UNIVERSITY OF LIVERPOOL

Muon Precision Physics Workshop (MPP2023)

Strip Module Development and Construction for the ATLAS ITk Upgrade

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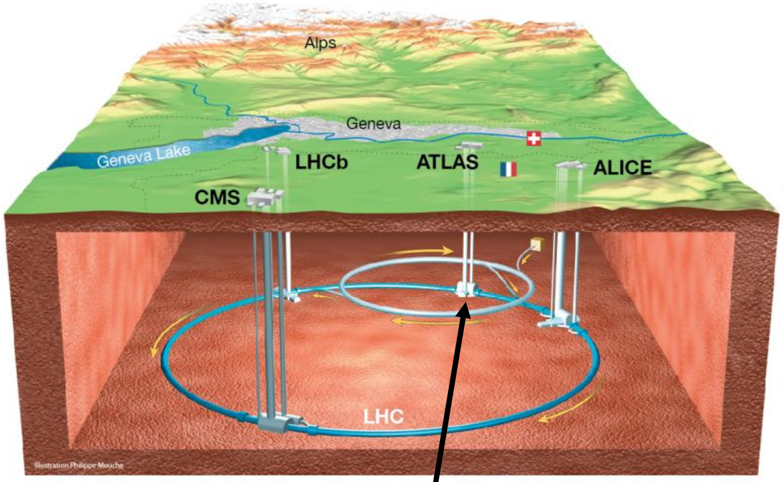
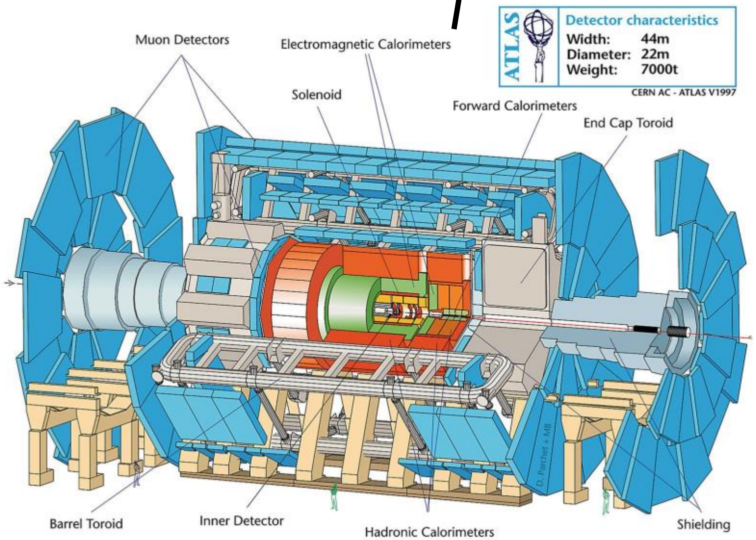
Outlook

- Introduction to LHC and ATLAS ITk
- Hybrid Assembly Process
- Module Assembly Process
- Experiences
- Lessons Learned (so far)

LHC



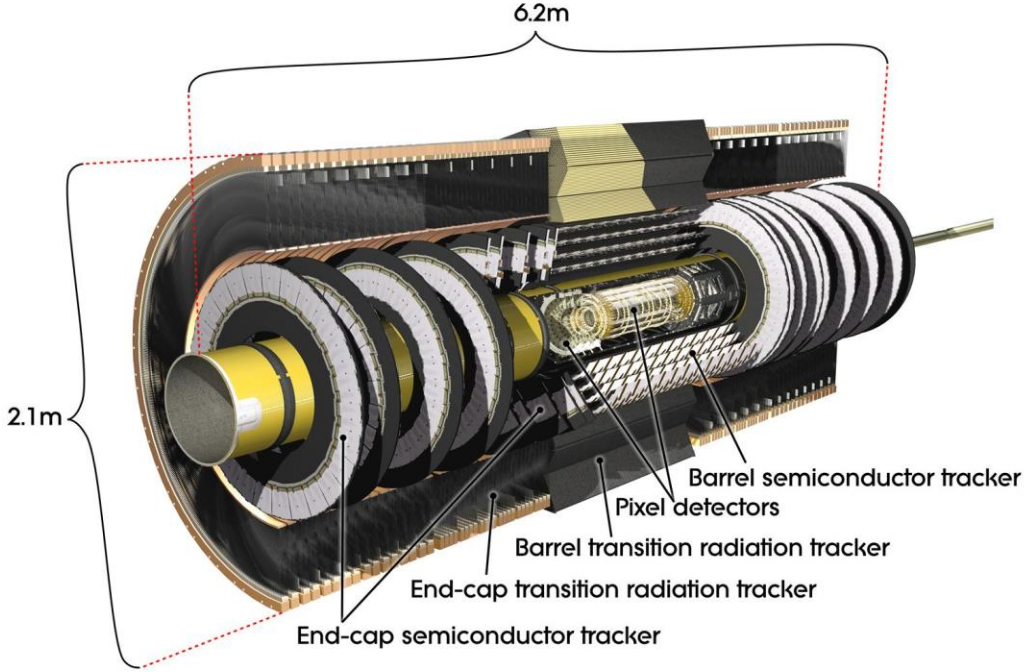


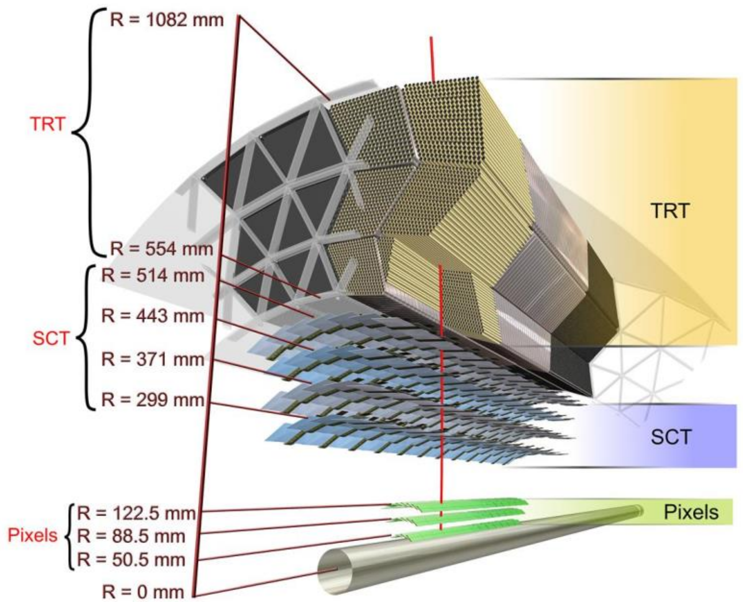
CERN (Council Européen pour la Recherche Nucléaire) hosts the largest particle accelerator LHC (Large Hadron Collider)

- 27 km circumference; 100 m underground
- Accelerates protons or ions
- Two beams travelling in opposite direction collide at four points around the machine
  - **ATLAS** (A Toroidal LHC ApparatuS
  - CMS (Compact Muon Solenoid)
  - LHCb (Large Hadron Collider beauty)
  - ALICE (A Large Ion Collider Experiment)

ATLAS and CMS: general-purpose detectors (different technical solutions and different magnet-system design)
ALICE: heavy-ion detector (study quark-gluon plasma)
LHCb: investigation of difference between matter and antimatter by studying b quarks

The current ATLAS Inner Detector



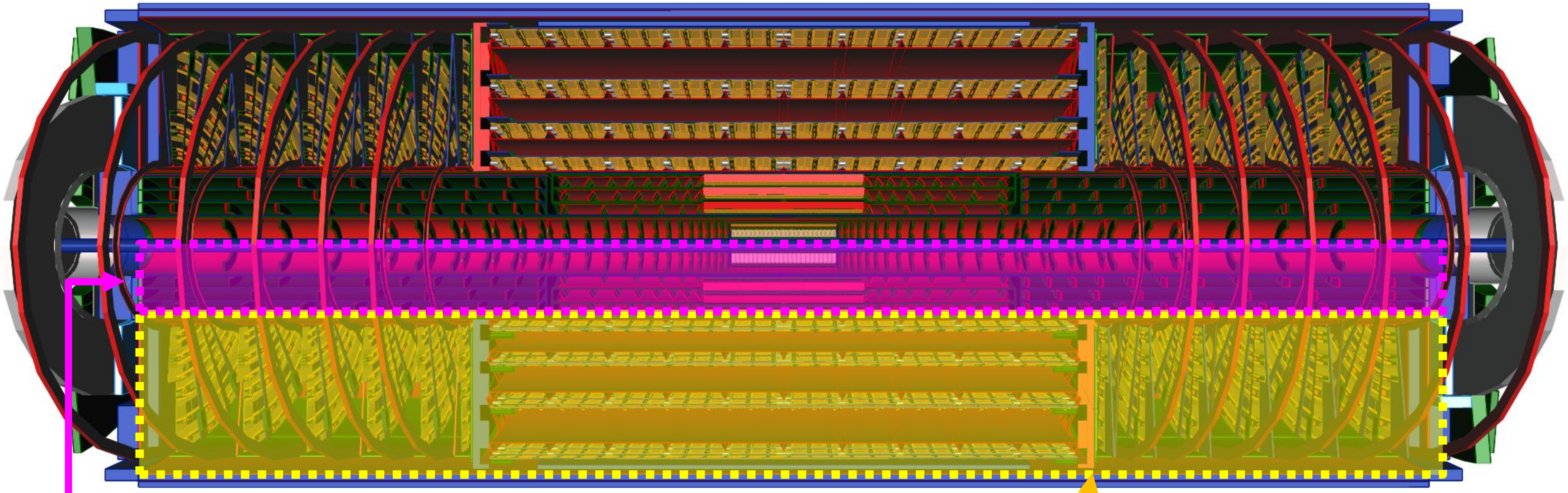


- Pixel Detector: 80 million pixels; 1.7 m^2 of silicon
- SCT (SemiConductor Tracker): 6 million channels; 60 m^2 of silicon; 80 µm strip pitch
- TRT (Transition Radiation Tracker): 350000 read-out channels, 12 m^3 volume
- 2013-2014: New pixel subdetector (Insertable B-Layer) installed at R=33 mm

New ITk Design

For high luminosity LHC (HL-LHC), replace the whole inner detector in LHC long shutdown 3 (LS3) 2026-2028

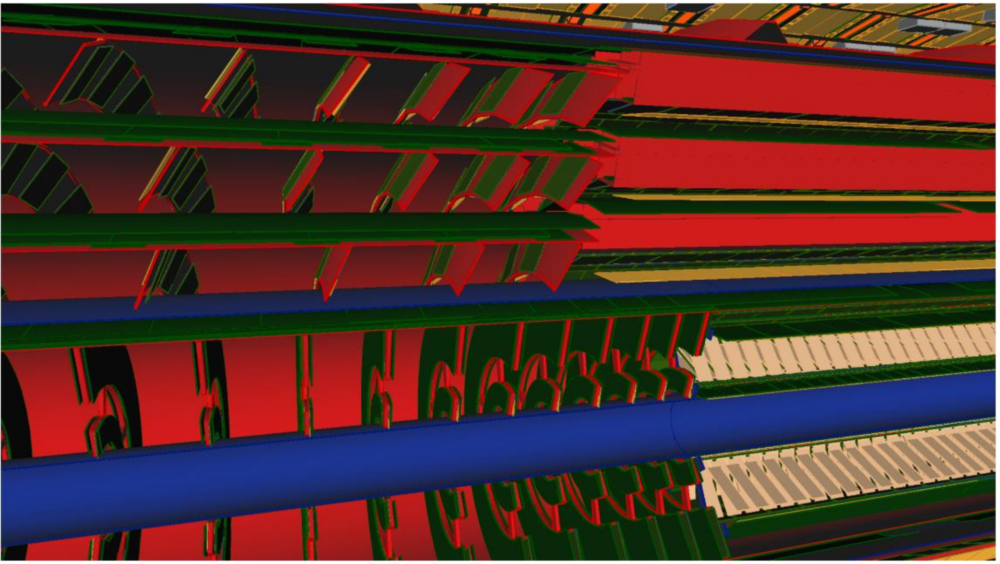
- All silicon Inner Tracker (ITk)
- Assembled and commissioned on surface, installed as single unit into the LAr cryostat



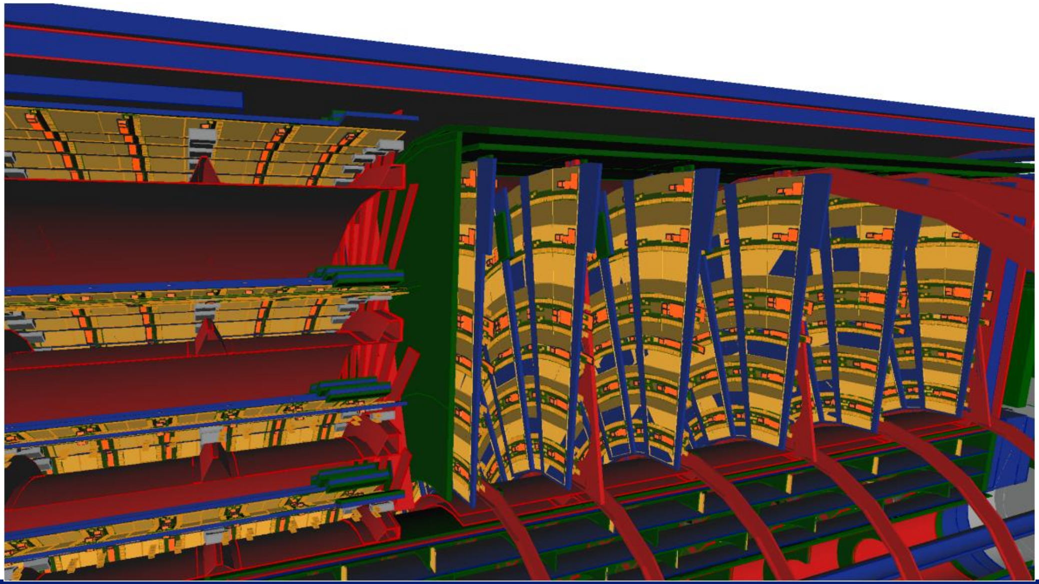
- Pixel region:
  - 5 barrel layers
  - 4 layers of pixel rings in the end-caps

