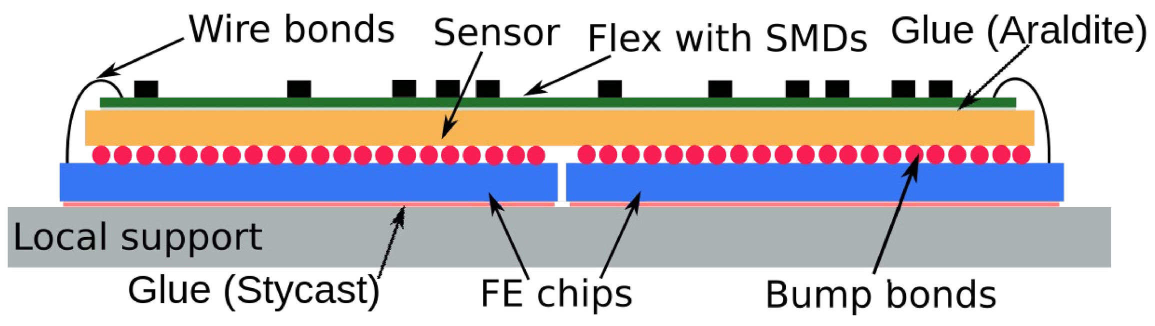
# ATLAS ITk pixel module bump bond stress analysis

Jörn Grosse-Knetter on behalf of the ITk Collaboration
II. Physikalisches Institut, University of Göttingen – email: jgrosse1@uni-goettingen.de

## Pixel Modules

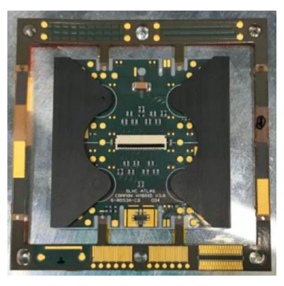
Pixel module structure:
- Hybrid of pixel sensor and 3 or 4 read-out chips (FE):
  - Connected channel by channel with SnAg or In bump bonds.
  - Bump bond pitch same as pixel size: 50 x 50 µm².
- Glued to thin PCB (flex).
- Mounting of modules on support structures forming barrel or end-cap layers.

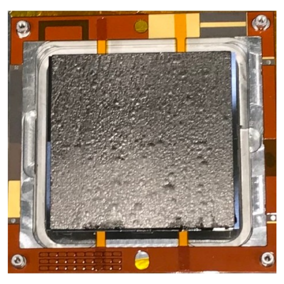


Module x-sec.

Compound structure of detector:
- CTE mismatch between components of/on module.
- Modules will be mounted on substrate with CTE ≤ lowest CTE local support – as proposed in ITk pixel: with rigid adhesive

→ stress through temperature variation during operation a concern.





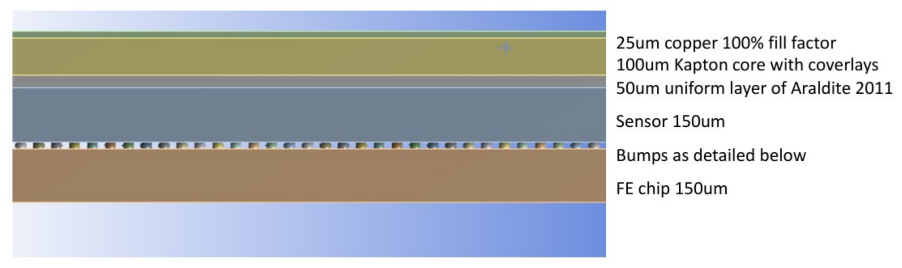
Investigated with modules with
- Prototype (RD53A) chips (½ size) or pre-production chips (full size)
- Real ITk bump bond pitch, SnAg bump bonds
- Flex with real Cu content
- Attached to carbon sheets (end-cap (EC) style, outer barrel (OB) style (PG), or TPG)

Dedicated campaigns with double-chip and four-chip modules from three bump bond vendors. Some samples coated with parylene (HV protection).

## Bump Bond Stress

Modules need to be cooled in operation (dedicated $CO_2$ cooling plant), but will be warm in-between.
Require all components to withstand order of 100 cycles of the cooling system between +25 and -45 °C @ 1°C/min.

