Thermomechanical design validation for quad pixel modules for the ITk

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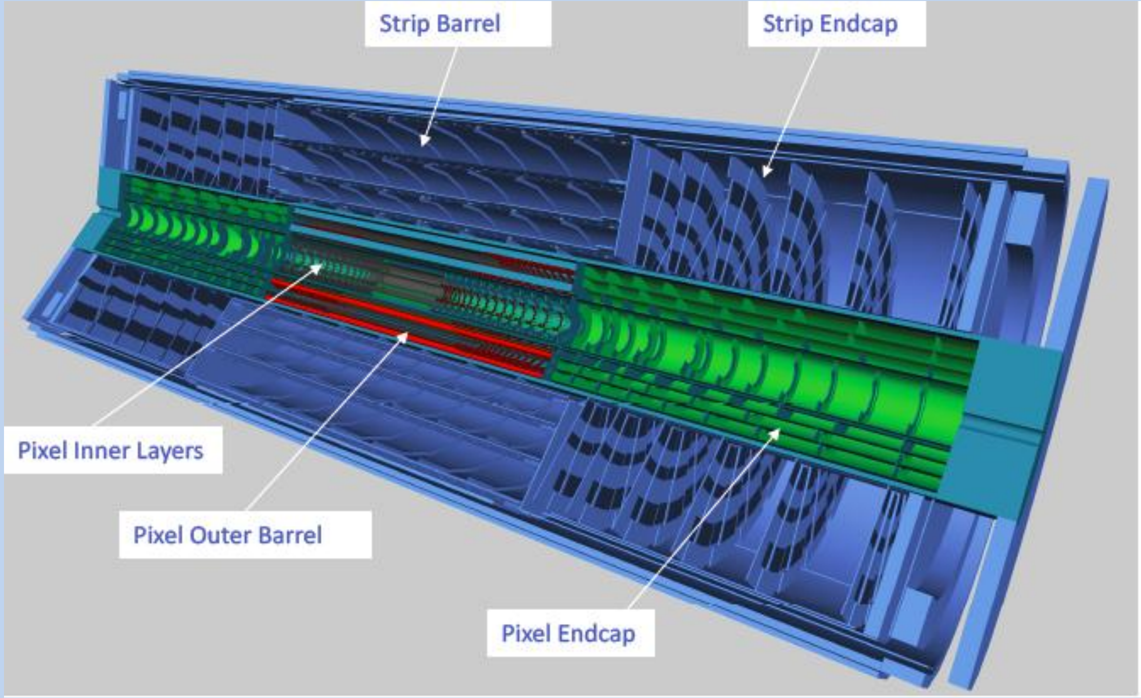
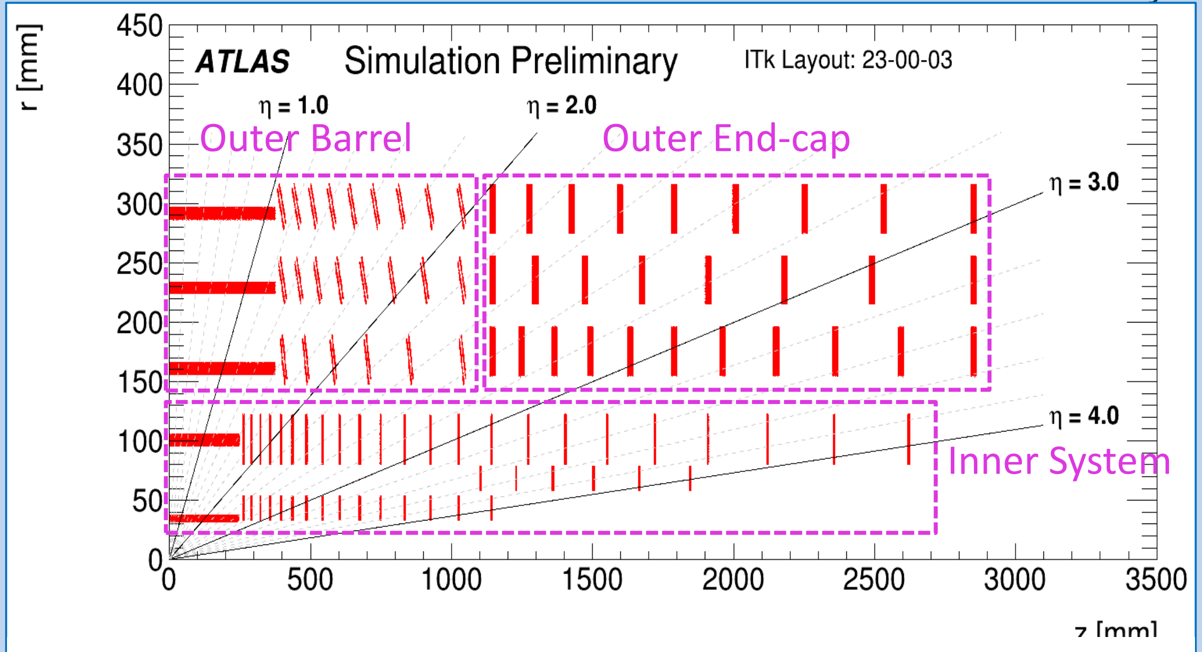
Introduction

- Overview of the ITk Pixel detector
- Description of the modules and the operational environment
- Development of a thermo-mechanically robust design
- Thermal cycling of real assembled modules
- Ongoing testing and future work
- Summary