- Strip region:
  - 4 barrel layers
  - 6 strip disks in each end-cap

ITk Design

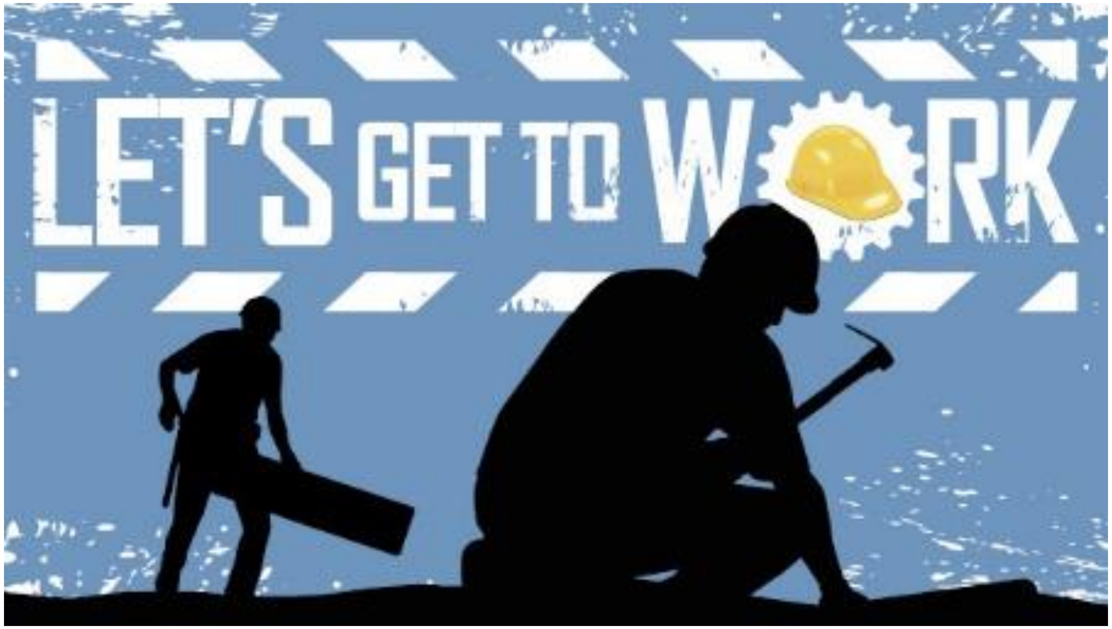


Pixel barrel and endcap
13 m^2 of silicon pixels
Typical pixel size of 50 x 50 µm



Strip barrel and endcap
165 m^2 of silicon strips
Barrel strip pitch of 75.5 µm
Endcap has variable strip pitch in range from 69 to 84 µm

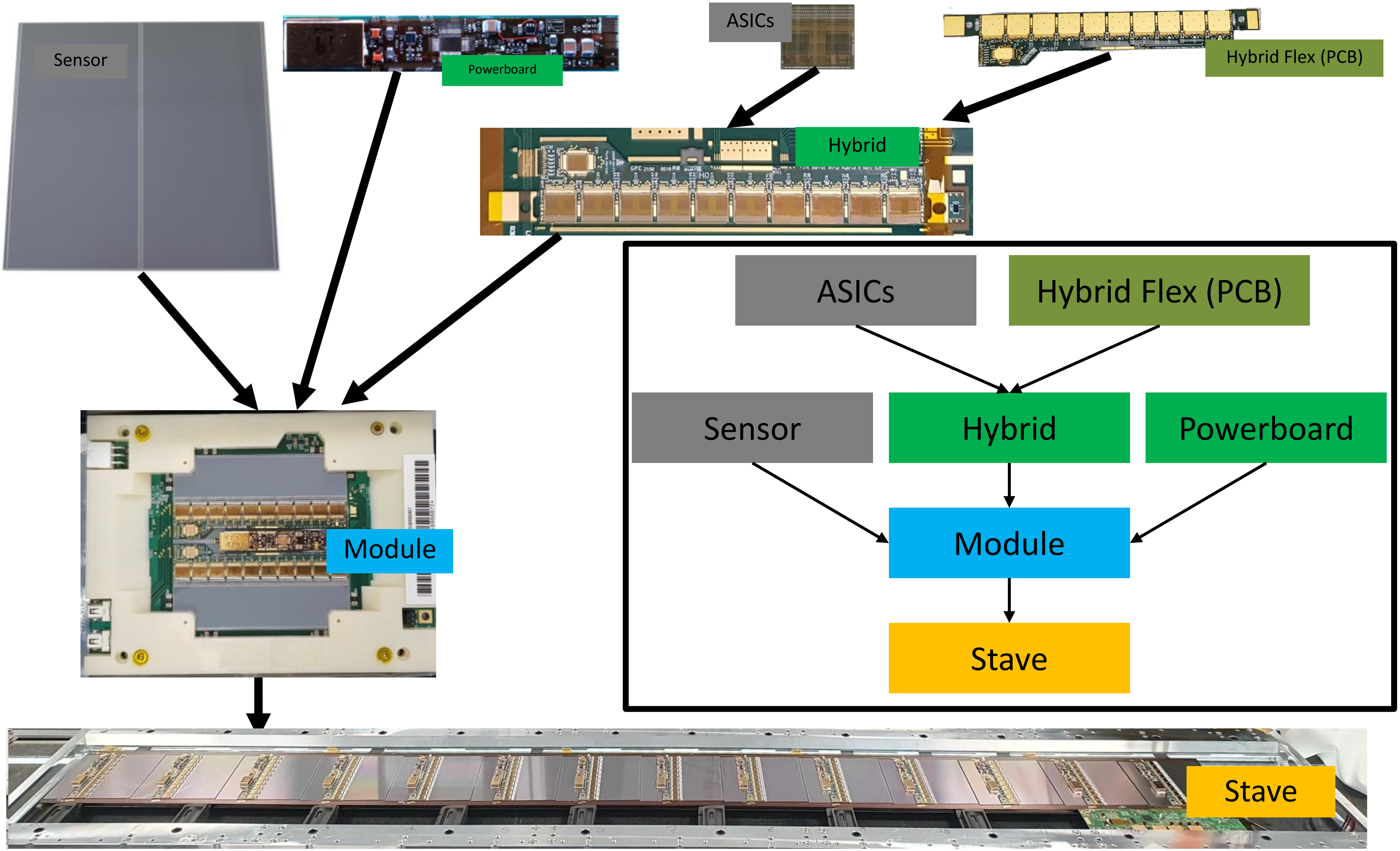
Now we have to build it.



Focus here on Strip Barrel Hybrid and Module Assembly done at Liverpool

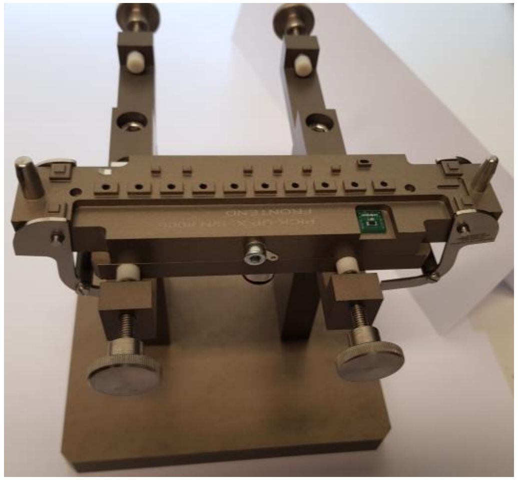
http://www.townsvillebulletin.com.au/news/city-leaders-get-behind-lets-get-to-work-campaign/news-story/aed4a435654904e981c2757b00a49cd5

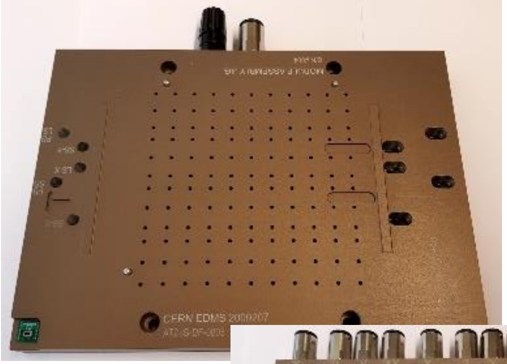
Assembly Chain

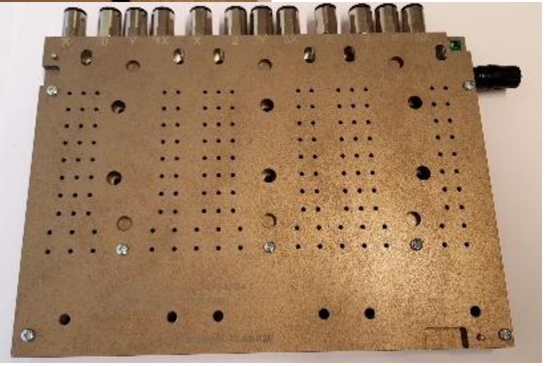


Tools

- Developed tools produced to high industry standards for the assembly process
  - Tolerances of tools based on required specifications of final objects for alignment and height precision
  - Tooling developed to make the assembly process as easy as possible
    - Adding features to prevent accidental wrong use as much as possible
  - Extensive design reviews to ensure tool drawings / specifications follow industry standards so that they can be manufactured outside

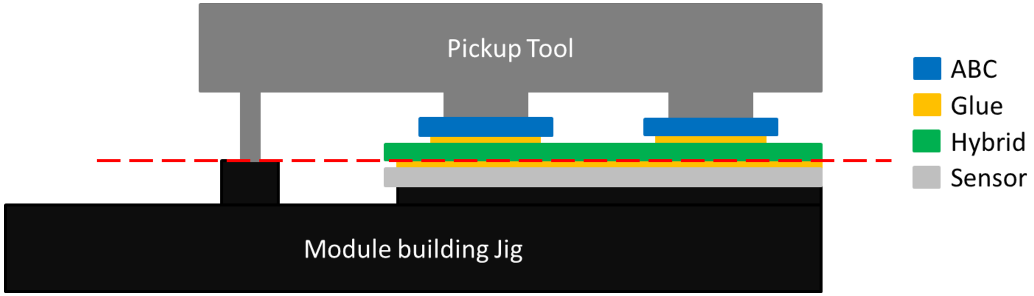






Tools

- Tools designed to control hybrid/powerboard to sensor glue height as good as possible
  - Need to take variations of materials into account: hybrid flex thickness not always uniform across circuit and thickness variations between flexes (manufacturer only guarantees thickness to be within +/-10% of target value)
  - ASIC and Sensor thickness very well controlled and values fixed
- Choose tool reference plane to be back of hybrids
  - Andy flex thickness variations are compensated by the ASIC to hybrid glue
  - Assembled hybrid stack-up (distance from bottom of hybrid to top of ASICs) is controlled



Hybrid Assembly

– Gluing of ASICs onto hybrid flex

– Wire-bonding

– (Testing)

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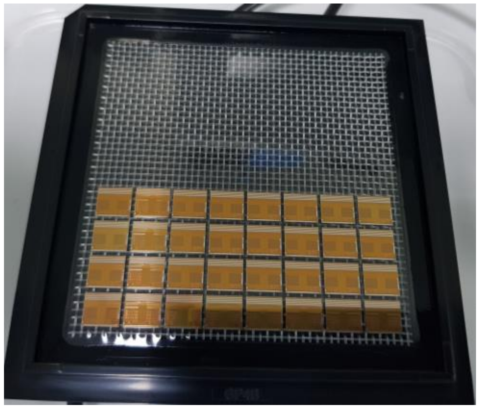
Hybrid Assembly

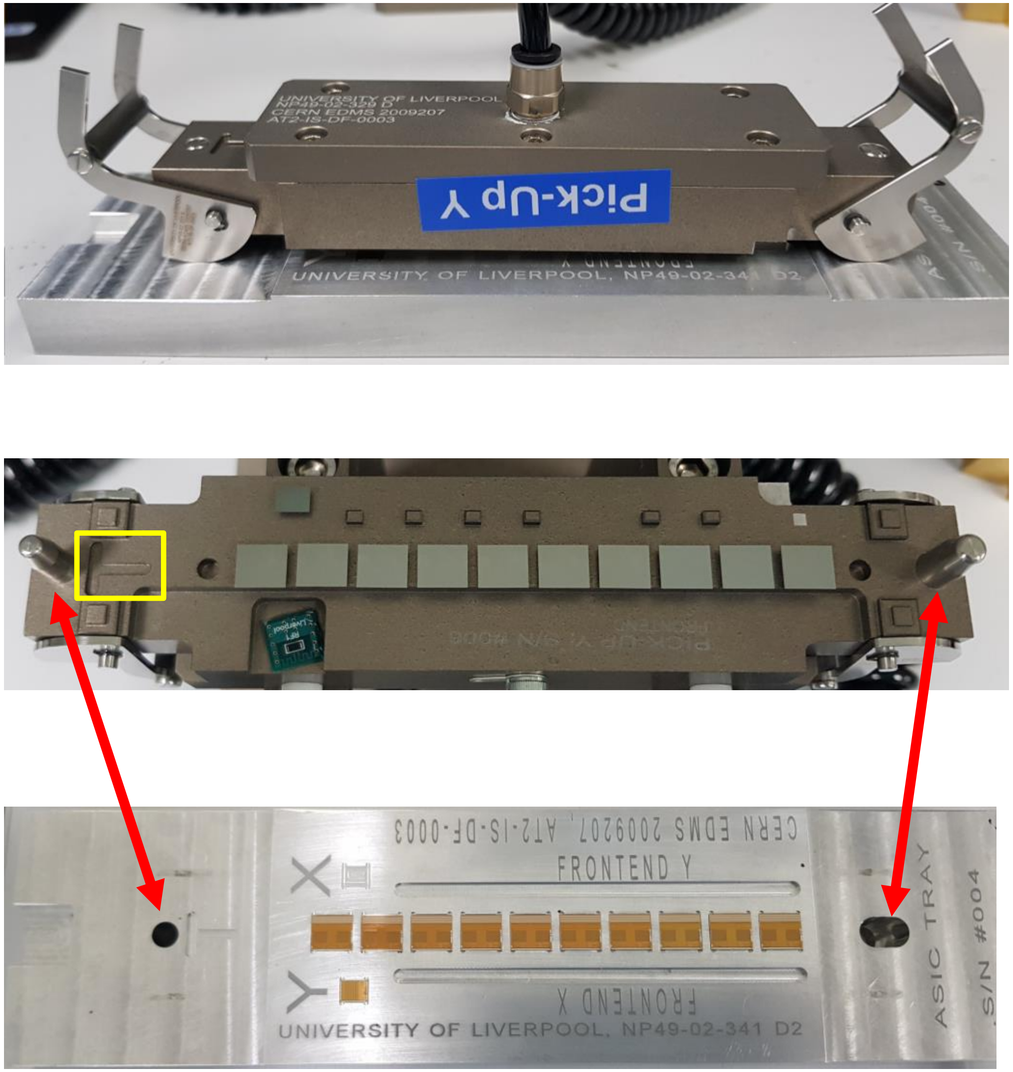


ASICs are shipped in Gelpaks

- Need to apply vacuum to back of Gelpack for releasing of chips
- Use vacuum pen to pick chips up