Prediction of bump stress and cycles to failure obtained from **FEA simulation**:
- High density array of bumps, individually modelled with full viscoplastic material properties.
- Flex with realistic Cu content.




Coffin–Manson law:

$$N_f = \frac{1}{2}\left(\frac{\Delta\gamma}{2\epsilon_f'}\right)^{(1/c)}$$

$\epsilon_f'$ fatigue ductility coefficient,
$N_f$ mean cycles to failure,
$c$ fatigue ductility exponent.

→ calculation of cycles to failure from total strain Δγ – **result**:

Results do not include creep and based on empirical values from similar parts

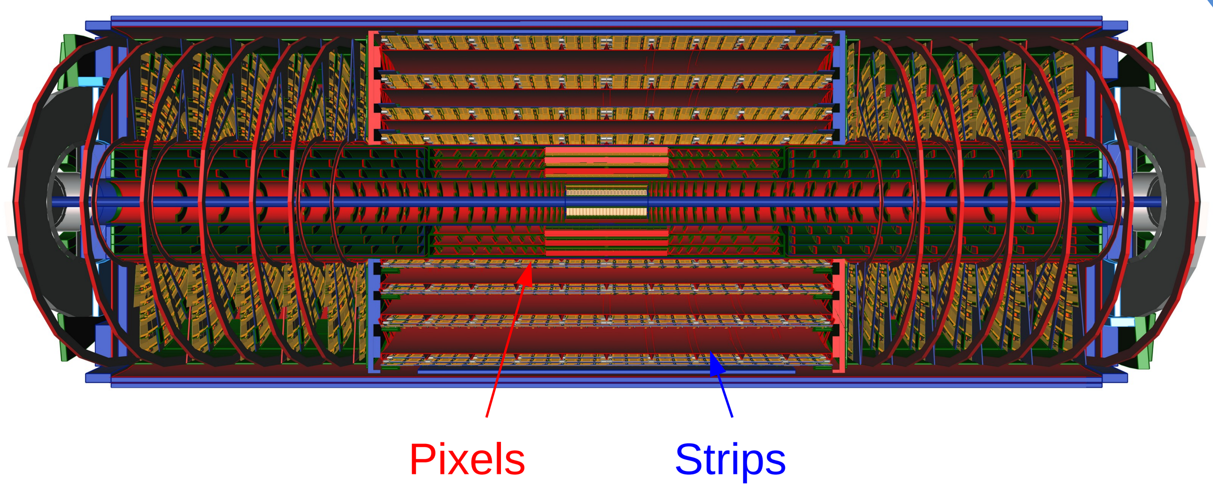
| | Temp range (°C) | | |
|---|---|---|---|
| | +60-> -55 | +40-> -45 | -25 -> -45 |
| ITk Pix 25um Cu 100um Araldite | 2400 | 7700 | 100,000 |
| ITk Pix 35um Cu 100um Araldite | 800 | 2600 | 35,000 |

**Experimental studies** involving thermal cycling of modules through specialised machines at several sites over +60 to -55 °C – wider range to see faster delamination than at range +25 and -45 °C.


Climate/shock chambers used for cycling studies

## The ITk-Pixel Detector

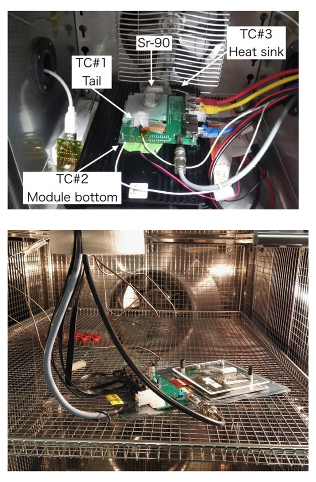
ATL-PHYS-PUB-2021-024



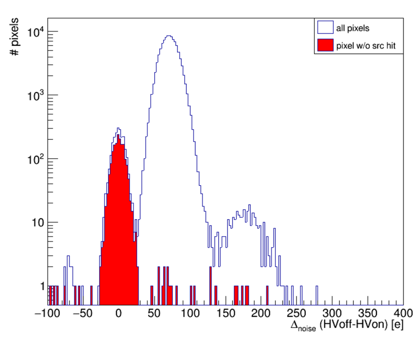

**Upgrade of ATLAS with HL-LHC**
- LHC will upgrade to higher inst. luminosity (HL-LHC)
- Upgrade of ATLAS: replacement of current tracking detector by all-silicon Inner Tracker (ITk)
- ITk comprises of 4 strip and 5 pixel layers in barrels and end-caps