Overview of ITk Pixel detector





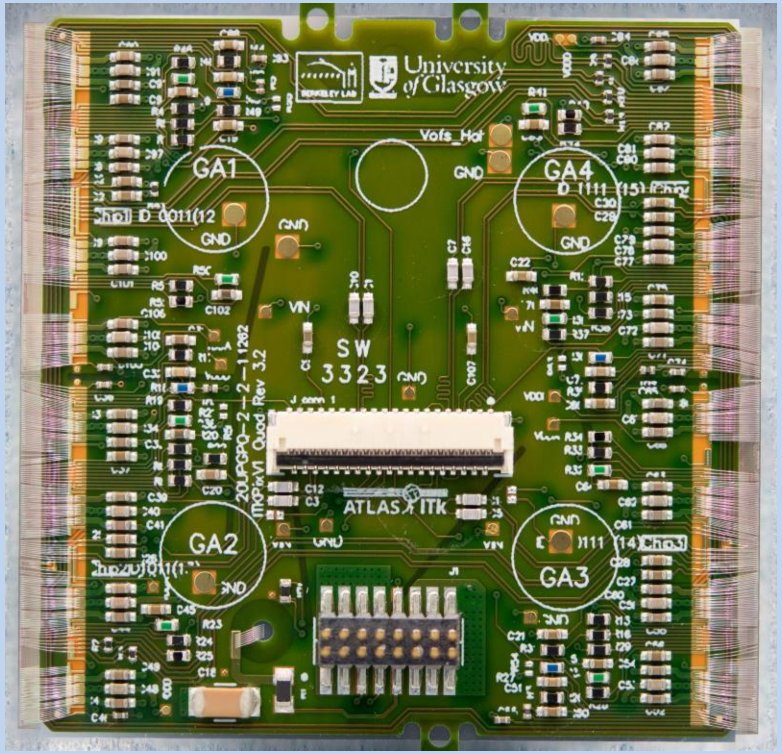
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/fig_01b.png

The ITk Pixel detector consists of multiple layers of horizontal, inclined and vertically mounted detector modules. There will be ~9000 modules with over 5 billion pixels covering ~13m^2.

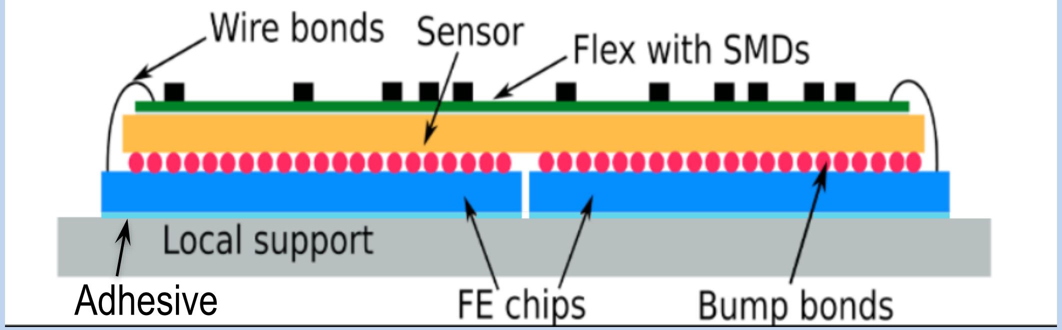
The new detector will operate in a very challenging environment. Different areas of the pixel detector will receive different doses during operation:

- 1.7 MGy for the outer barrel,
- 3.5 MGy for the outer endcap
- 7.3 MGy for the inner system
- Maximum fluences of 2.3×10^{15}cm^{2}1MeV n_{eq} to 9.2×10^{15}cm^{2}1MeV n_{eq} will be experienced in different areas of the detector

Design of ITk Pixel Quad detector modules and variants

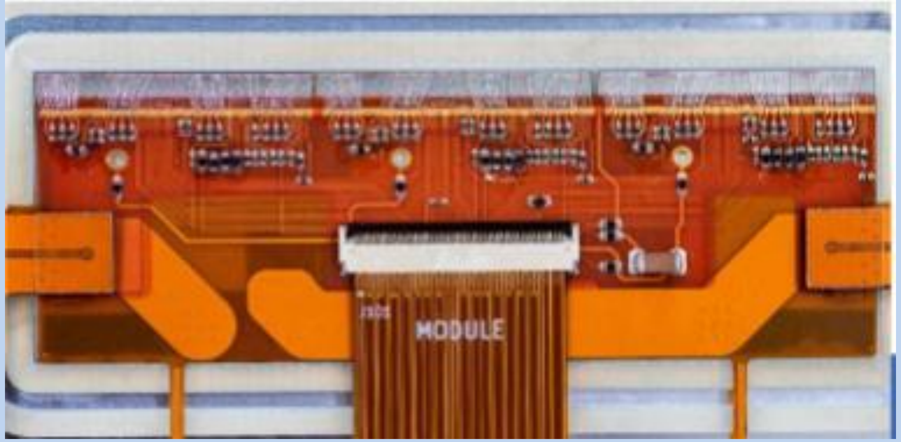


Schematic of assembled module, showing the stack up of the detector from the local support to the flexible PCB on the top with the wirebonds visible on the sides.



Not shown is a conformal coating of parylene which gives HV isolation and strengthens the assembled module

Quad Modules make up ~95% of installed detectors. Comes in 2 flavours and 3 types:
Outer system 150um sensor
Outer system 150um sensor with wirebond protection canopy
Inner system 100um thick sensor
All chips are 150 um thick



