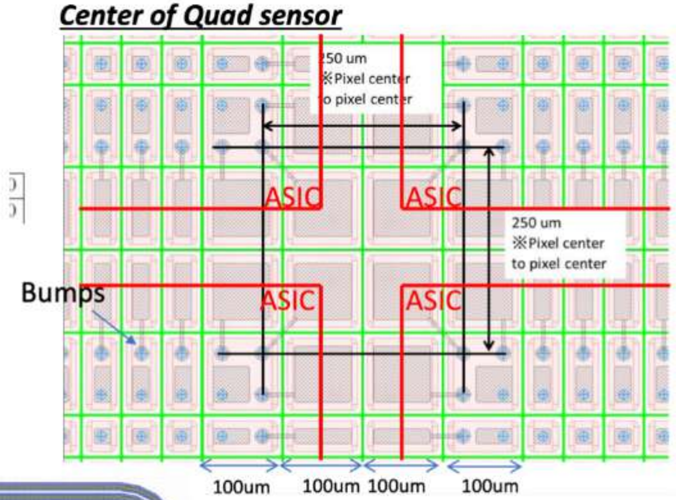
Two types of sensors:

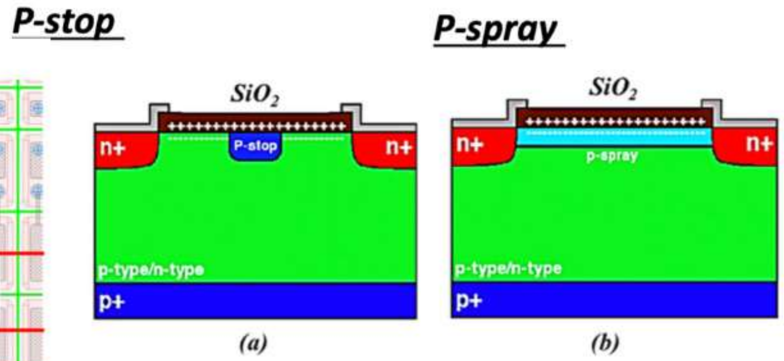
Planar:

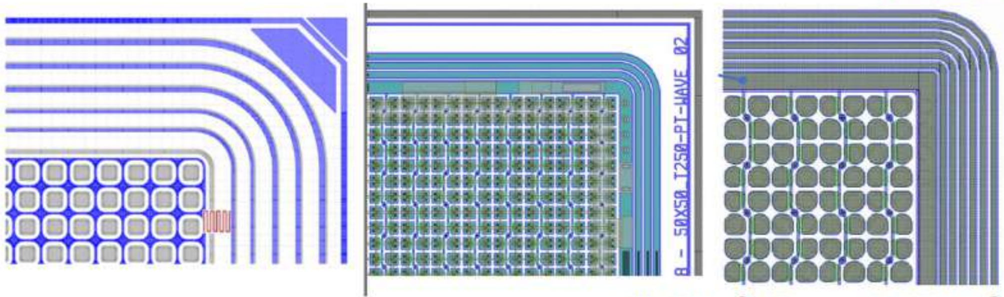
Various design detail left up to vendor :

- *p*-stop vs. *p*-spray insulation
- Polysilicon bias or punch-through
- Guard-ring geometry