Chips placed in alignment jig with precision machined pockets to ensure correct placement of chips for gluing process

Hybrid Assembly

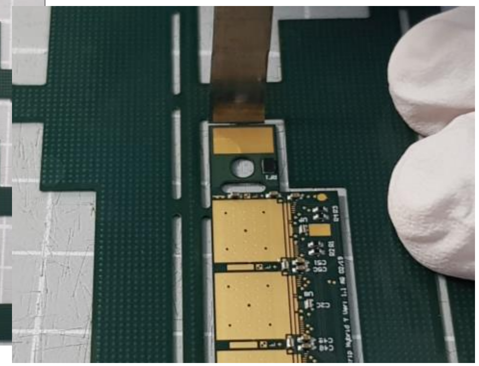


Precision vacuum tool used to pick up ASICs from alignment jig

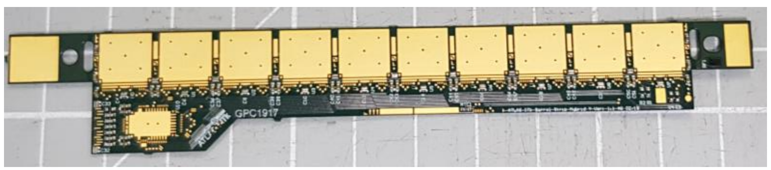
Dowel holes and pins in jigs and vacuum tool used for alignment

- T marking on all tools for visual alignment (orientation)
- Differing hole diameters to prevent accidentally placing tool in wrong orientation

Hybrid Assembly



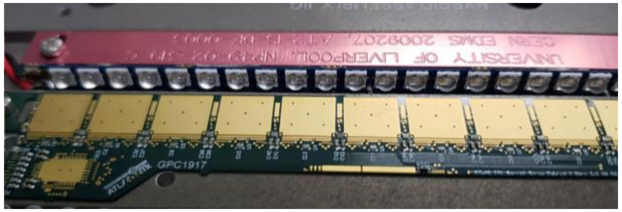
- Hybrid flexes manufactured and delivered in arrays
- Need to cut out the individual flexes for assembly



Flex then placed on dedicated vacuum jig

- Dowel pins for precision alignment of hybrid
- Using sacrificial tabs on hybrid

Hybrid Assembly



For ASIC assembly, use UV-curable glue (Loctite 3525)

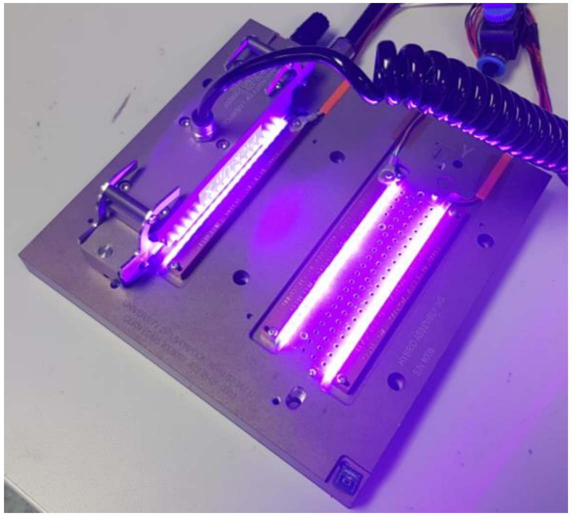
- UV LEDs on bars in pockets of the assembly jig to ensure that the maximum light output from the centre of the LED is directed towards the glue gap (120µm)

UV glue applied on hybrid using a dot pattern

Vacuum tool with ASICs placed on jig

- Vacuum tool has machined contact points to control glue thickness
- Lift legs on vacuum tool allow controlled placement and its removal

Hybrid Assembly



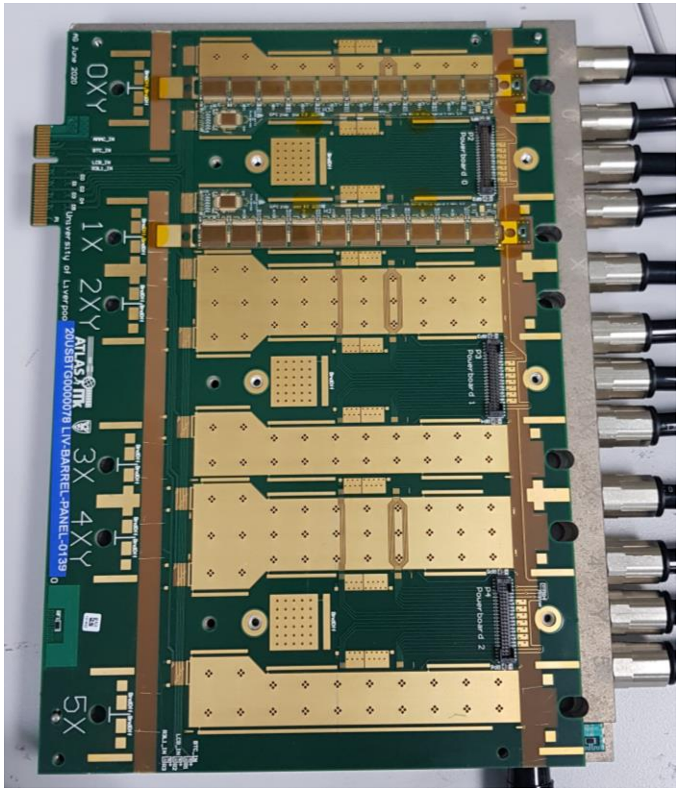
!!! UV light is harmful for your eyes. For the purpose of this picture, the protective cover was removed and UV-protection glasses suitable for these particular LEDs were used when taking the picture.

UV glue cured for 3 minutes

- Studied varying curing times during prototyping

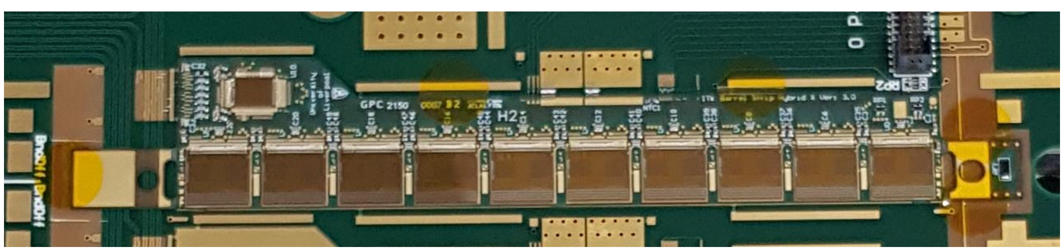
Afterwards, fully assembled hybrid with ASICs is picked up with the vacuum tool

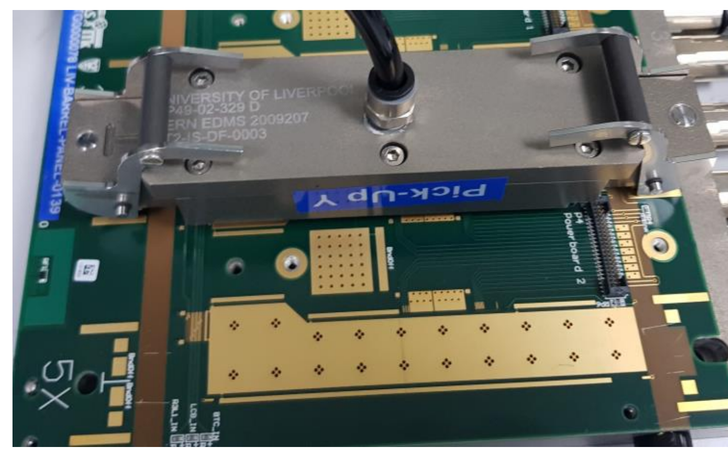
Hybrid Assembly



Hybrids placed on dedicated PCB for wire-bonding and electrical tests

- Dowel holes in test PCB and vacuum jig below for alignment
- Use polyimide glue dot to temporarily hold hybrids in place
- Panel size chose to be industry standard for testing in crates (COTS)
- All hybrids are electrically tested before they can be used for module assembly





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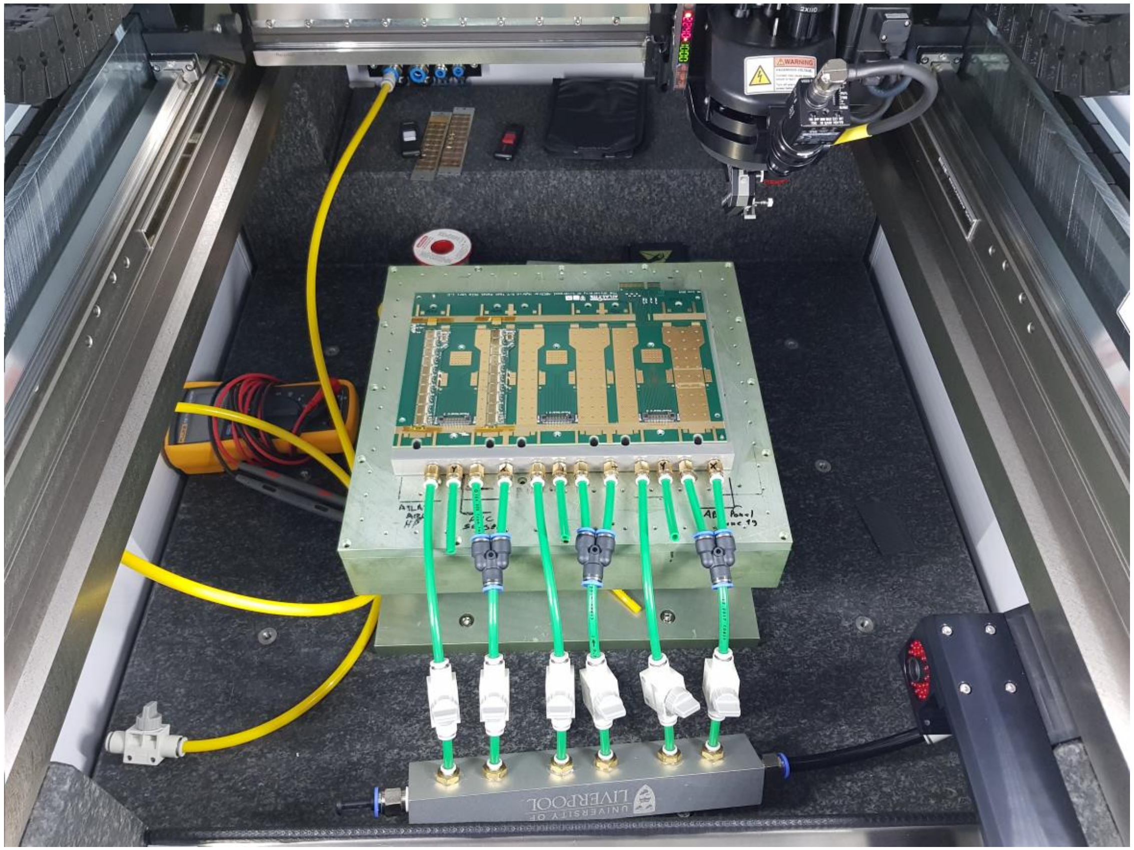
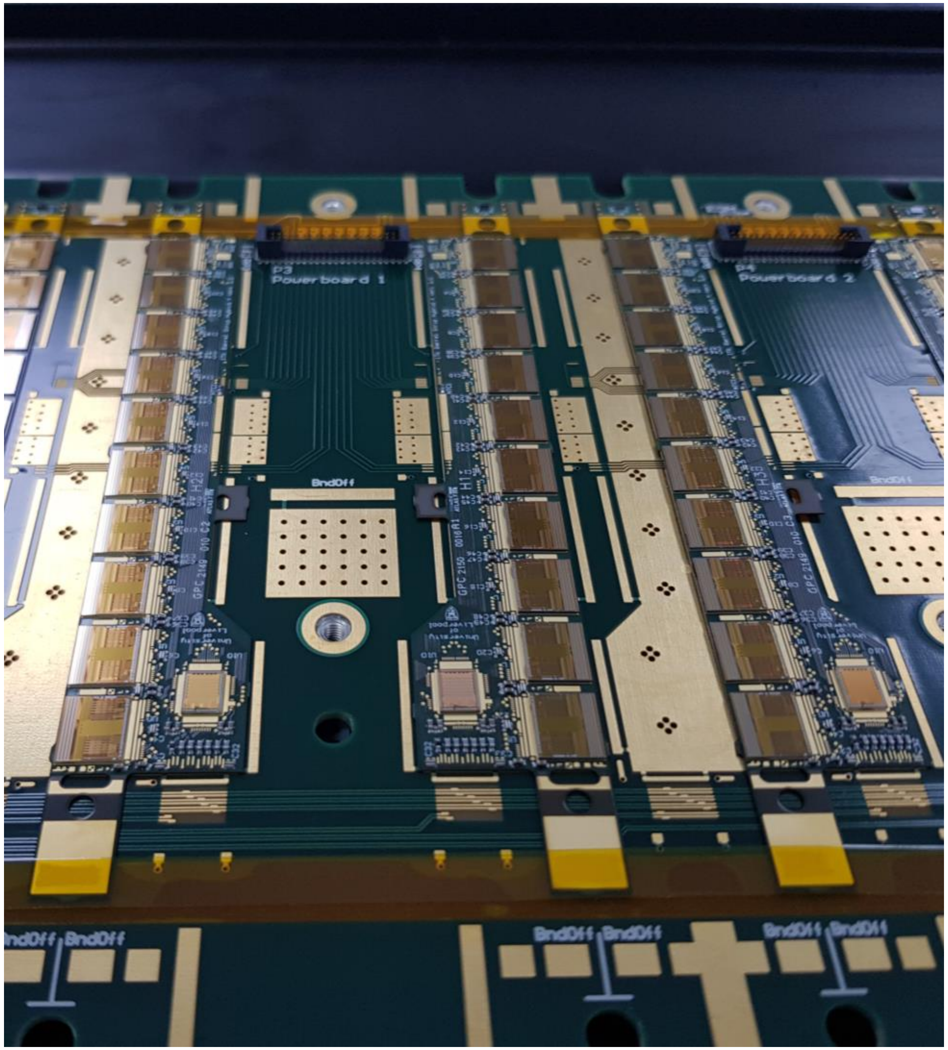
Hybrid Assembly