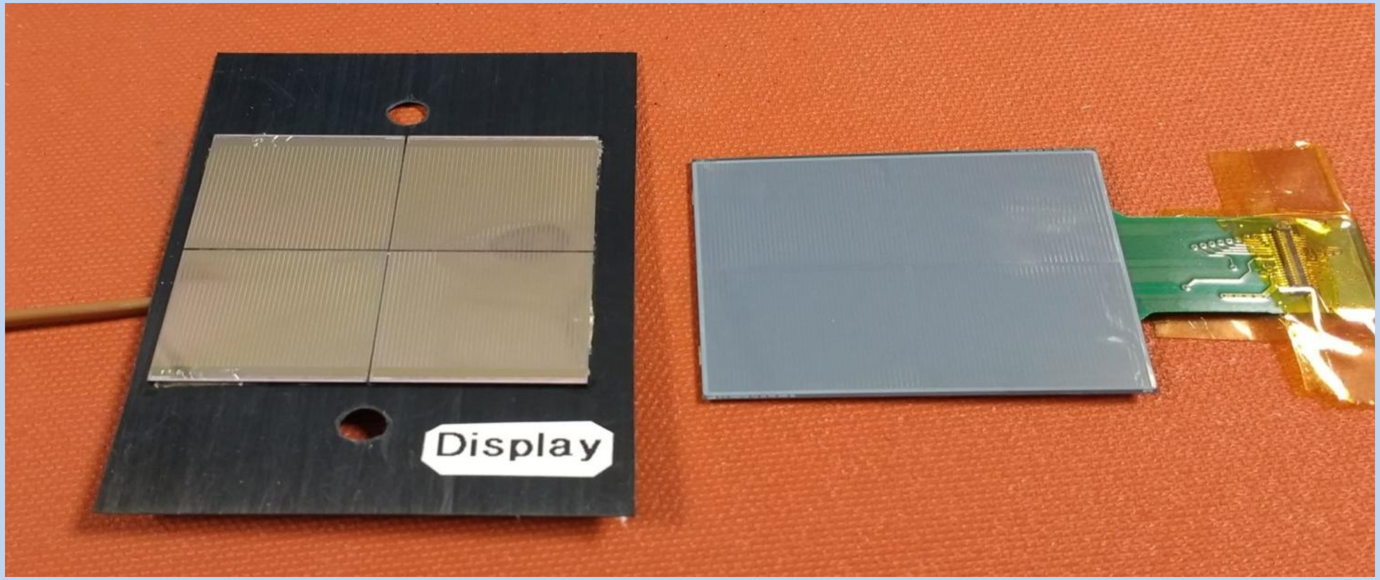
Inner system Triplets: 3x single 3D modules joined by a flexible PCB, comes in 3 flavours 1 linear and 2 rings of different radii. The sensor is ~250um thick.

Operational conditions

- Two changes from IBL driving the changes to the operational environment:
  - Vastly increased luminosity and consequently higher dose/ fluence as outlined above require more cooling power to maintain low sensor temperatures and prevent thermal runaway.
  - Higher power consumption: higher power per module due to the increased number of pixels and the ~6x increase in the area covered.
- These both mean that the detector needs much better cooling and a lower starting point to achieve the required operational temperature
  - Coolant will be delivered at -45^{o}C to achieve an operational temperature for powered modules of ~-25^{o}C, therefore unpowered modules could reach -45^{o}C
  - This is significantly colder than before
- This regime means that the stress caused by CTE mismatch in the module stack is much higher.
  - To ensure the modules perform over the whole expected lifetime a thermal cycling range of -55^{o}C -> +60^{o}C has been used for modelling and testing.
  - 100 cycles of -55^{o}C -> +60^{o}C chosen as the design verification standard

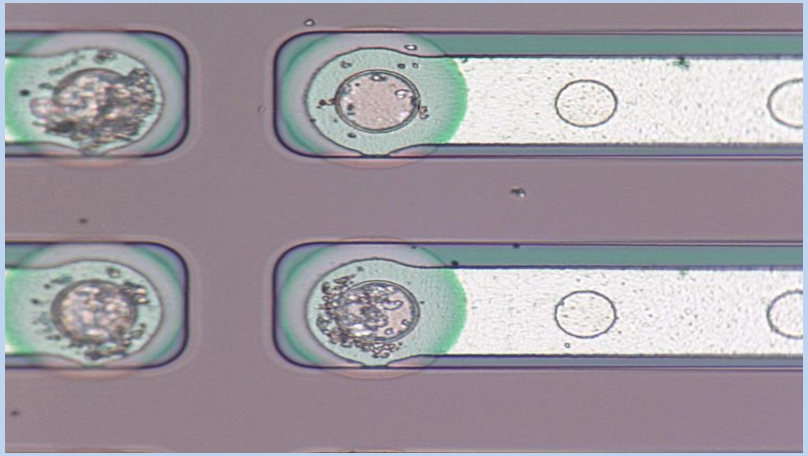
Previous generation module under ITk conditions

“The Problem”



FE-I4 module as used for the IBL, attached to carbon fibre support.