Requirements defined on performance

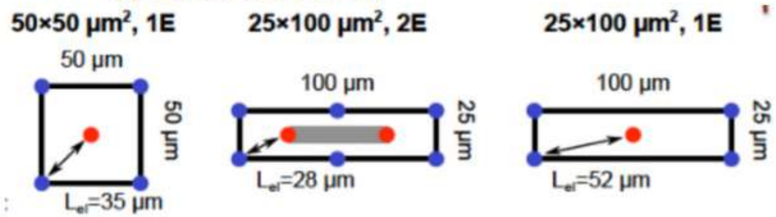


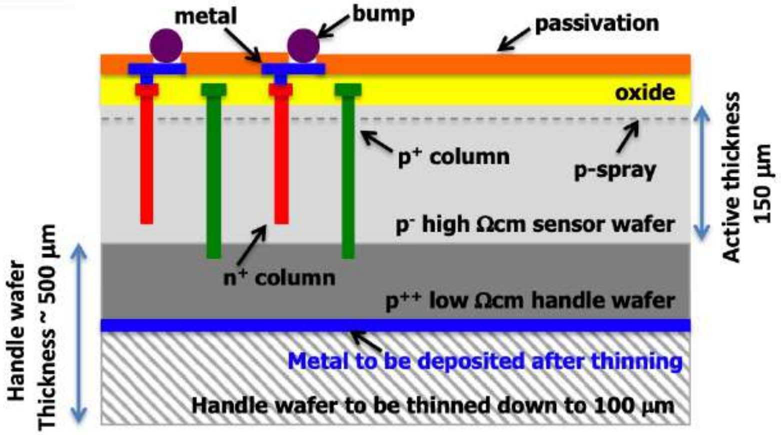




Inner system uses 3D sensors

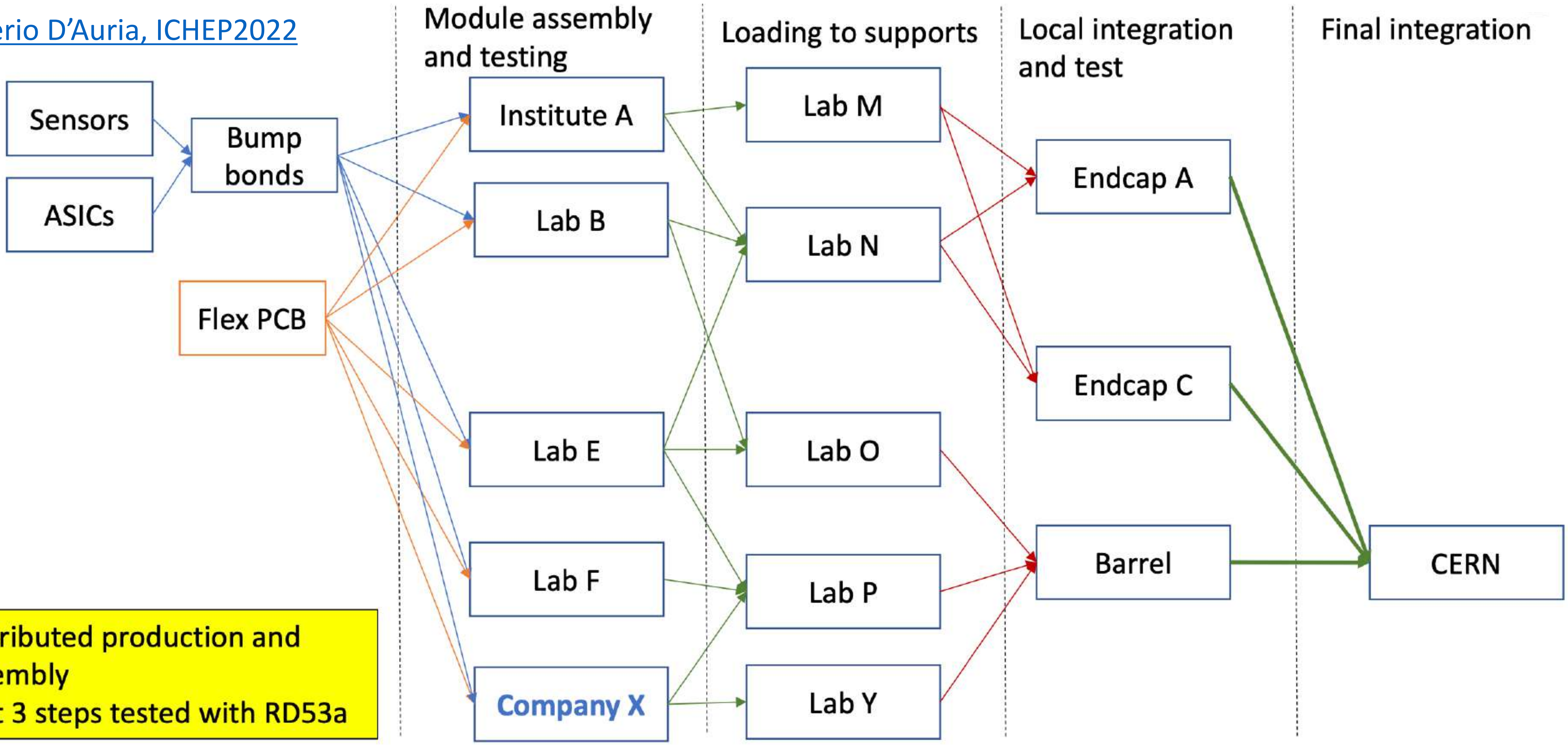
- High radiation tolerance
- Lower bias voltage