→ build *O*(10k) pixel modules in next years
→ must verify that design ensures reliable operation over 10 years of HL-LHC

## Cycling: Bump Defects



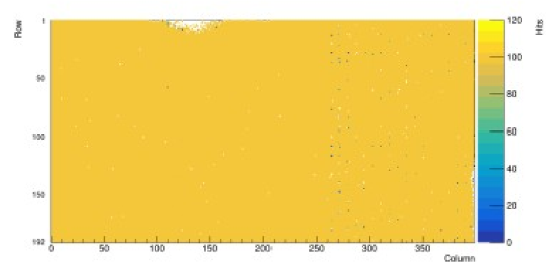

Measurements between cycling



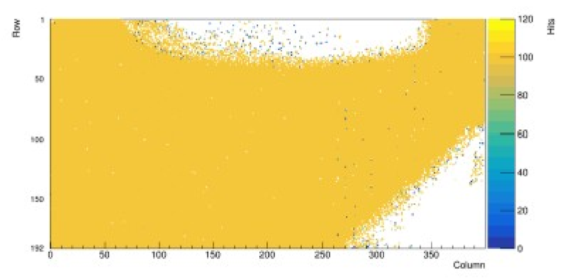
**Tests of module bump quality**:
- Source tests: too few / no hits seen
  → bump connection lost (requires β, γ, or X-ray source).
- Noise or cross-talk: sensor influences amplifier
  → information on bump connectivity (easier in-situ).

Example of early delamination

150 cycles



500 cycles



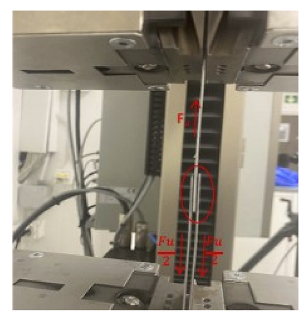
| Sample | vendor | Substrate | Parylene | Module | chip | Number of thermal cycles with <0.1% disconnects | Max. number of cycles/number of disconnects |
|---|---|---|---|---|---|---|---|
| DCM34 | C | OB TPG | N | Dual | 2 | 50-100 | 500/985 |
| GD02 | C | OB TPG | N | Dual | 1 | 10-50 | 700/2539 |
| GD02 | C | OB TPG | N | Dual | 2 | 10-50 | 700/13594 |
| GD01 | C | EC CFRP | N | Dual | 1 | 100-250 | 500/1523 |
| GD01 | C | EC CFRP | N | Dual | 2 | 100-250 | 500/583 |
| DCM32 | C | EC CFRP | N | Dual | 1 | >1000 | 1000/46 |
| DCM32 | C | EC CFRP | N | Dual | 2 | >1000 | 1000/17 |
| KEKQ14 | C | OB PG | Y | RD53-Quad | 1-4 | >100 | 100/0 |
| KEKQ17 | C | OB PG | Y | RD53-Quad | 1-4 | >100 | 100/0 |
| KEKQ18 | C | OB PG | Y | RD53-Quad | 1-4 | >100 | 100/0 |
| GLA2 | C | EC CFRP | N | RD53-Quad | 1-4 | >100 | 100/0 |
| GLA3 | C | EC CFRP | Y | RD53-Quad | 1-4 | >100 | 100/0 |
| GLA4 | C | EC CFRP | Y | RD53-Quad | 1-4 | >100 | 100/0 |
| RD08 | A | EC CFRP | N | Dual | 1 | >1000 | 1000/0 |
| RD08 | A | EC CFRP | N | Dual | 2 | 500-1000 | 1000/155 |
| RD05 | A | EC CFRP | N | Dual | 1 | >1000 | 1000/31 |
| RD05 | A | EC CFRP | N | Dual | 2 | >1000 | 1000/0 |
| RD04 | A | EC CFRP | N | Dual | 1 | >1400 | 1400/26 |
| RD04 | A | EC CFRP | N | Dual | 2 | 1200 | 1600/81 |
| DCM2 | A | OB TPG | N | Dual | 1 | >100 | 100/42 |
| DCM2 | A | OB TPG | N | Dual | 2 | 250-500 | 1000/248 |
| DCM5 | A | OB TPG | N | Dual | 1 | 10-50 | 250/354 |
| DCM5 | A | OB TPG | N | Dual | 2 | 50-100 | 500/136 |
| B10 | B | EC CFRP | N | Dual | 1 | >50 | 50/0 |
| B10 | B | EC CFRP | N | Dual | 2 | 50-100 | 1000/37490 |
| B15 | B | EC CFRP | N | Dual | 1 | 500-1000 | 1000/855 |
| B15 | B | EC CFRP | N | Dual | 2 | 100-250 | 500/41497 |
| B17 | B | EC CFRP | N | Dual | 1 | 0-10 | 1000/8027 |
| B17 | B | EC CFRP | N | Dual | 2 | 100-500 | 1000/11699 |