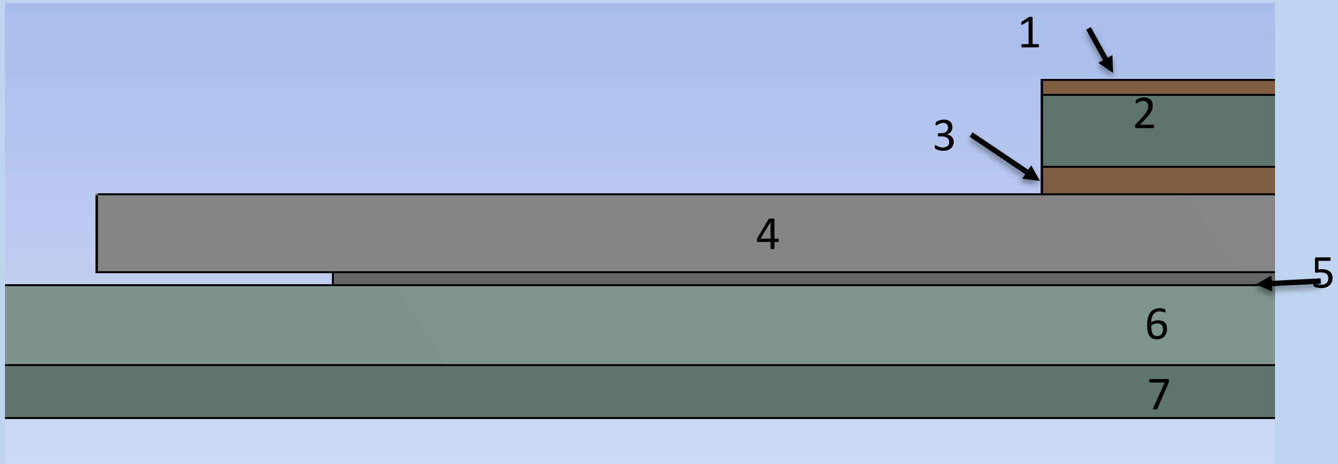
Close up on sheared bumps



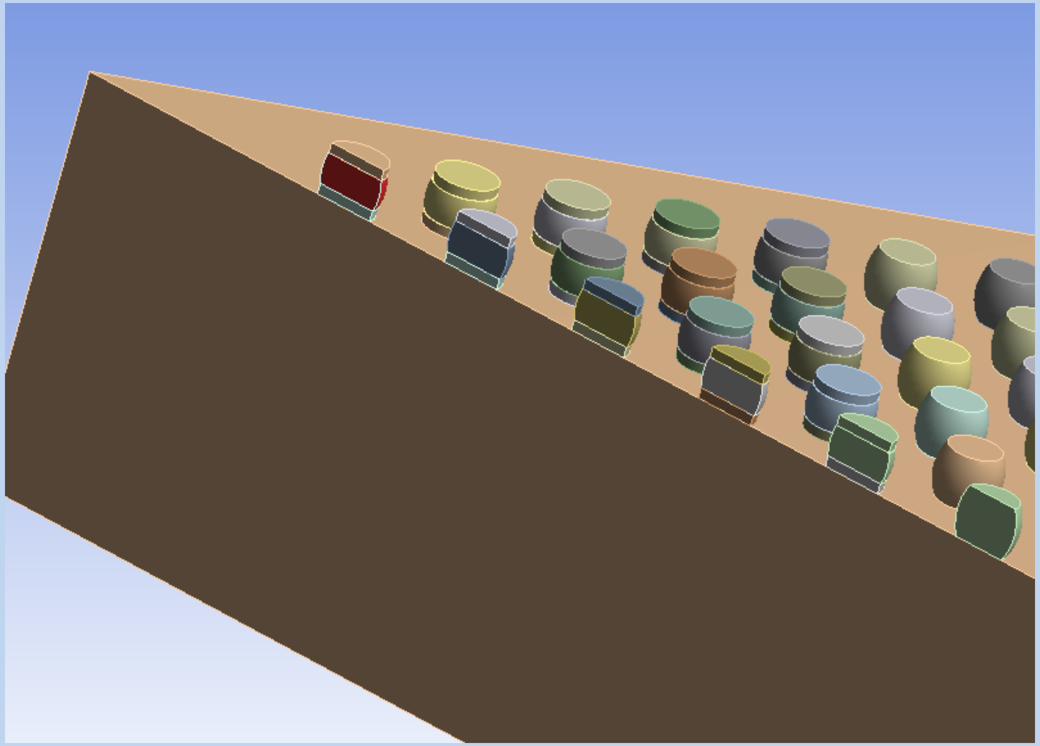
FE-I4 has pixel pitch 50x 250 μm compared to ITkPix 50x50 μm This operated successfully at -20^{o}C and failed catastrophically at -55^{o}C. The design wasn’t optimised for the larger temperature range so the shear stress caused by the CTE mismatch between the PCB and the Si/solder/Si module unzipped the bump bonds.

FEA models of Quads "The solution"

Linear models for investigating of model parameters. Variations in flex copper thickness, glue thickness, substrate properties all investigated. These models are only dealing with bumps made of SAC 305 solder



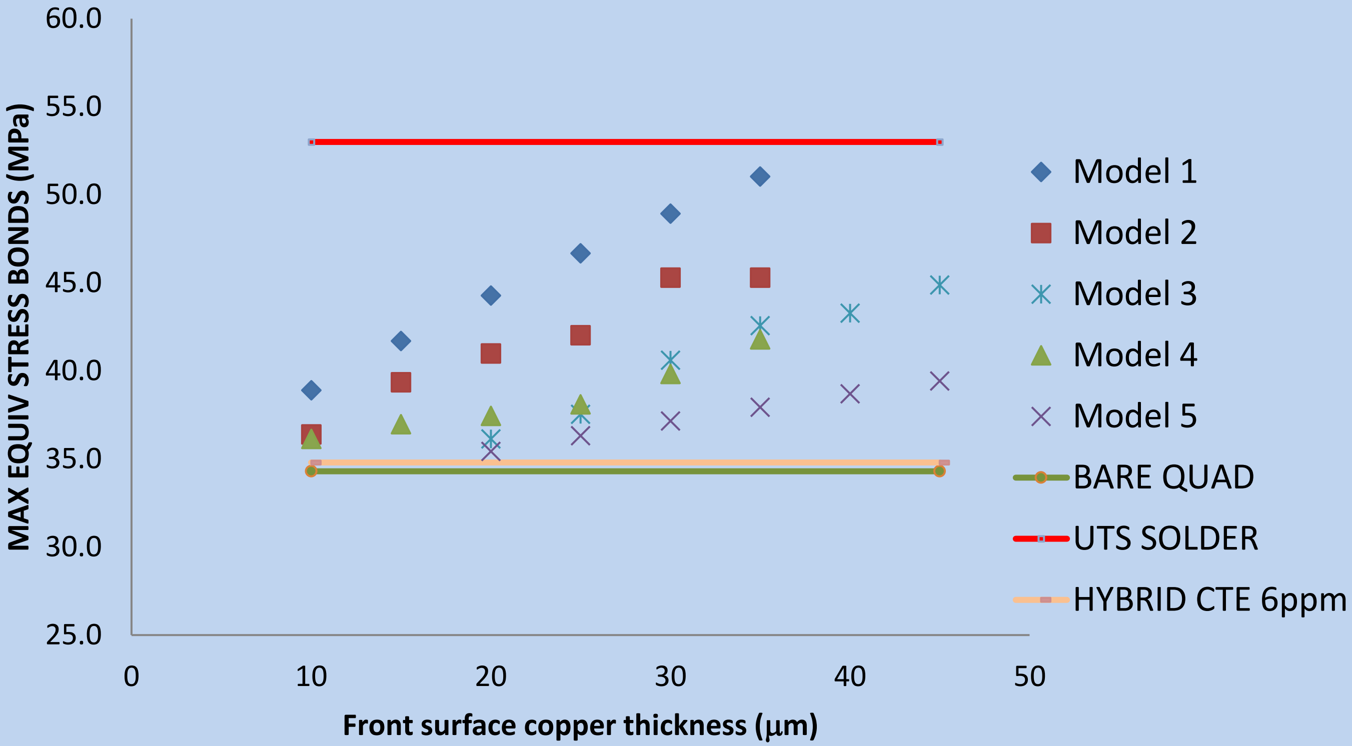
1: uniform copper layer
2: PCB substrate, polyamide
3: Adhesive layer, epoxy
4: Si Detector
5: Bump bond layer, SAC 305 solder
6: Si FE ASIC
7: Local support adhesive



Viscoplastic models for detailed stress/ strain calculations. Individual bumps modelled using symmetry and sub region modelling.