General production model

Saverio D’Auria, ICHEP2022



Module assembly and testing

Loading to supports

Local integration and test

Final integration

Sensors

ASICs

Bump bonds

Flex PCB

Institute A

Lab B

Lab E

Lab F

Company X

Lab M

Lab N

Lab O

Lab P

Lab Y

Endcap A

Endcap C

Barrel

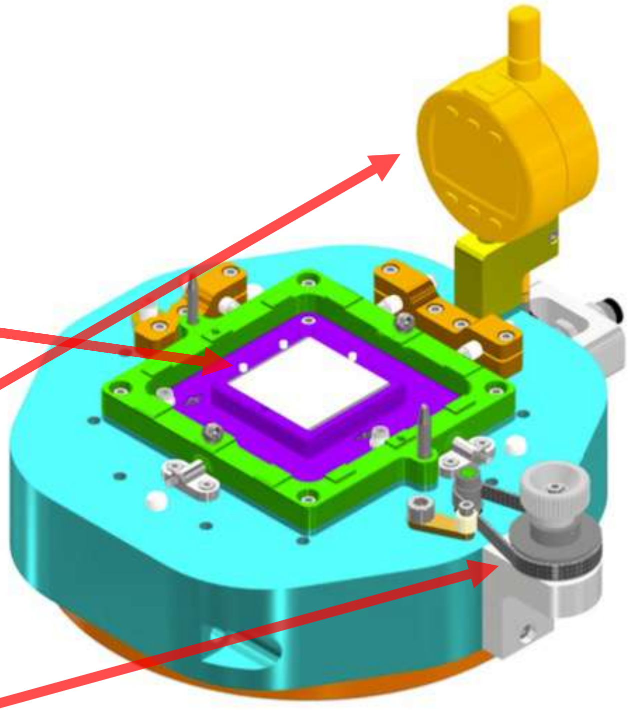
CERN

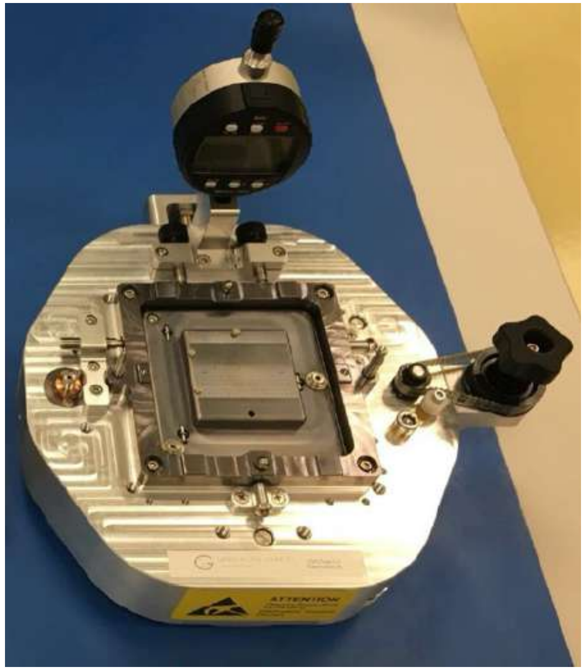
Distributed production and assembly
First 3 steps tested with RD53a

Bare module jig 1/2

- Inlay similar to RD53A tool
  - Alignment as in previous version of the tool: using three dowel pins
  - Improved vacuum hole pattern

