Electrical Defects in Co-cured Bus-Tapes and Quality Control Strategies

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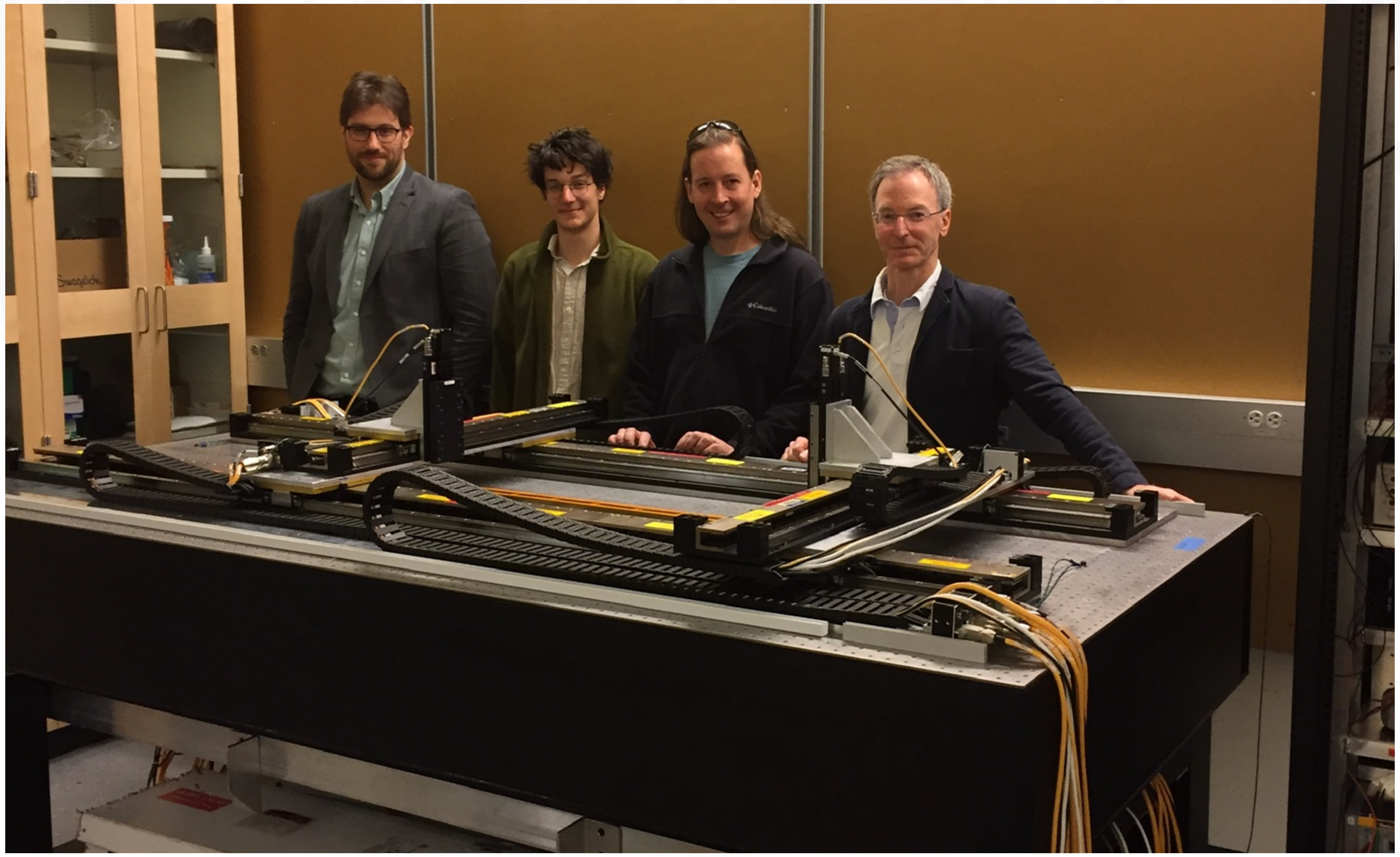
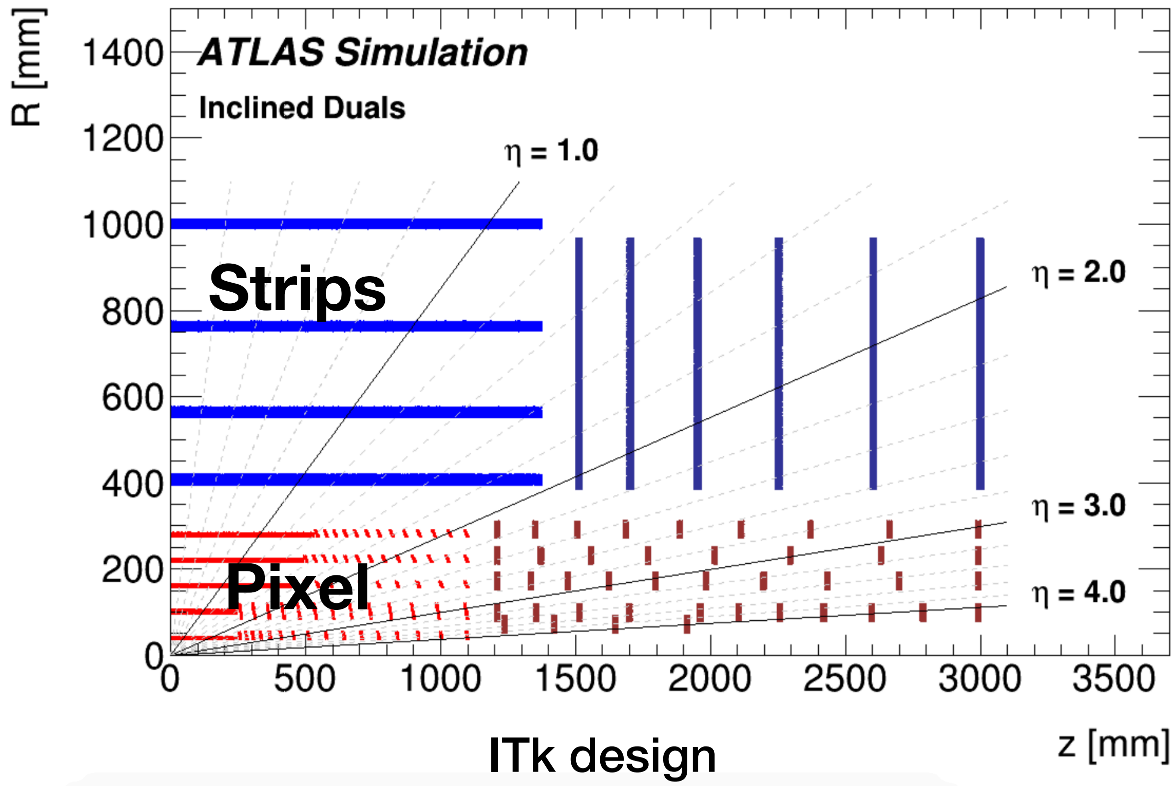
Outline