Material properties for both at end

Results of models



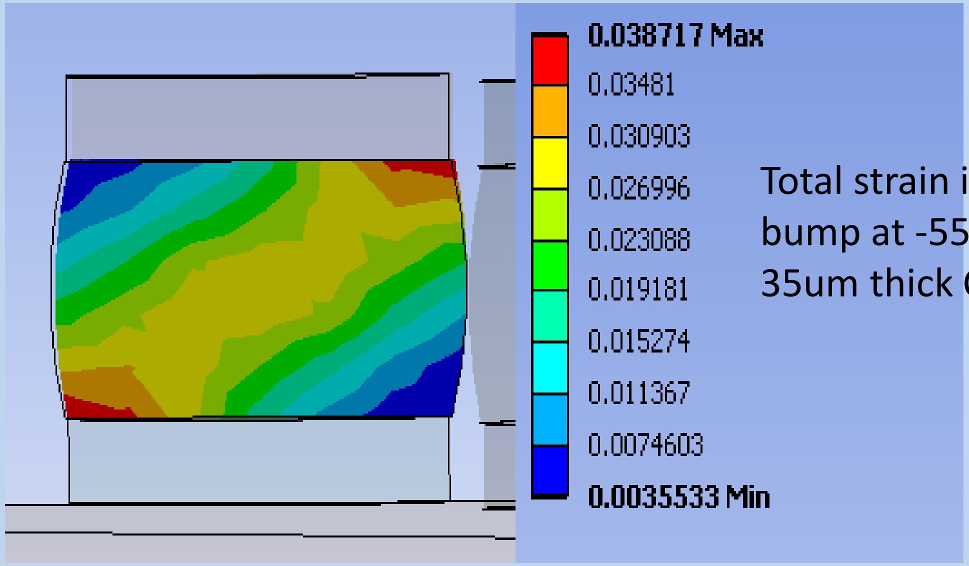
- Linear models identified copper thickness as the key parameter for bump stress.
- A range of copper thicknesses were modelled to find a suitable value.
- This used is used for viscoplastic models
- Strain range from visoplastic models used to calculate cycles to failure using Coffin-Manson law (below left)

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

where

ϵ_f' fatigue ductility coefficient,
N_f mean cycles to failure,
c fatigue ductility exponent.

Coffin-Manson law



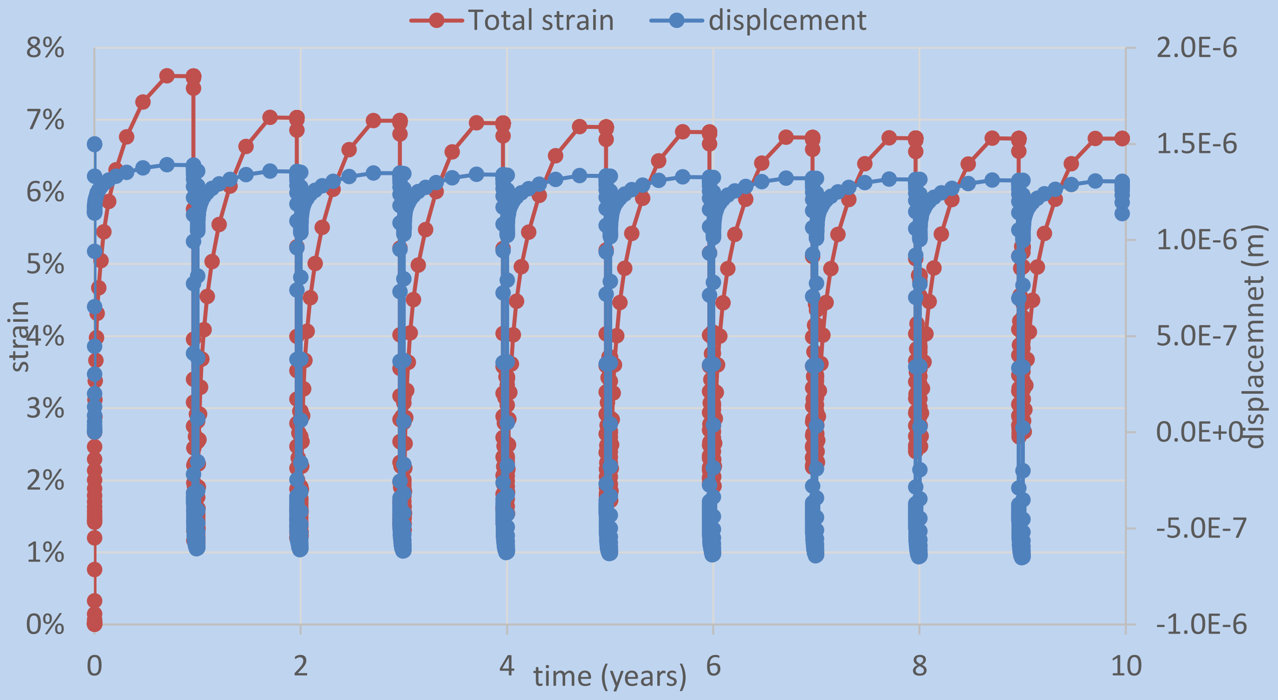
Total strain in corner bump at -55°C for 35um thick Cu layer

Results of models (2)

	Temp range (°C)		
	+60-> -55	+40-> -45	-25 -> -45
ITk Pix 25um Cu in flex with 100% fill factor	2400	7700	100,000
ITk Pix 35um Cu in flex with 100% fill factor	800	2600	35,000

Cycles to failure for calculated using the whole strain range for an ITkPix module cycled over several different temperature regimes.