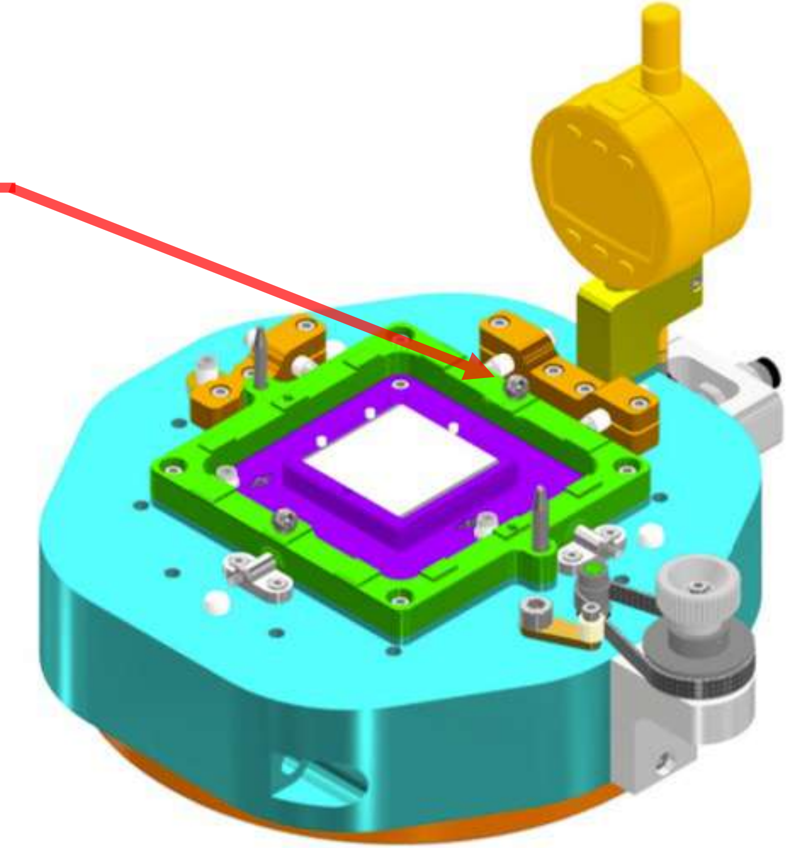
- New concepts
  - Screw for setting inlay z height: this defines the thickness of the glue layer
  - Dial gauge for monitoring inlay z height
  - Knob for lowering and lifting the inlay
  - Adjustable parallelism of bare module plane, fixed during tooling calibration

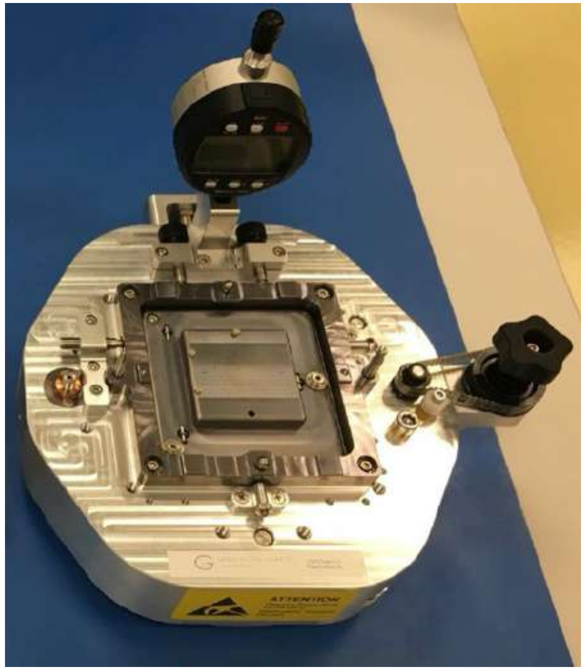




Bare module jig 2/2

- New concepts (cont'd)
  - Frame for flex jig positioning by two spheres
  - Inlay calibrated by fine-thread screws to adjust surface to be parallel to flex jig frame