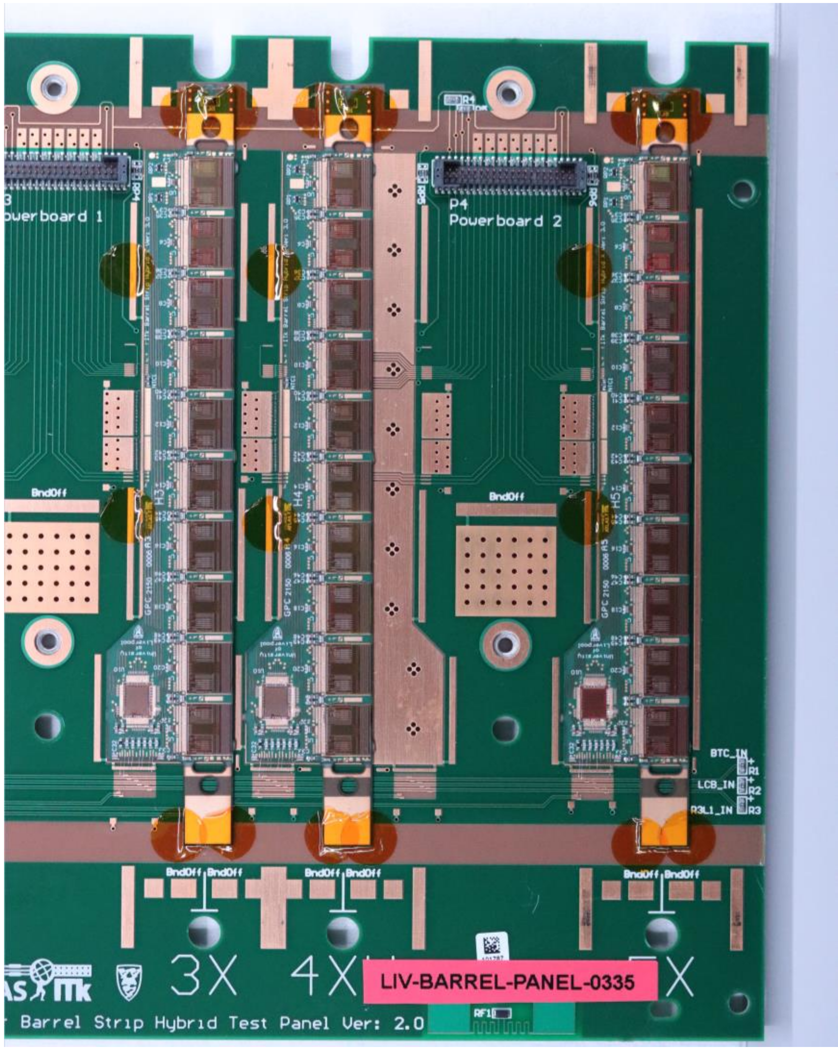


Wire-bonding:

- 25µm diameter aluminium wire used to create electrical connection between ASICs and hybrid flex (as well as hybrid and test panel)
- Using ultrasonic wedge-bonding machine [Hesse BJ820]
    - All barrel sites use same machine which makes program exchange and helping each other easier

Assembled Hybrids

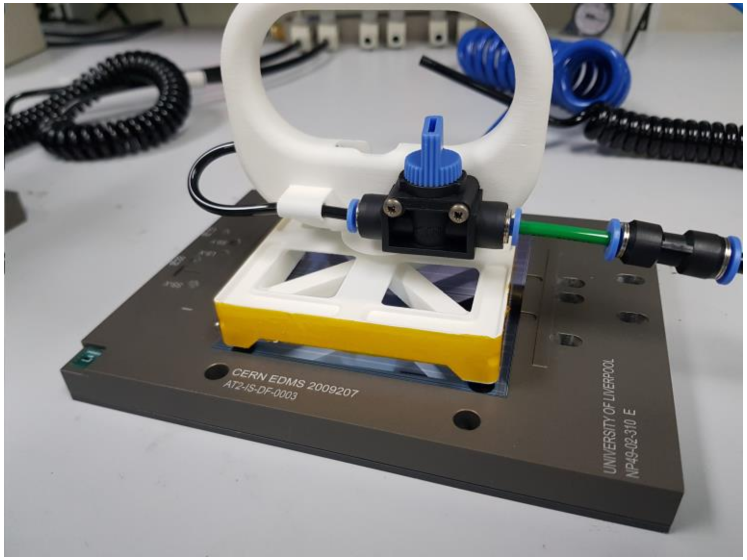




Module Assembly

- Gluing of hybrids and powerboards onto sensor
  - Barrel powerboards are fully assembled in industry
- Wire-bonding
- (Testing)

Module Assembly

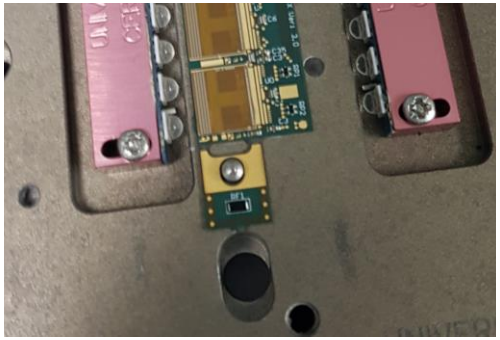


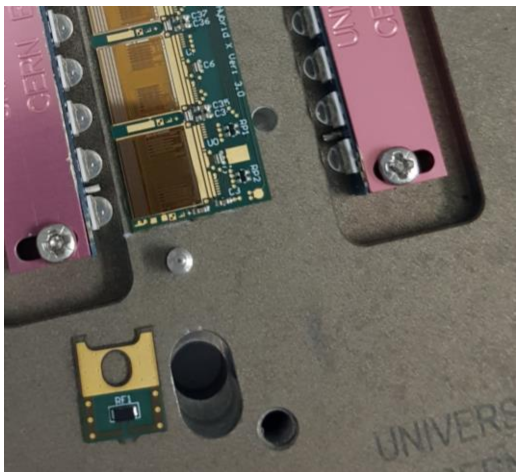
Place sensor on module assembly jig

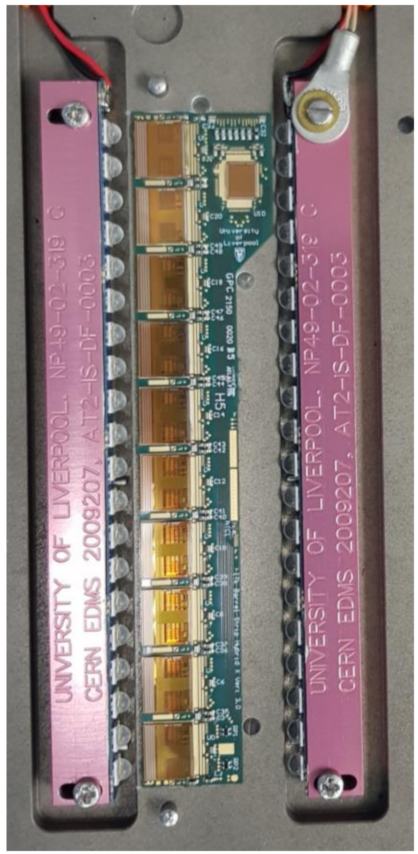
- Sensors delivered in a transport frame
- Dedicated vacuum tool for sensor pick-up and placement on jig

- Alignment through three dowel pins
  - Push sensor against pins
  - Switch vacuum of jig on
  - Remove vacuum tool
  - Check that sensor is in contact with all three pins

Module Assembly







Hybrid placed back on assembly jig

- Sacrificial alignment tabs are removed

Module Assembly

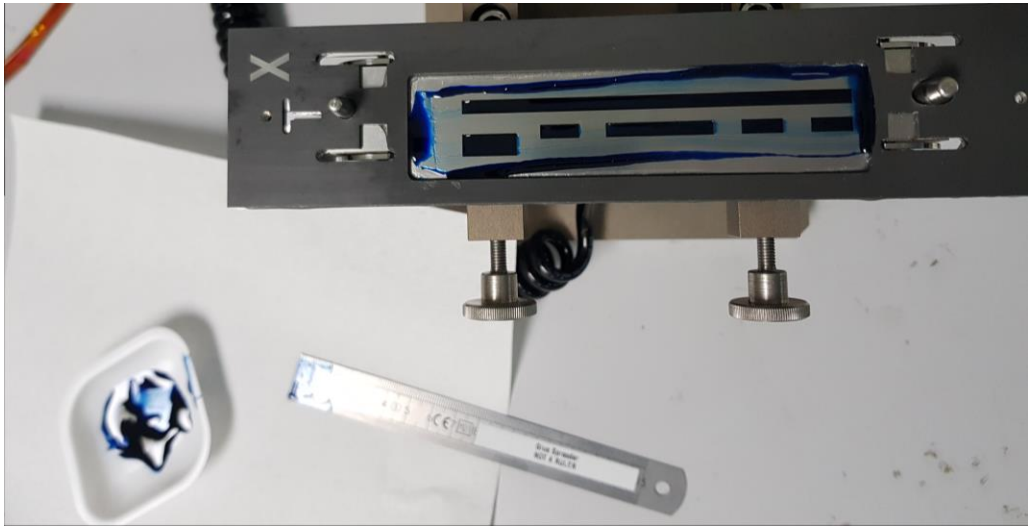
Pick hybrid up with vacuum tool

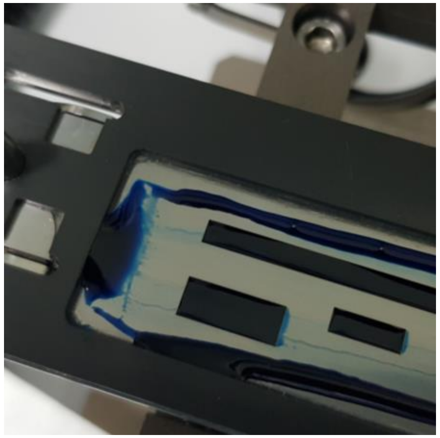
- From this point on re-alignment of the hybrid is not easily possible

Place glue stencil on top of hybrid

- Alignment with the dowel pins

Module Assembly





Glue for attachment of hybrids and powerboards to the sensor surface: Eccobond F112 (aka True Blue)

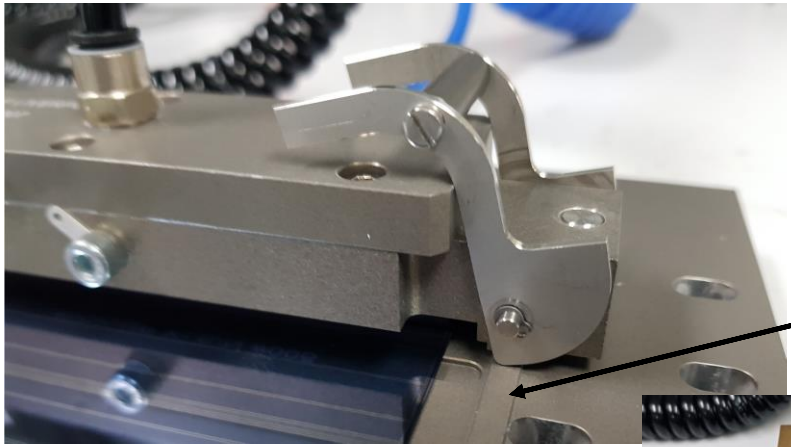
- Two component glue
- Very thin after mixing, requires some pre-curing before it can be used for glue application

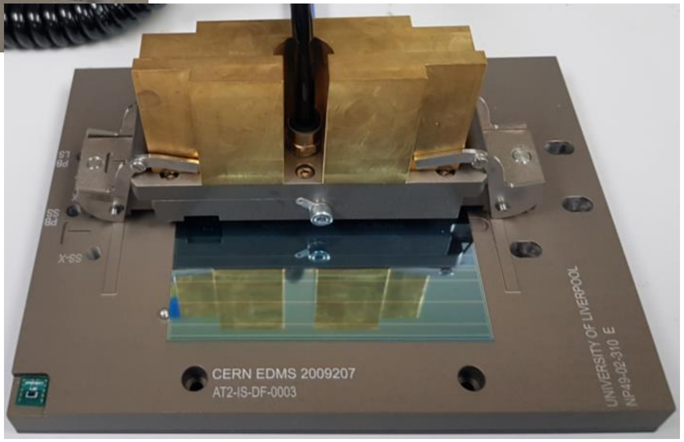
Dispense glue on stencil using a "spreader"

- Important to use as few strokes as possible (two in opposing directions is ideal)

Module Assembly

After stencil removal, check that glue deposition looks good



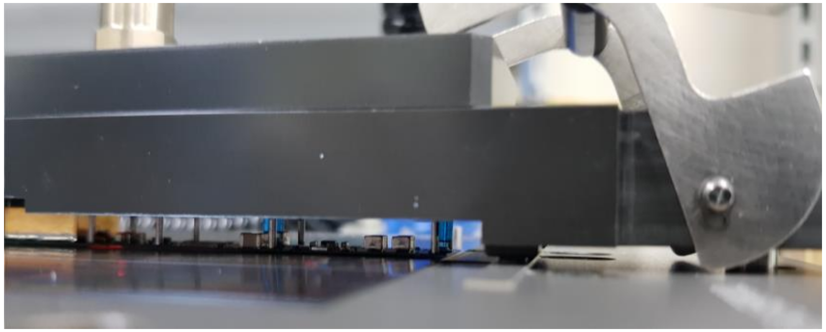


Place hybrid with glue on sensor

- Landing areas on jig set glue height
- Weight on vacuum tool during curing

Glue needs between 4-6 h to cure enough so that the vacuum tools can be removed

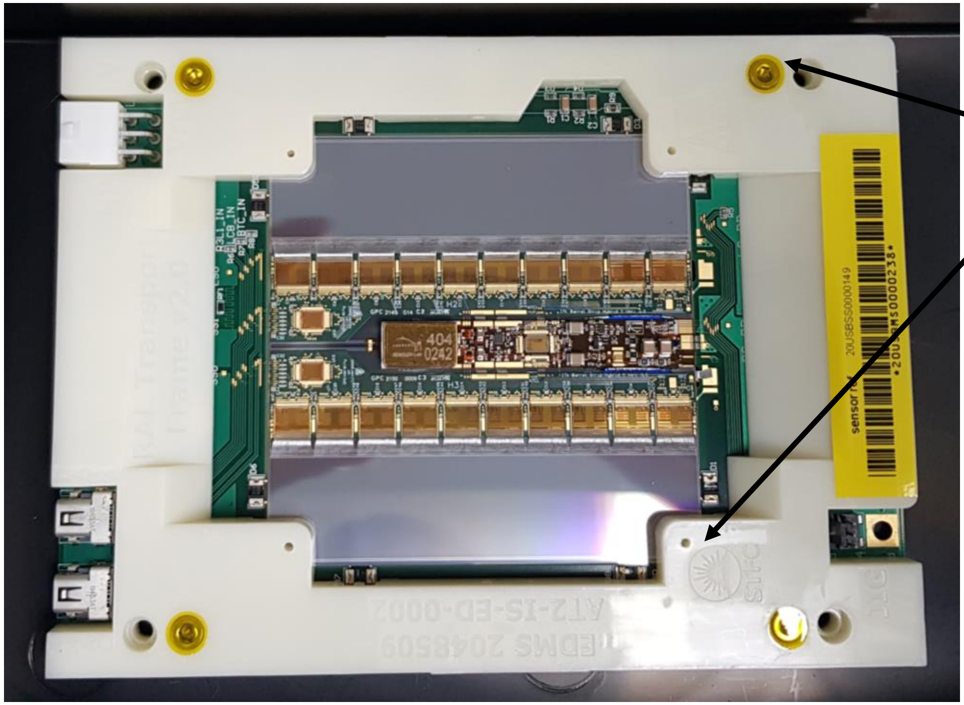
Module Assembly



Powerboard gluing follows same process

- Dedicated alignment jig with dowel pins
- Own pick-up tool
- Glue stencil for more area coverage because of cooling requirements