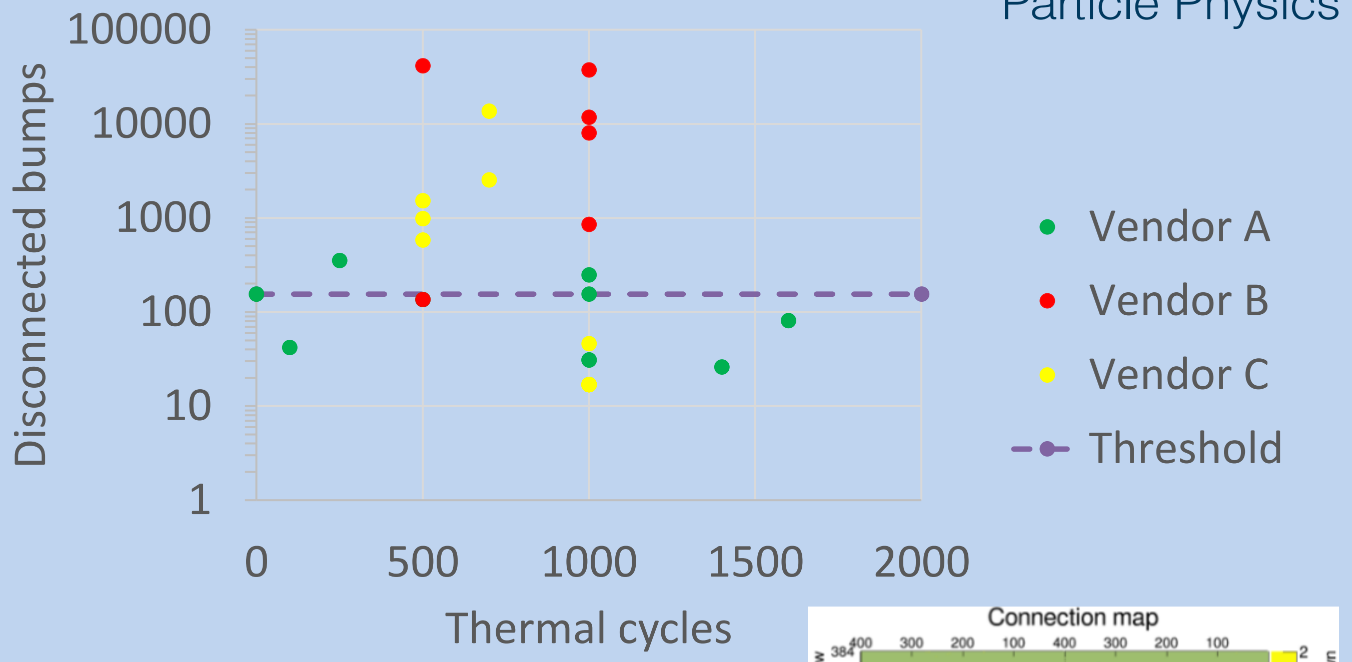
- Long term cycling models give the maximum strain range over 10 yr as 14%.
- Expected strain failure for SAC 305 solder is 24%.
- Modelling suggests that modules should survive the expected thermal cycling regimes.



<u>The maximum force per bump over all testing regimes was calculated to be 0.003N</u>

Thermal cycling of modules

Real assembled wire bonded modules attached to local support material and thermally cycled -55 -> +60°C to test for bump disconnections to verify the design. The design verification is 100 cycles with less than 0.1% additional bump delaminations.



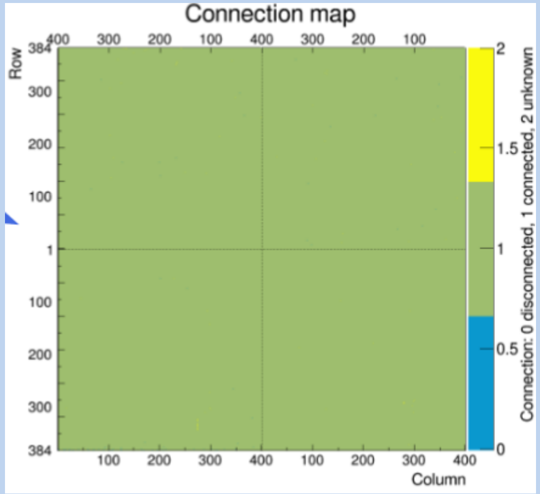
Vendor A: good quality bumps, only one failed the QA test without parylene

Vendor B: Poor bumps, showed early, and large numbers of, disconnections without parylene

Vendor C: Initial problems later modules behaved well, the majority survived QA with and without parylene

Vendor	Min. cycles to threshold	Max. cycles to threshold	
Vendor A	25-50 (1)	>1000 (5 of 10)	9 of 10 >100 cycles
Vendor B	0-10 (1)	500-1000 (1 of 6)	2 of 6 > 100 cycles
Vendor C	10-50 (2)	>1000 (2 of 13)	10 of 13 >100 cycles