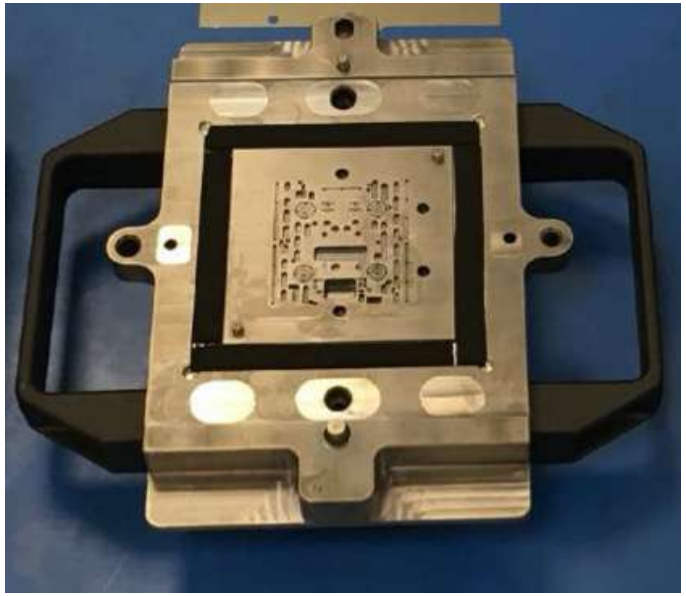




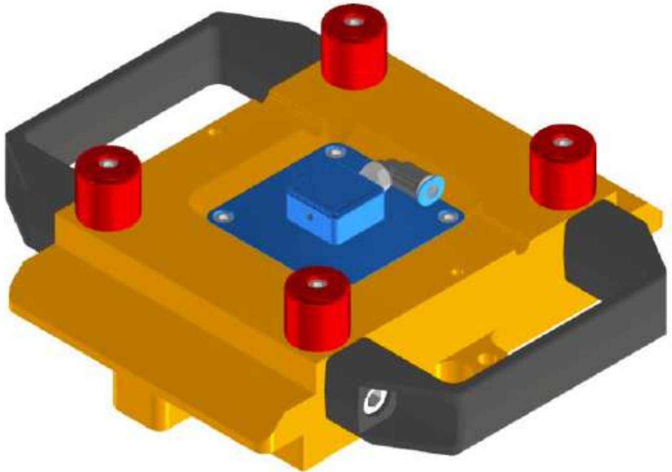
- Tooling calibration steps performed once to compensate for manufacturing tolerances
- **Adjustment of glue gap for each module compensates thickness variation of components**

Flex jig

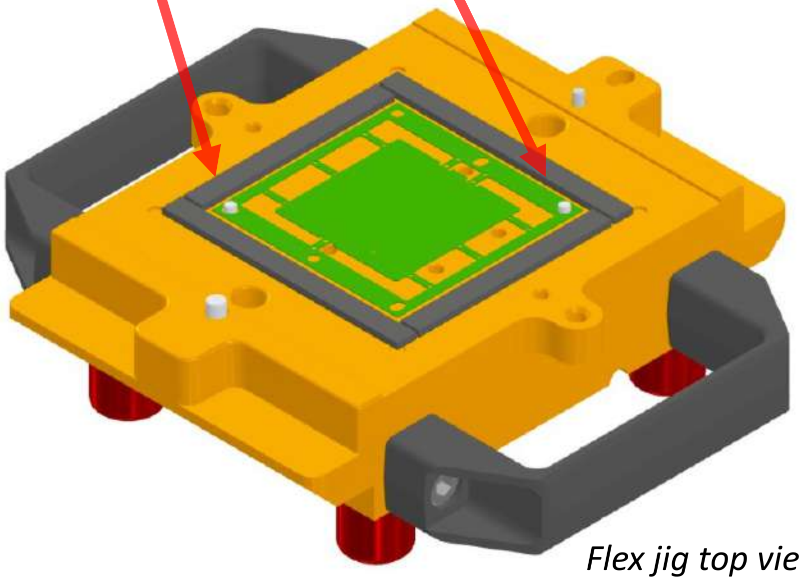
- Alignment of flex jig by hole and slot to spheres from bare module jig
- Flex-specific inlay: flex alignment by two dowel pins matching hole and slot on flex



Flex jig top view



Flex jig bottom view



Flex jig top view