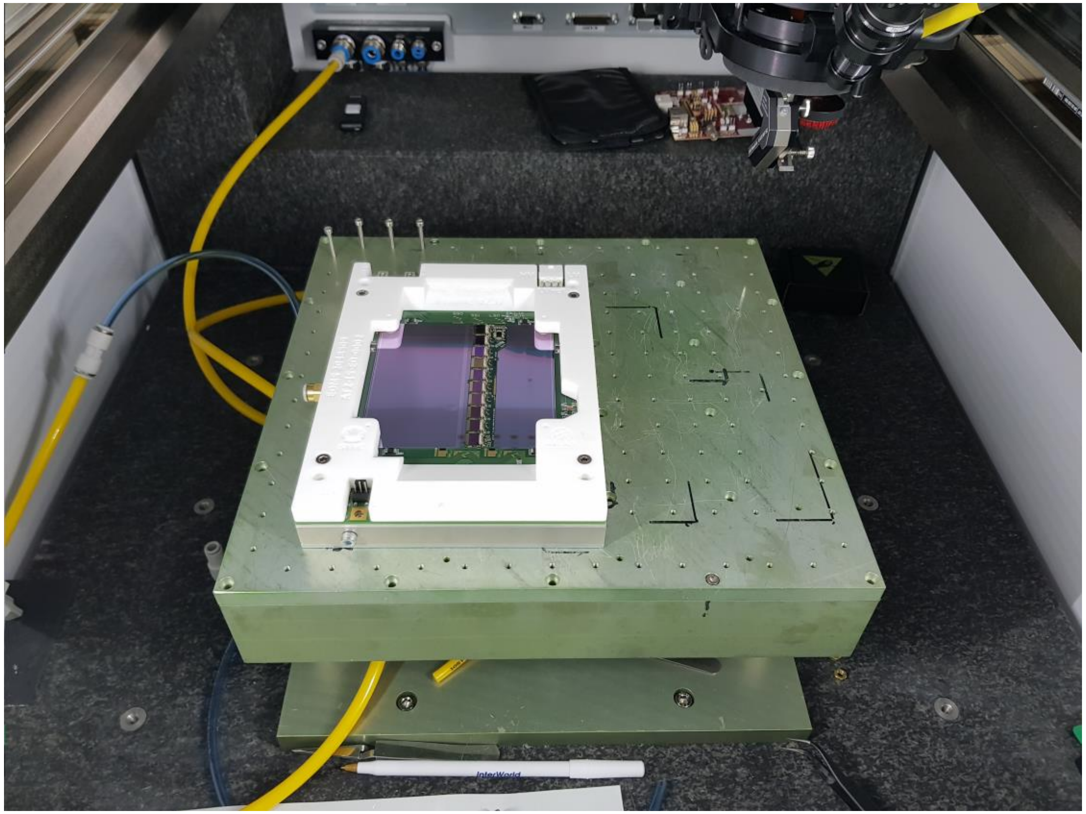
Module Assembly



After hybrid and powerboard gluing, assembled module is transferred onto module frame for electrical testing

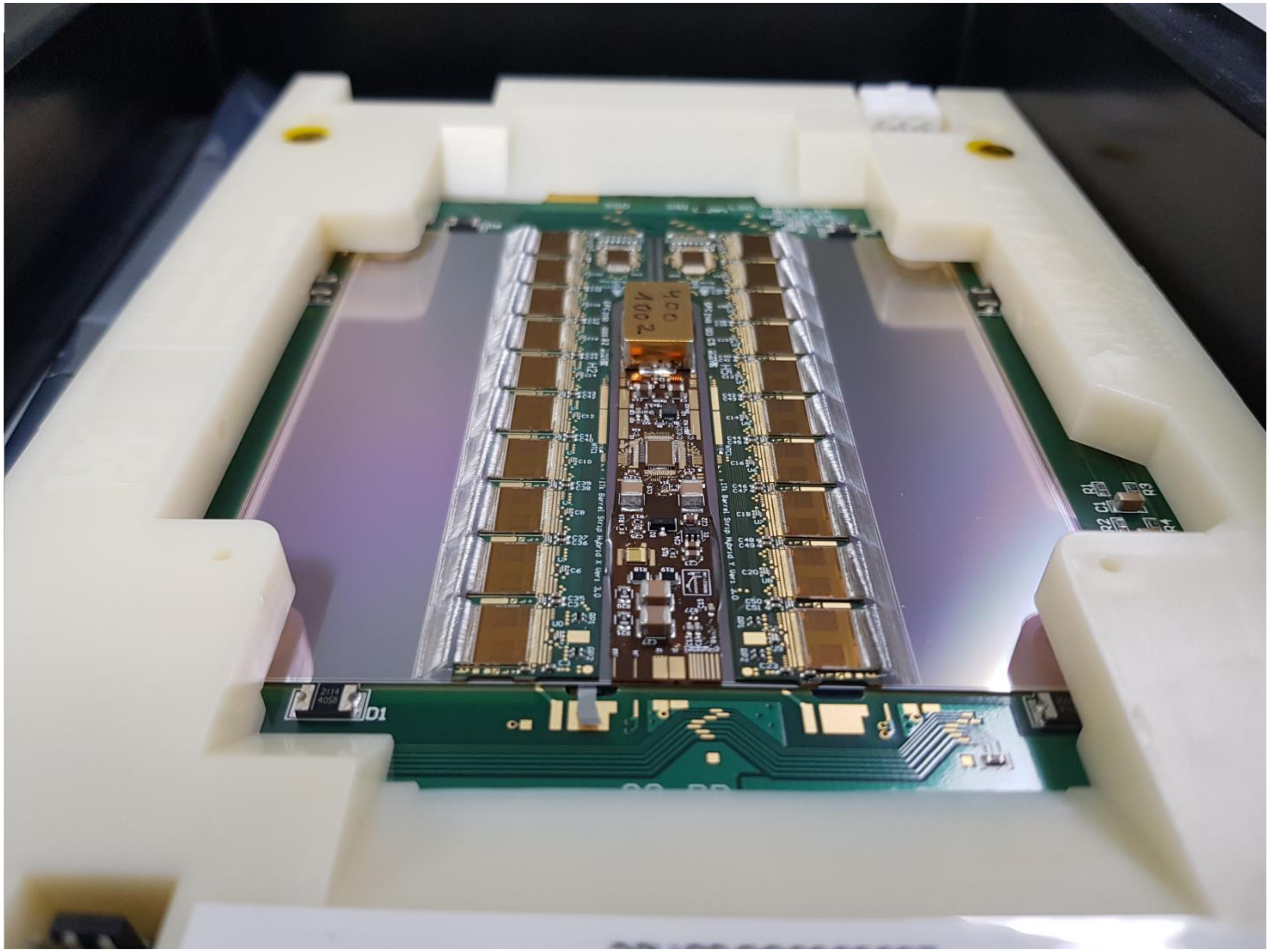
- White transport frame screwed to module frame
- Suction cups press on four corners of module to hold it in place
- Transport frame designed so that the module can be wire-bonded while inside of the frame

Module Assembly



Similar to hybrids, electrical connections done through wire-bonding

Assembled Module



Experiences

– QC

– Cold Noise

– Module/Sensor breaking

QC

Not mentioned all the QC steps we do:

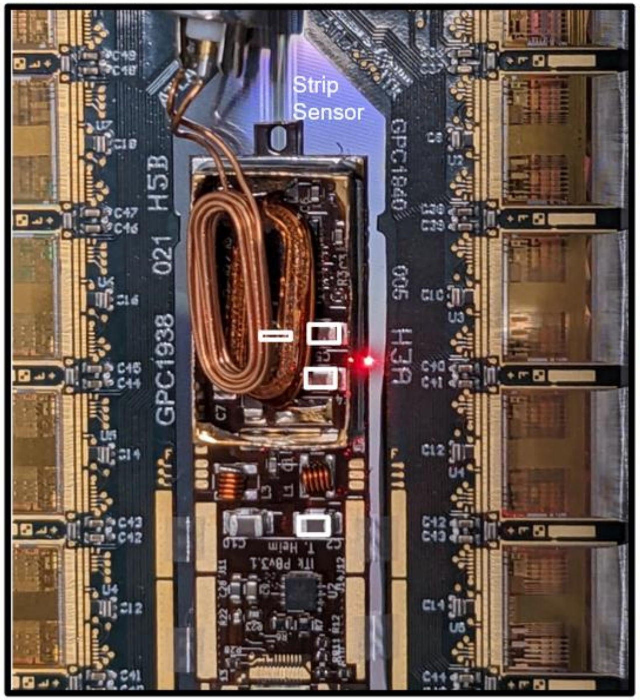
- Weighing of components to determine glue weight
- Metrology for alignment and glue heights
- Visual inspection for any issues arising from assembly process
- Extensive electrical tests
  - 100 hour hybrid burn-in
  - Thermal cycling of modules (10 cycles from -40°C to +20 °C)
- Reception tests of shipped components
  - Visual inspection and if applicable electrical test

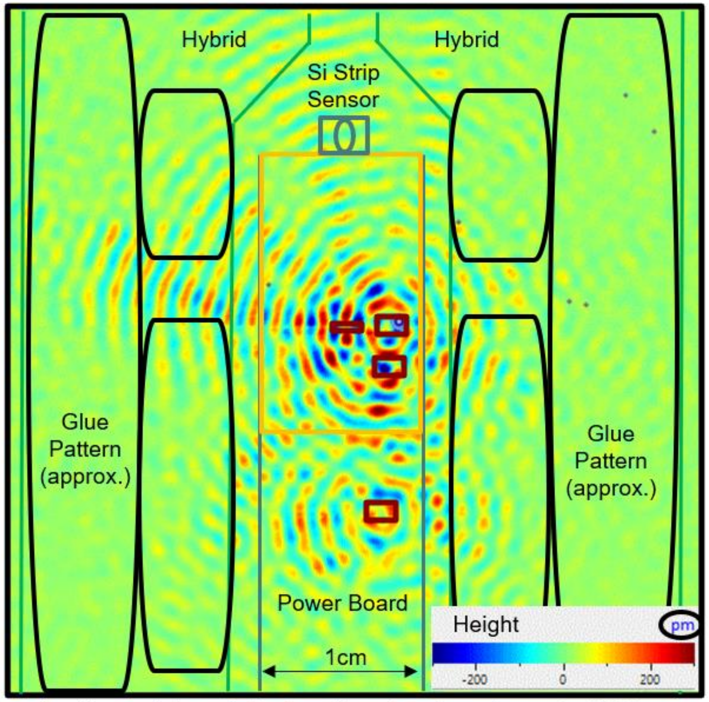
Initial specifications were very ambitious for the chosen assembly methods

Experience and QC measurements during pre-production has given enough evidence that this could be descoped without having an impact on quality and usability

- Placement of part tolerance of +/-100µm in X/Y
  - Relaxed to +/-200µm
- Glue weight control within +/-2.4mg (target 42mg)
  - Relaxed to having a lower limit but no upper limit (as long as glue seepage does not affect further assembly steps)

Cold Noise





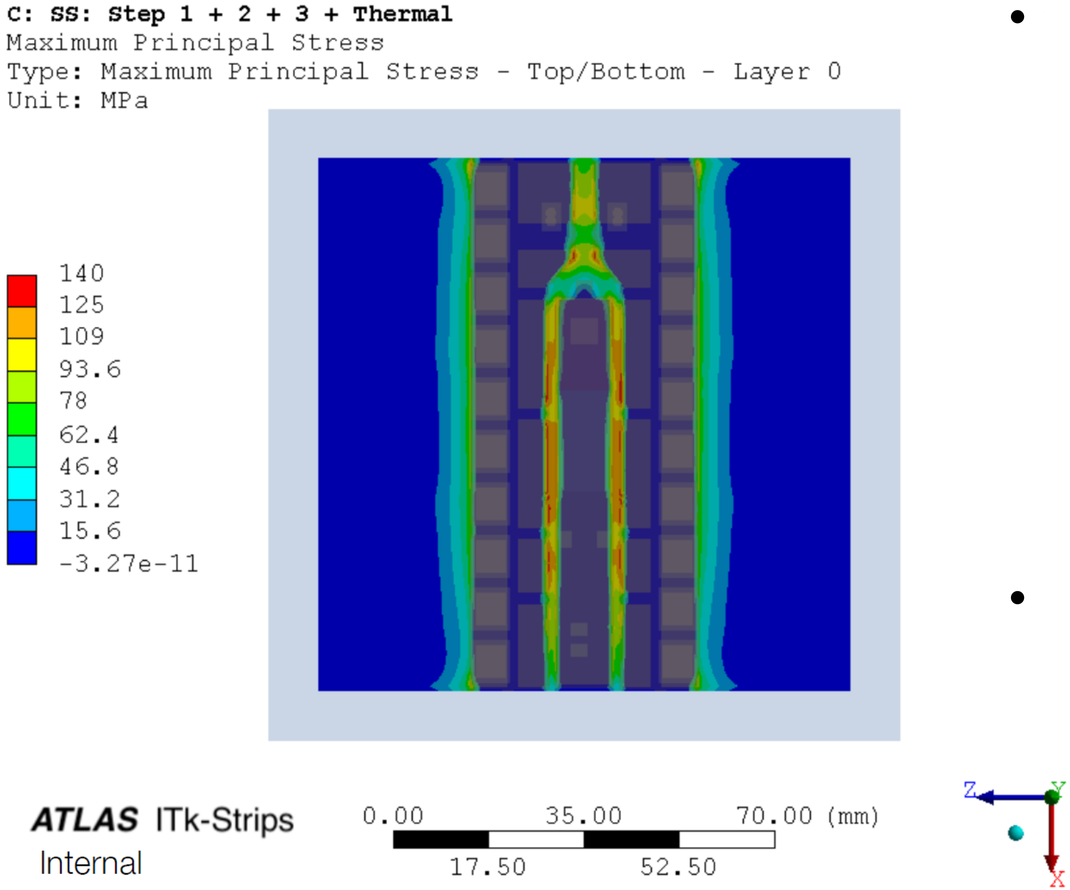
- During pre-production, modules were tested using the full QC chain including thermal cycling
- First time we observed noisy strips appearing during cold testing
  - Noise peaks grow with decreasing temperature, disappearing upon return to room temperature