| Sample | vendor | Substrate | Irradiated | Number of thermal cycles with <0.1% disconnects | Max. number of cycles/number of disconnects |
|---|---|---|---|---|---|
| KEKv1-1 | B | OB TPG | N | >100 | 100/0 |
| KEKv1-2 | B | OB TPG | N | >100 | 100/0 |
| KEKv1-2 | B | OB TPG | 6.3e15/500Mrad | >200 | 200/0 |
| KEKv1-3 | B | OB TPG | N | >100 | 100/0 |
| KEKv1-3 | B | OB TPG | 6.3e15/500Mrad | >200 | 200/0 |
| KEKv1-4 | B | OB TPG | N | >100 | 100/0 |
| KEKv1-19 | B | OB TPG | N | >100 | 100/0 |
| KEKv1-19 | B | OB TPG | 6.3e15/500Mrad | >200 | 200/0 |

**Results:**
- Vendors A, C: delamination starts > 100 cycles; end-cap/PG support slightly better than TPG
- Vendor B: several modules with delamination < 100 cycles
- Vendor B with parylene: increased bump connection strength

## Shear Tests

Better understanding of adhesion → measure bond strength in lap shear tests.



Module samples, sandwiched between Al strips, bonded with ARALDITE 2011, pull tested to failure.

| Test | Vendor and module type | Test type | Surface preparation | Bumps per FE | Ultimate force per chip (N) | Ultimate bump strength (N) |
|---|---|---|---|---|---|---|
| 1 | Vendor-A single chip module | Double lap shear test | Acetone cleaning | 400*336 | >652.8 | > 0.0049 |
| 2 | Vendor-A single-chip module | Single lap shear test | Plasma cleaning | 400*336 | >693 | > 0.0052 |
| 3 | Vendor-A single-chip module | Single lap shear test | Heavy acetone and alchohol cleaning | 400*336 | >1060 | > 0.0079 |
| 4 | Vendor-A single-chip module | Single lap shear test | Scotch-brite | 400*336 | >1450 | > 0.0108 |
| 5 | Vendor-B quad module FE-1 | Single lap shear test | Scotch-brite | 400*384 | 853 | 0.0056 |
| 6 | Vendor-B quad module FE-2 | Single lap shear test | Scotch-brite | 400*384 | 219 | 0.0016 |

**Results**

Most modules: failure at adhesive layer, not at bump bonds → only lower limit of force.
In case failure is observed, turn force into bump strength.
Observed difference between vendors A, B support cycling results.

## Summary

- Measurements confirm simulation: thermal cycling is risk to bump bond integrity
  - Result depends on vendor (UBM and bump bond specifics)
    – supported by shear stress measurements
  - Result depends on carbon support material: TPG vs end-cap or outer barrel support
  - Parylene coating reduces effect, before and after irradiation
- Vendors A and C qualified even with harsher cycling range
- Benefit from parylene coating – go forward with vendor B: gain more statistics and thus more confidence in vendor B until production
- Upcoming studies: 3-chip modules and In bump bonds (promis. FEA)