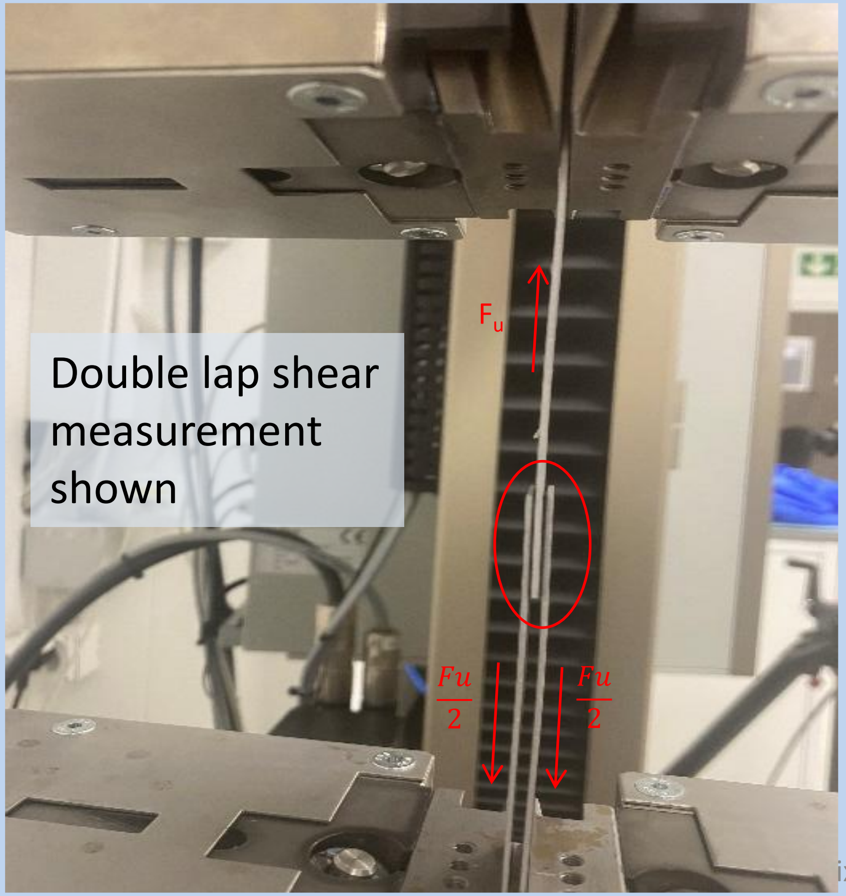
Example of a disconnected bump scan (0 disconnects)



Bump shear tests

Lap shear measurements were performed on modules from two vendors to understand the bump failures show in the previous slide.

Test	Vendor and module type	Test type	Surface prep	Ultimate bump strength (N)
1	Vendor A single-chip module	Double lap shear	A	>0.0049
2	Vendor A single-chip module	Single lap shear	B	>0.0052
3	Vendor A single-chip module	Single lap shear	C	>0.0079
4	Vendor A single-chip module	Single lap shear	D	>0.0108
5	Vendor B quad module 1st FE	Single lap shear	D	0.0056
6	Vendor B quad module 2nd FE	Single lap shear	D	0.0016



Double lap shear measurement shown

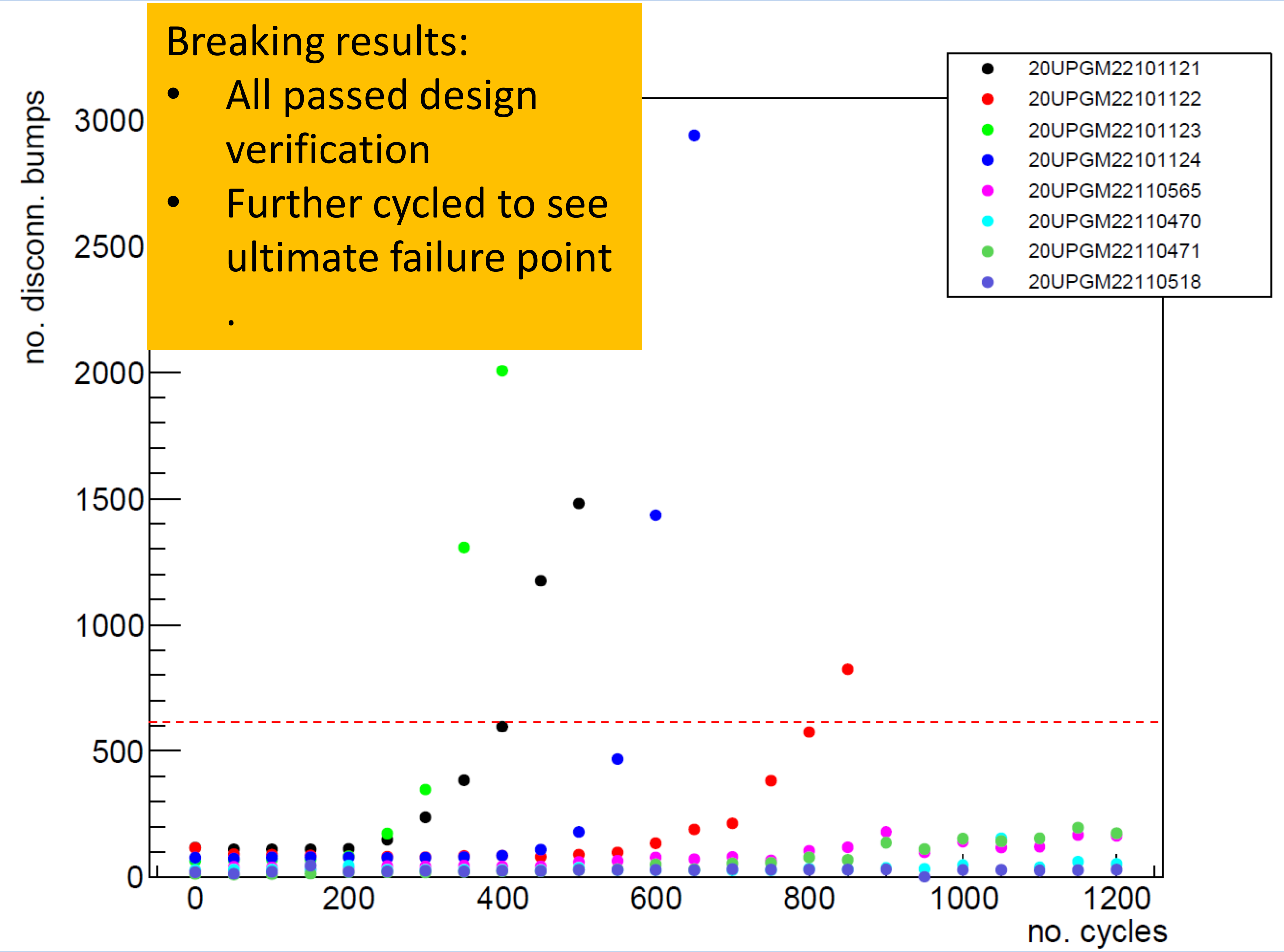
- Vendor A break occurred in adhesive layer between the Si and the test elements.
    - Sets lower limit of bump strength of 0.0108 N
- Vendor B modules shear in the bump layer at a lower level
    - These modules were not well assembled.
    - Feedback to vendor improved the quality of the bump bonding