- Extensive testing undertaken to understand the cause of this "cold noise"
  - Observed in region under the powerboard
  - Bypassing the powerboard shows no cold noise
  - Using highly sensitive laser vibrometer, vibrating (singing) capacitors on powerboard have been identified
    - Amplitude about 1 nm at 2 MHz
- True Blue shows no cold noise for one barrel module type, but for the other
  - Possible mitigation strategies are changing the glue thickness and/or the glue pattern

Investigation still ongoing

https://indico.cern.ch/event/1255624/contributions/5445245/

Modules Breaking



https://cds.cern.ch/record/2876143

- Observed pre-production modules physically breaking on staves when they were tested cold (~15% of modules)
  - No cracked modules in module QC test systems that do thermal cycling
  - Very limited testing of staves during prototyping because of part availability
- Started extensive investigation including detailed FEA stress simulations
  - Identified high stress areas in regions where cracks have been observed
  - Simulations now used to test changes in parts and assembly process to reduce the built-up stress

Investigation still ongoing

Lessons Learned (so far)

- Being ambitions with specifications at the planning phase is fine, as long as you are happy to descope based on data/experience
- Having dedicated detailed procedure document of the processes is important
  - Enough flexibility for site to site difference
- Finding a good glue is a long process
    - Irradiation campaigns
    - Material properties and interaction with glued objects
  - Having at least one viable fully qualified alternative is very important
    - The production of our preferred initial glue was stopped at beginning of pre-production but we had an alternative that could be used in the meantime while looking for more glues

- During the prototyping phase it would be good to do extensive tests with components that are as close to the final objects as possible using the methods that would be used in the detector
  - Chips
  - Electronic circuits
  - Support structures (e.g. staves)
  - Using similar testing and assembly methods at the expected temperature range
- Detailed FEA simulations in the prototype phase can help spotting potential issues that are not visible in tests (low statistic or because full final assembly can't be tested)

Additional Material

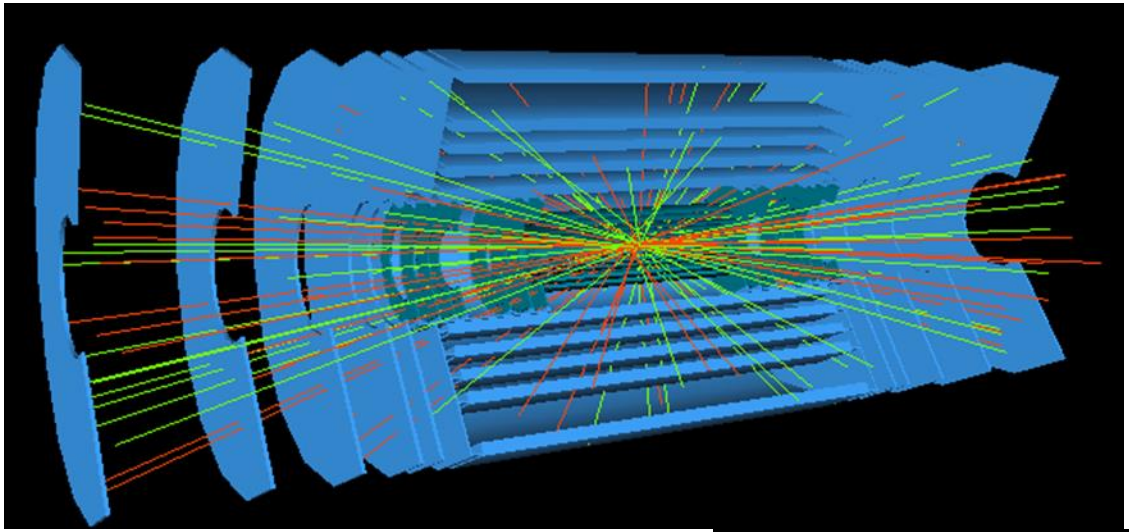
- More detailed videos of whole assembly process available on cernbox
  - https://cernbox.cern.ch/s/QNfbCEEDeE3hLgs
  - They were made as part of the site qualification (when travel was restricted)
  - Used mix of prototype tool sets that have been improved for pre-production

BACKUP

Expected HL-LHC Conditions

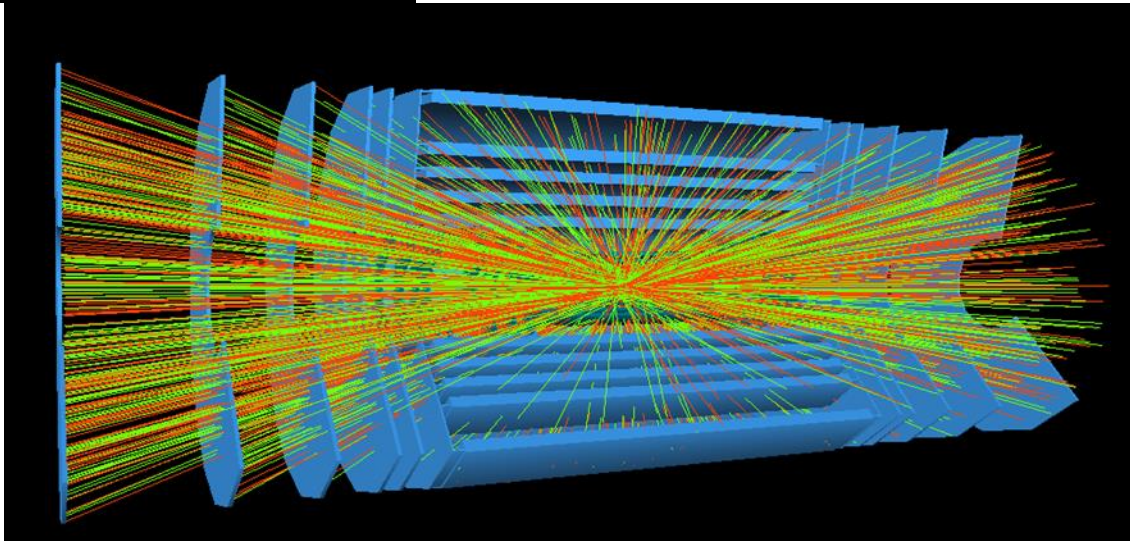
	Current ATLAS SCT	ATLAS ITk HL-LHC conditions
Luminosity	1×10^{34} cm^{-2} s^{-1} (2016 1.37×10^{34} cm^{-2} s^{-1})	7.5×10^{34} cm^{-2} s^{-1}
Integrated luminosity	300 fb^{-1}	3000 fb^{-1} (Ultimate 4000fb^{-1})
Silicon pseudorapidity Coverage (η)	2.7	4.0
Silicon area (strips)	60 m^2	178 m^2
Expected fluence (innermost strips)	2×10^{14} n_{eq}/cm^2	12×10^{14} n_{eq}/cm^2
Expected fluence (pixel)	~10×10^{14} n_{eq}/cm^2	187×10^{14} n_{eq}/cm^2
Pile-up	52 (Run 3)	≈200

Pile-Up



Pile-up 23

Pile-up 230



ATL-UPGRADE-PROC-2012-003; arXiv: 1201.5469

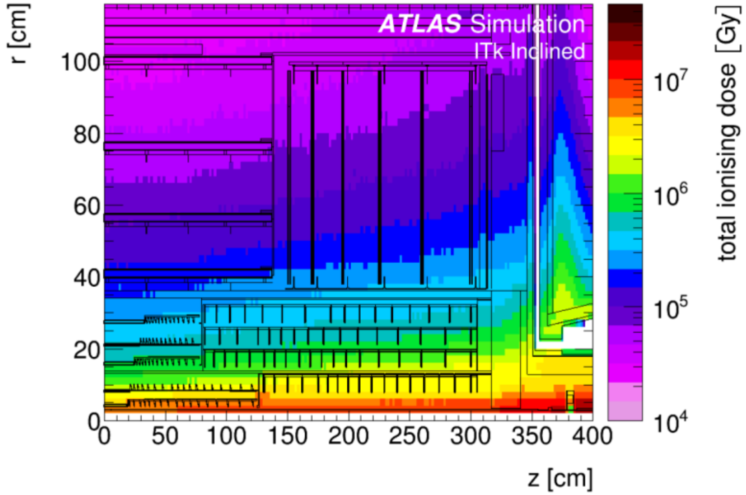
Requirements for HL-LHC

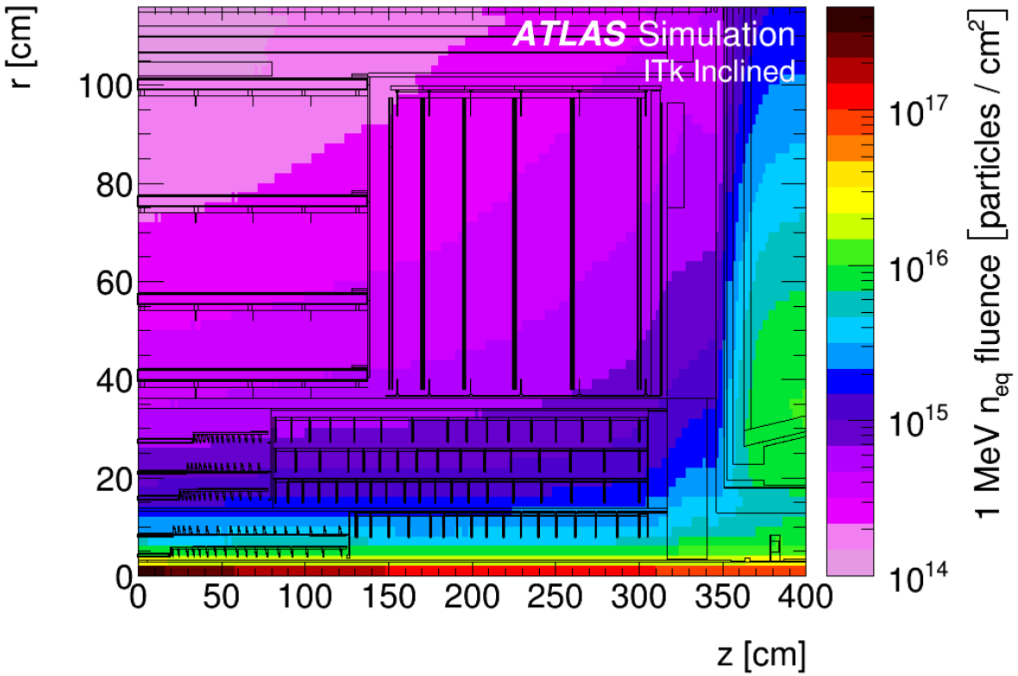
- Inner detector design limits below HL-LHC requirements:
  - Above design fluence the hit efficiency drops below the limits for pattern recognition
    - Pixel system designed for 400 fb-1
    - SCT designed for 700 fb-1
    - IBL designed for 850 fb-1
  - TRT straws will approach 100% occupancy for the expected pile-up, therefore a different solution had to be found

- New design of ATLAS Inner Detector is required
  - Current solenoid magnet (2T) stays
  - Detector performance at least as good as it is now
    - Robust against 10% loss of channels or modules
  - Full detector hermeticity
  - TRT removed and whole volume covered with silicon
  - ITk envelope: 2.5 m wide, 3.2 m high, 7.5 m long
    - Inside the beam-pipe must be taken into account
  - Assembled and commissioned on surface; installed as a single unit into LAr cryostat
  - Beam-pipe and inner two pixel layers must be removable without disturbing rest of ITk
  - Low material budget
  - At end of detector life-time need to operate with noise occupancy at least one order of magnitude lower than that due to hits
  - Link occupancy always below 90%
    - < 0.1% occupancy in pixel layers
    - < 1% occupancy in strip layers

Expected Irradiation Fluence

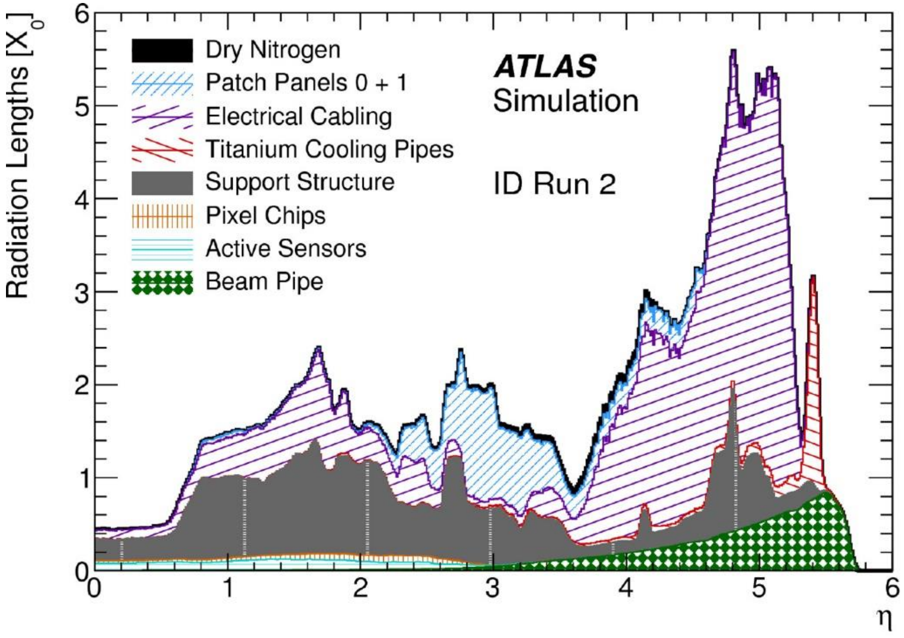
The modules must be designed to work for the full life-time of the HL-LHC (10+ years), which requires a high radiation tolerance to the expected fluence and ionizing dose.



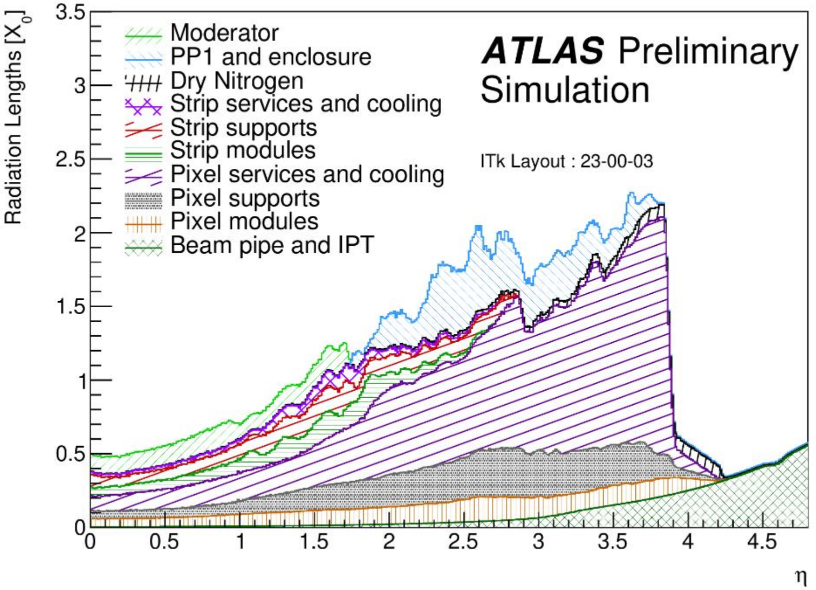


Layer	Radius [mm]	Maximal Fluence [n_{eq}/cm^2]	Maximal Dose [MRad]
Strips			
Long Strips	762	3.8×10^{14}	9.8
Short Strips	405	7.2×10^{14}	32.5
End-cap	385	1.2×10^{15}	50.4
Pixels			
Layer 0	39	1.87×10^{16}	1268
Layer 1	75	0.59×10^{16}	549
Layer 2	155	0.22×10^{16}	129
Layer 3	213	0.15×10^{16}	87
Layer 4	271	0.11×10^{16}	53
End-cap	80	0.62×10^{16}	477

Radiation Length



Current ATLAS Inner Detector

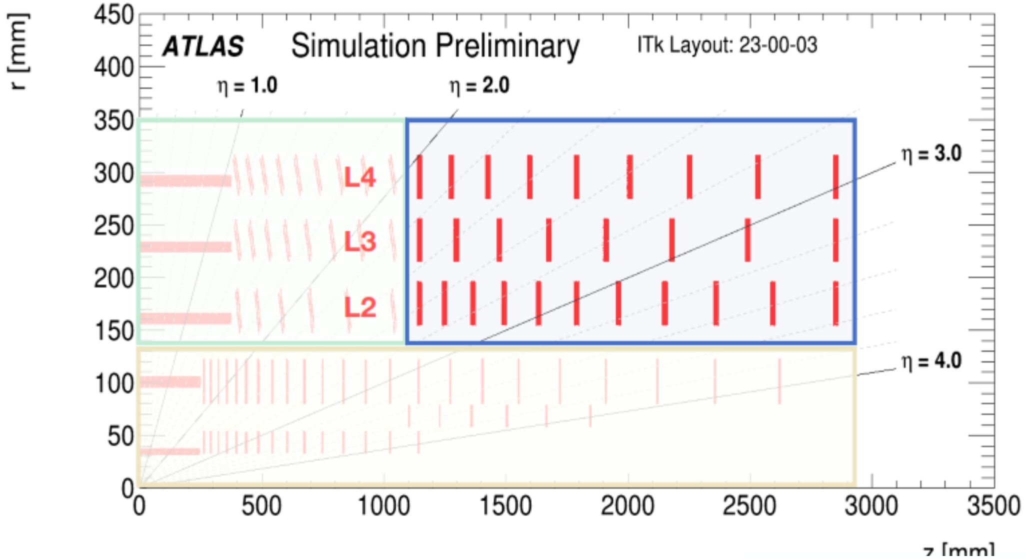


New ITk layout.

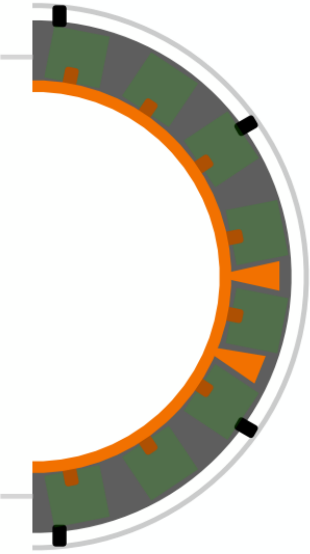
UK Pixel Groups

- UK will build one end-cap in its entirety (other in Italy)
  - 24 L2 half-rings (2 spares)
  - 18 L3 half-rings (2 spares)
  - 20 L4 half-rings (2 spares)
  - 1300 functional modules

Pixel upgrade project leader is from UK: Craig Buttar

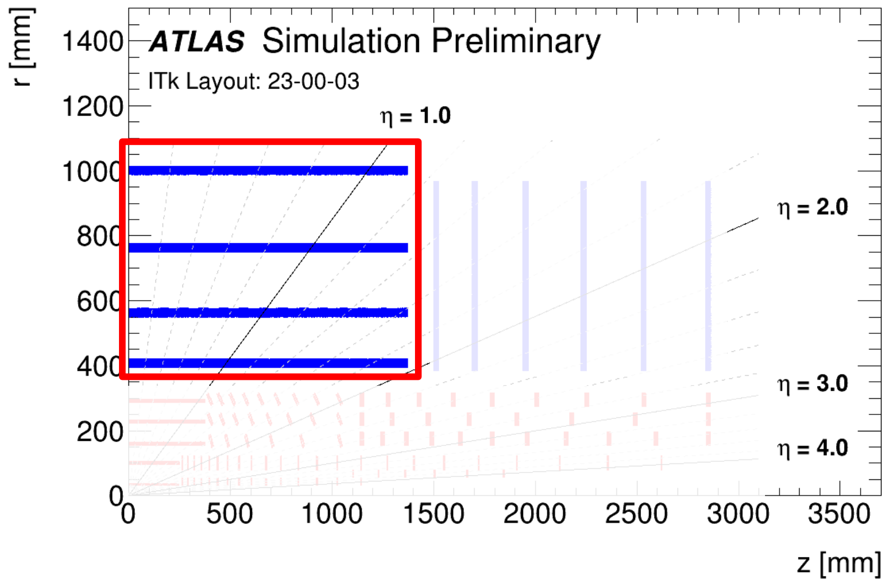


- Edinburgh: flex reception testing
- Glasgow: pixel ASIC reception testing, flex reception testing, module assembly and testing
- Lancaster: sensor testing, half ring construction
- Liverpool: module building and testing, module parylene coating, construction of half-shells that hold half rings, mounting and integration of all half rings
- Manchester: half ring construction
- Oxford: module building and testing, half ring loading and testing
- RAL: half ring production, half ring loading and testing
- Sheffield: half ring construction
- UCL: DAQ support



UK Strip Groups

- Birmingham: hybrid assembly, module assembly
- Cambridge: sensor QC, module assembly
- Glasgow: module assembly
- Lancaster: cooling pipe bending
- Liverpool: hybrid flex QC, hybrid assembly, module assembly, stave core assembly
- QMUL: sensor QC, stave core QC
- Oxford: bus tape testing, stave core assembly
- RAL: ASIC probing, hybrid assembly, module assembly, stave loading
- Sheffield: module assembly, cooling pipe welding
- Warwick: module assembly at Birmingham



Together with IHEP (China), the UK builds ½ of the strip barrel (including support structures)

- ~4400 modules

Strips upgrade project leader is from UK: Craig Sawyer

Hybrid Design

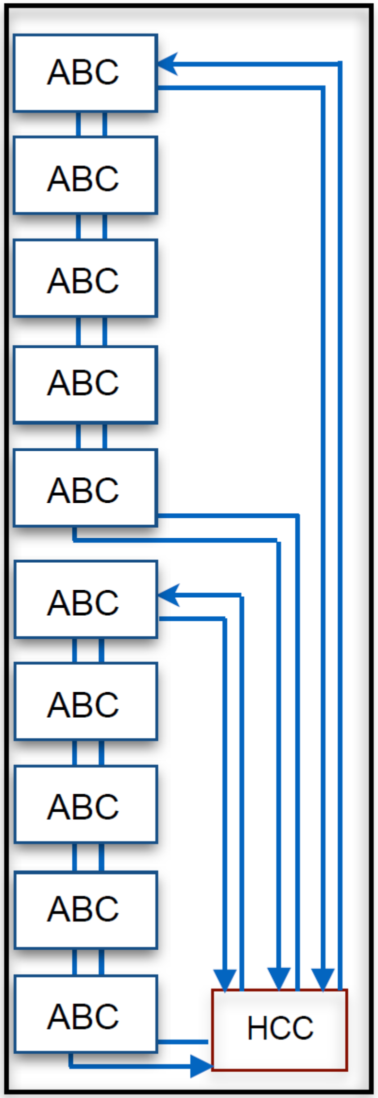
HCC receives signals from ABC and builds packets. It also receives clock and control signals (TTC) and distributes them to the ABC.

In the prototype hybrids the data connections from the ABCs are in the form of two bidirectional loops. In the barrel each loop has five ABC130s.

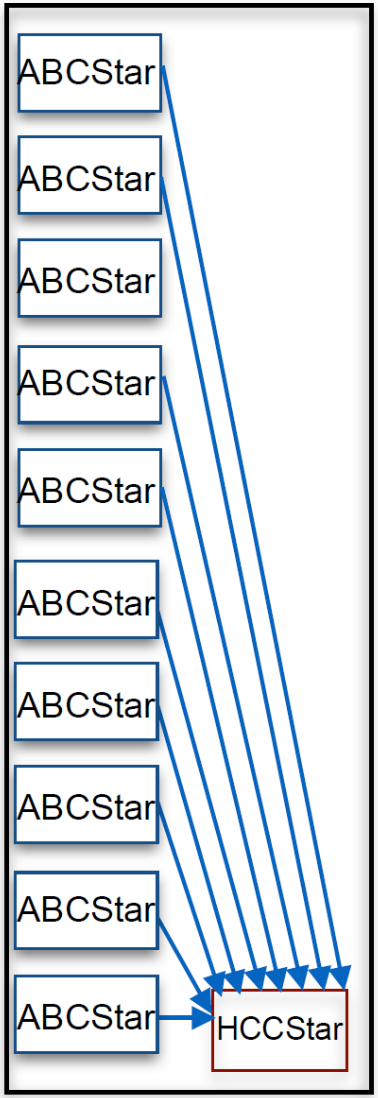
The increase in trigger rate for the final design required a change in hybrid design towards the "Star" architecture: each ABCStar has a Point-to-Point connection with the HCCStar.

Each HCCStar has 11 input channels for data packets from ABCStar chips, which result in the requirement of two HCCStar for the end-cap hybrids R2-R5.