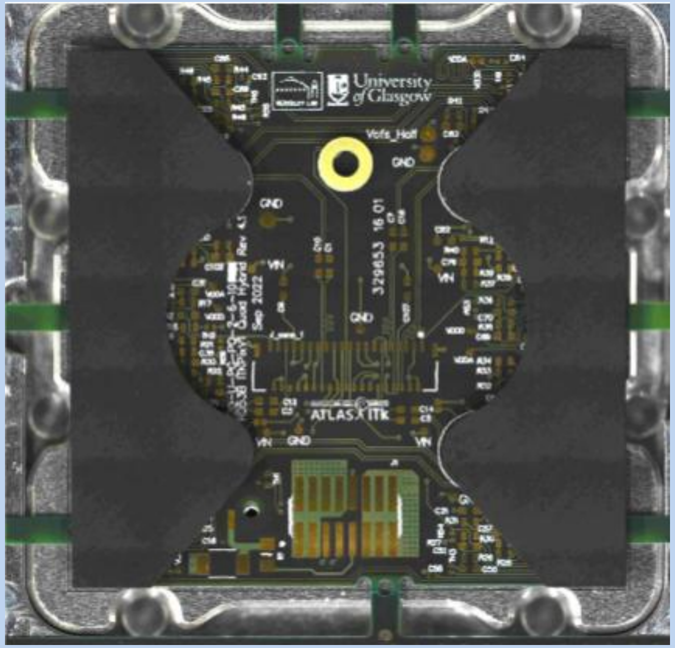
Ongoing testing and future work

After feedback to vendors more modules were produced for thermal cycling.

Breaking results:

- All passed design verification
- Further cycled to see ultimate failure point
  .





Module with wirebond protection canopy and strain relief washer attached.

- All modules survived 100 thermal cycles at CERN
  - Passed the QA/ design validation tests
- Further tests at Goettingen show minimum cycles to threshold is 400-450 for all modules.
- The spread of the start of delamination is very wide
  - This needs further investigation.

Summary

- The ITk Pixel detector is a step change in the use of pixelated detectors in Particle physics detectors
- The challenging environment makes the design very demanding
  - Higher radiation dose/ fluence
  - Higher module power requiring more aggressive cooling
- A design has been tested and verified to survive the harsh operational environment
  - Identified critical factor, Cu content of flex PCB
  - Modelled different Cu thickness to get acceptable range
  - Thermally cycled modules to validate the design
- Working with all hybridisation vendors to ensure that we receive high quality modules
  - All vendors produce modules which pass design validation
  - Looking to expand capacity by introducing new vendors/ increasing production rate
- Very close to beginning full production of ATLAS ITkPix modules

Bonus material

Material properties

Material	Density (Kgm^{-3})	Youngs modulus (GPa)	Poisson ratio	CTE ($10^{-6}/^oC$)
Copper	8300	110	0.34	18
Kapton substrate	1420	2.5	0.34	20
Glue (Araldite 2011)	1100	1.9	0.3	85
Sensor (Si)	2329	188	0.34	2.6 (temp dependent)
Bump bonds(BB) (20% fill factor)	1500	10	0.34	21
FE chip (Si)	2329	188	0.34	2.6 (temp dependent)
Base adhesive (where used)	1100	1.9 (0.1->8)	0.34	85

Viscoplastic properties

Parameter	Value
Density (Kg/m³)	7500
Young's modulus (GPa)	51
Poisson's ratio	0.36
CTE (ppm/C)	23.5
Initial Deformation Resistance So (Mpa)	2.15
Activation Energy Q/Universal Gas Constant R	9970
Pre-exponential Factor A	1.80E+07
Multiplier of Stress ξ	3.50E-01
Strain Rate Sensitivity of Stress m	1.53E-01
Hardening/Softening Constant ho (MPa)	1530
Coefficient for Deformation Resistance Saturation Ŝ (Mpa)	2.54
Strain Rate Sensitivity of Saturation (Deformation Resistance) n	0.028
Strain Rate Sensitivity of Hardening or Softening a	1.69

Anand model for SAC 305 solder which models the time and temperature dependence of the solder.

Calculation of the cycles to failure

- Coffin–Manson law allows calculation of the cycles to failure based on the total strain (elastic+plastic+thermal) range, $\Delta\gamma$, over the thermal cycle.
- This is used here to predict the cycles

to failure of 50% of the corner most bumps

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

where

ϵ_f' fatigue ductility coefficient,
N_f mean cycles to failure,
c fatigue ductility exponent.

- This was later modified to take into account the effect of different cycle parameters

$$2\epsilon_f' \approx 0.65$$

and

$$c = -0.442 - 6 \times 10^{-4}\bar{T}_S + 1.74 \times 10^{-2} \ln(1+f),$$

where

$\bar{T}_S$ mean cyclic solder joint temperature, °C,
f cyclic frequency, $1 \leqslant f \leqslant 1000$ cycles/day.

232 IEEE TRANSACTIONS ON COMPONENTS, HYBRIDS, AND MANUFACTURING TECHNOLOGY, VOL. CHMT-6, NO. 3, SEPTEMBER 1983

Fatigue Life of Leadless Chip Carrier Solder Joints During Power Cycling

WERNER ENGELMAIER