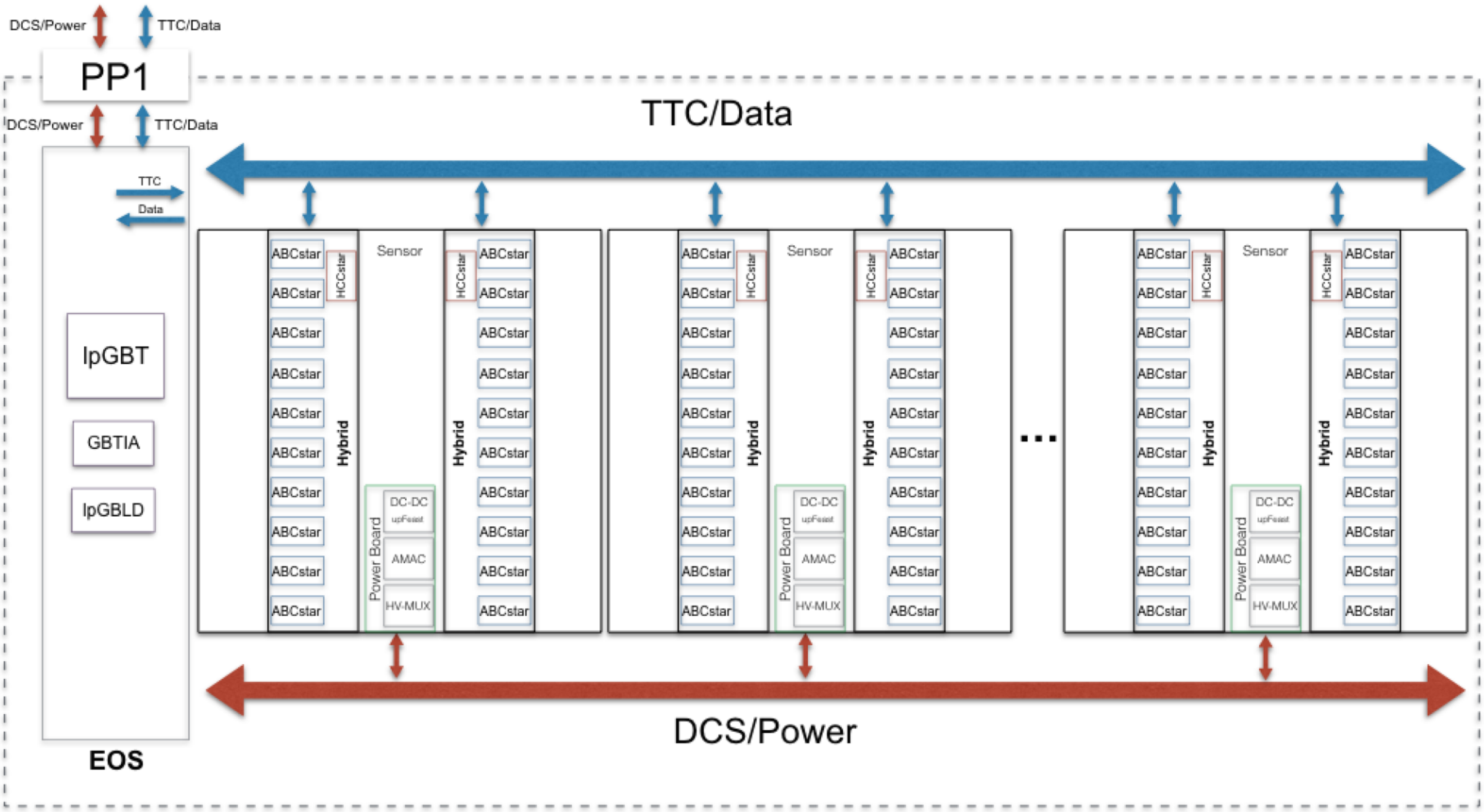
Prototype



Production

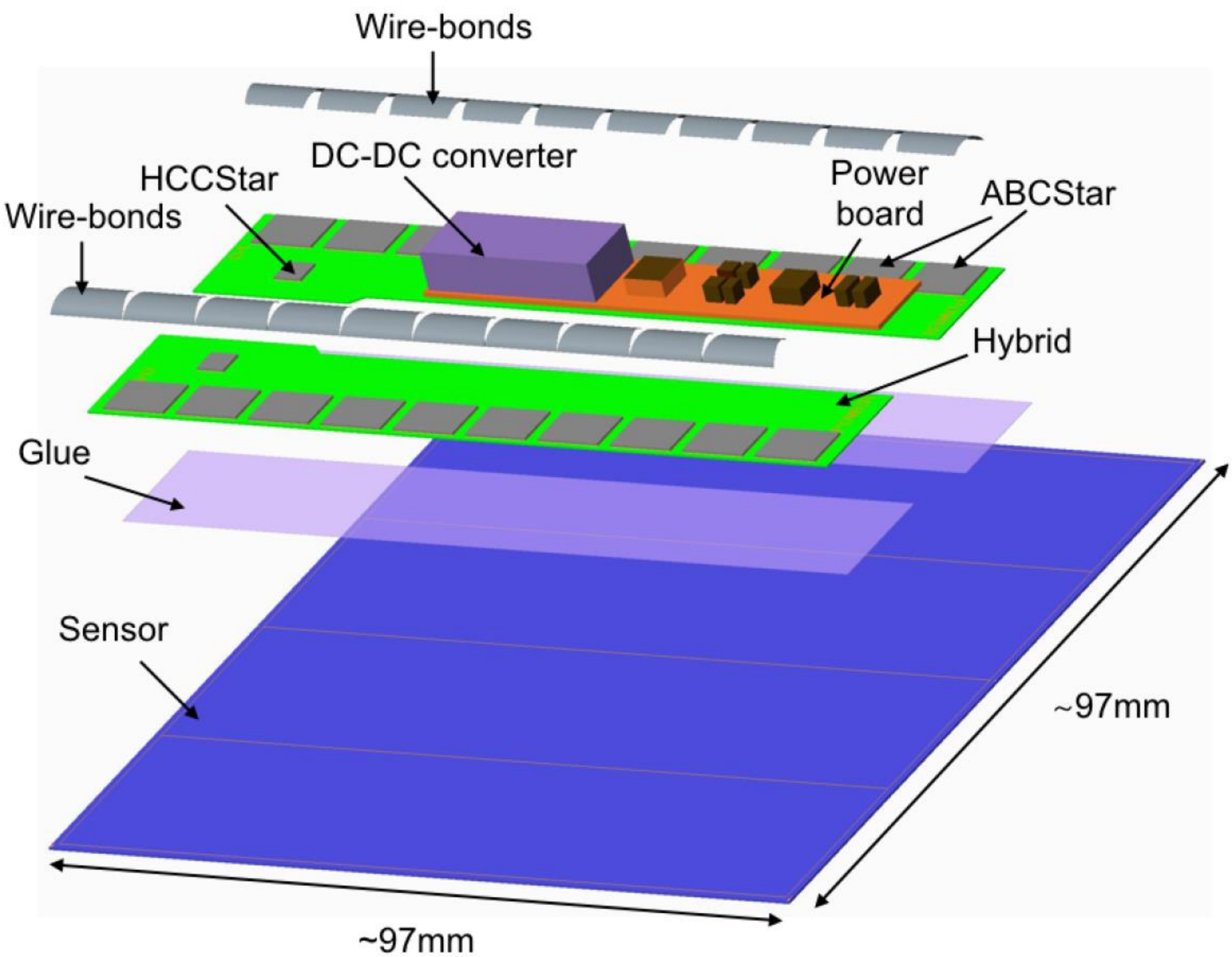


Stave/Petal Layout



Staves and Petals have in common that DCS/Power and TTC/Data are separated to two different sides of the module.
At the end of each stave/petal is the EoS (End-of-Substructure) card, which contains all the links to the outside (low-power GigaBit Transceiver lpGBTx, Versatile link VTRx fibre optic driver)

Short-Strip Module



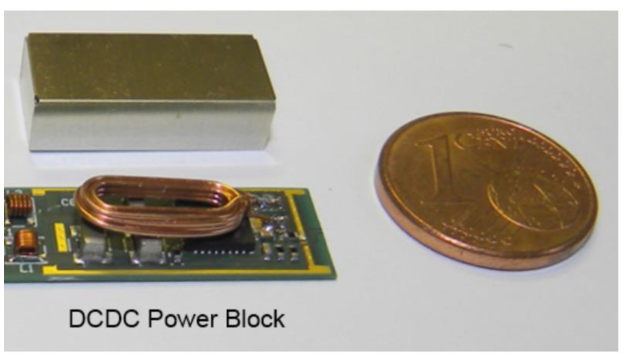
An example barrel module:

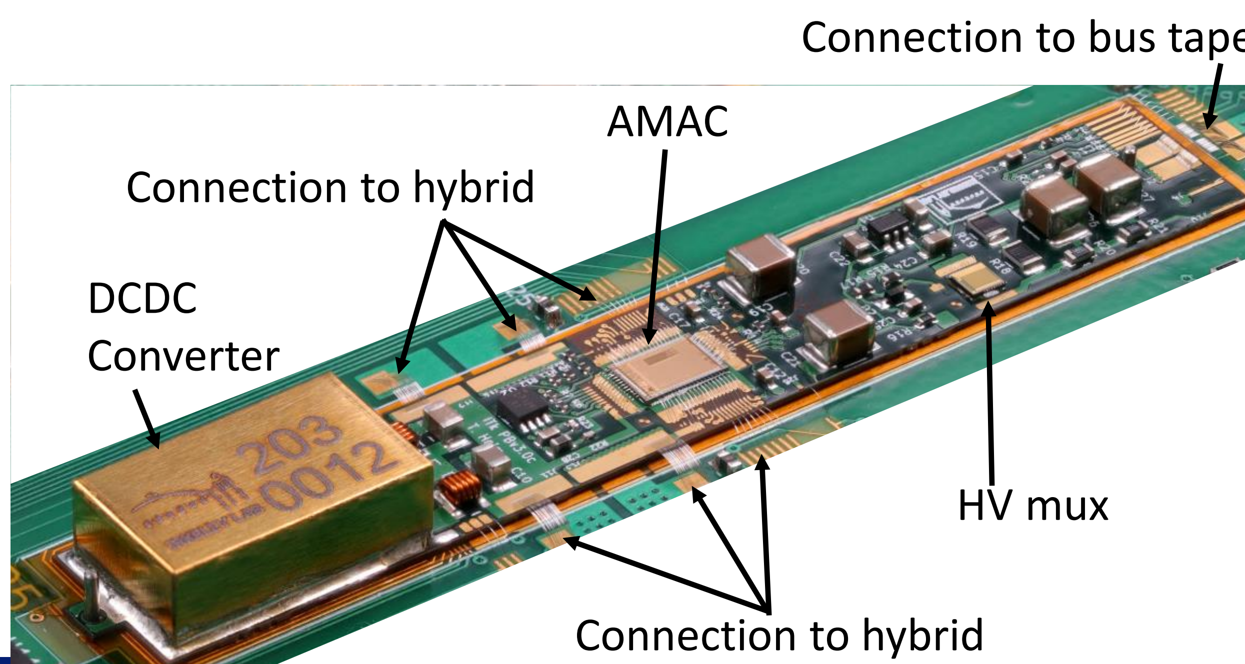
Exploded view shows the different components

Power-Board

The modules need power for sensor and ASICS, which is realised in the power-board:

- DC-DC buck converter for low-voltage bPOL12V ASIC)
  - ITk requires more power than the current SCT => more efficient power distribution required
    - Point-of-load DC to DC conversion allows higher voltages in the off detector power supplies, which reduces the current in the cables and therefore the ohmic losses
  - DC-DC converter requires a coil => for EMI shielding covered by a shield box
- High voltage filter and switch (HV mux)
  - Limited space for cables requires shared high-voltage lines for modules. The HV switch allows to disable single modules in the high voltage chain.
- Monitoring for HV and LV currents, module temperature, controlling of the modules (AMAC ASIC)





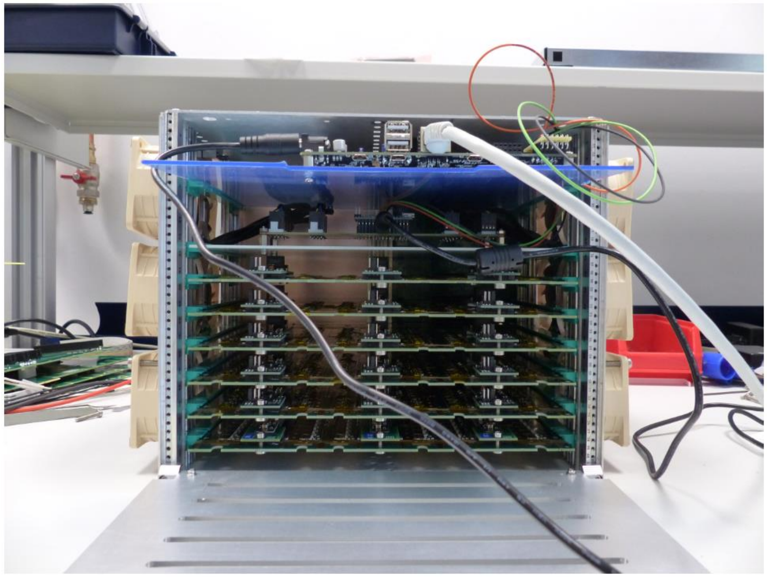
Hybrid Burn In

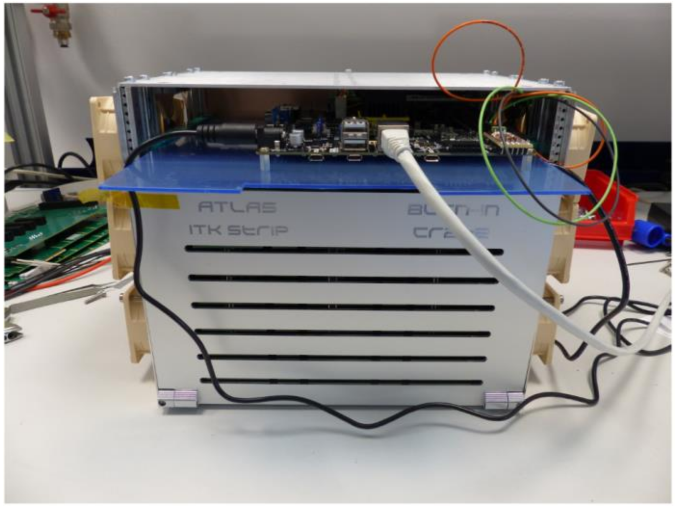
Before hybrids can be used for module assembly, they have to be burned in:

- 100h running at 40°C to check hybrid operation stability at elevated temperature
    - Temperature limited by glass transition temperature of glue
- Checking input noise and threshold uniformity and communication

One common system, based on off the shelf crate mechanics

- Allows testing of up to 6 hybrid panels
    - Crate mechanics and electronic boards independent of hybrid flavour
    - Only hybrid panel design depends on hybrid type, but connectorisation unified
- Fans and temperature readout to control hybrid temperature

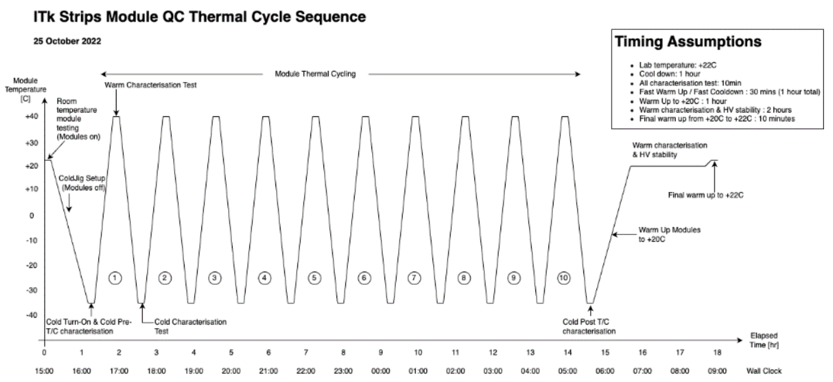


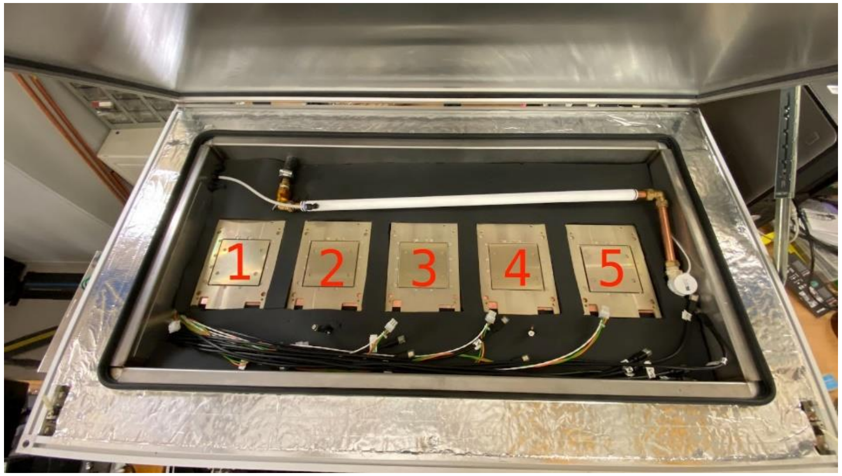


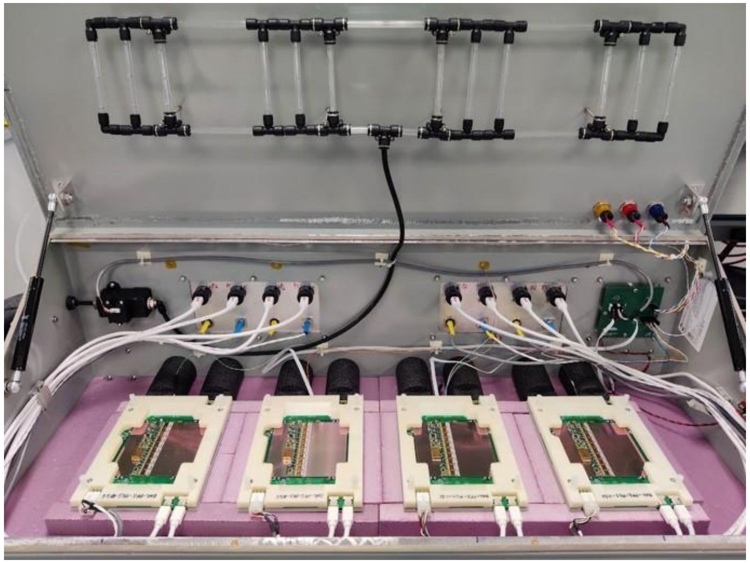
Module Cold Box

After module assembly, part of the QC program is to perform thermal cycles of modules:

- 10 cycles from -35°C to +0°C and back







Three different setups developed (UK/China, USA, Endcap), all use common software for control and tests