- Introduction to ATLAS ITk Strips detector
- Local support structures
- Bus-tape overview and design
- Observed bus-tape defects
- Quality control strategies

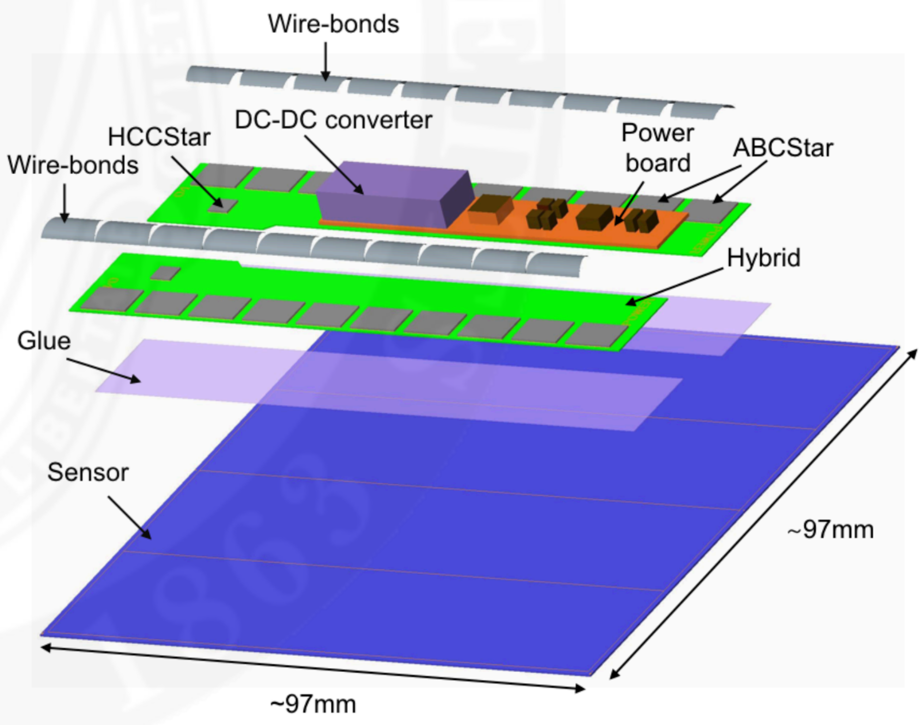


(Very) Brief Introduction to ITk Strip Detector

- Current ATLAS Inner Detector will be replaced with new all-silicon Inner Tracker (ITk) to accommodate tracking and radiation conditions at HL-LHC
- ATLAS ITk consists of pixel detector at small radius and a large-area **strip tracking detector** surrounding it
- Strips detector consists of silicon modules mounted on local support structures
- Strip modules:
  - Basic detector unit consisting of silicon sensor, a hybrid circuit hosting read-out ASICs, and a power board
  - Adhesively attached to local support structure and electrical connections made via wire-bonding



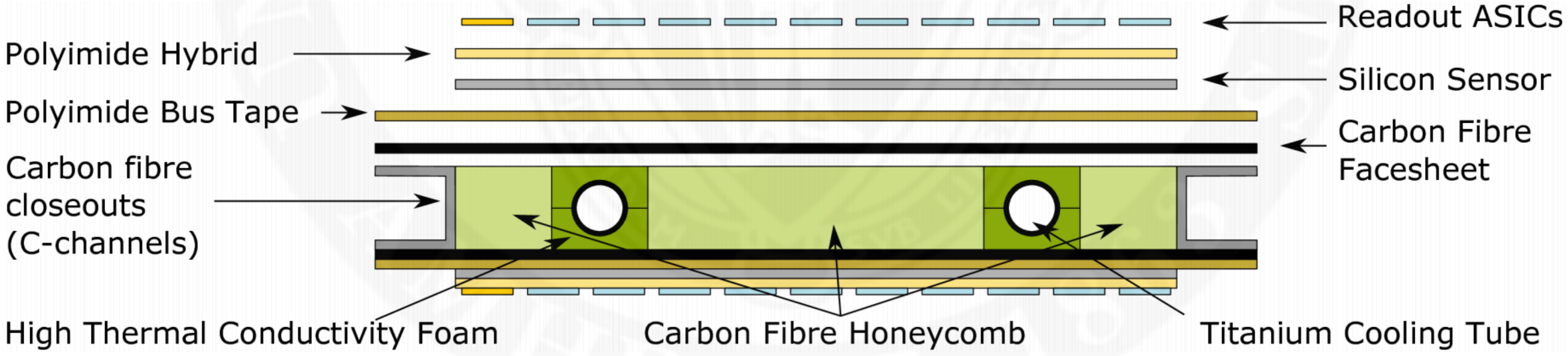
ITk design



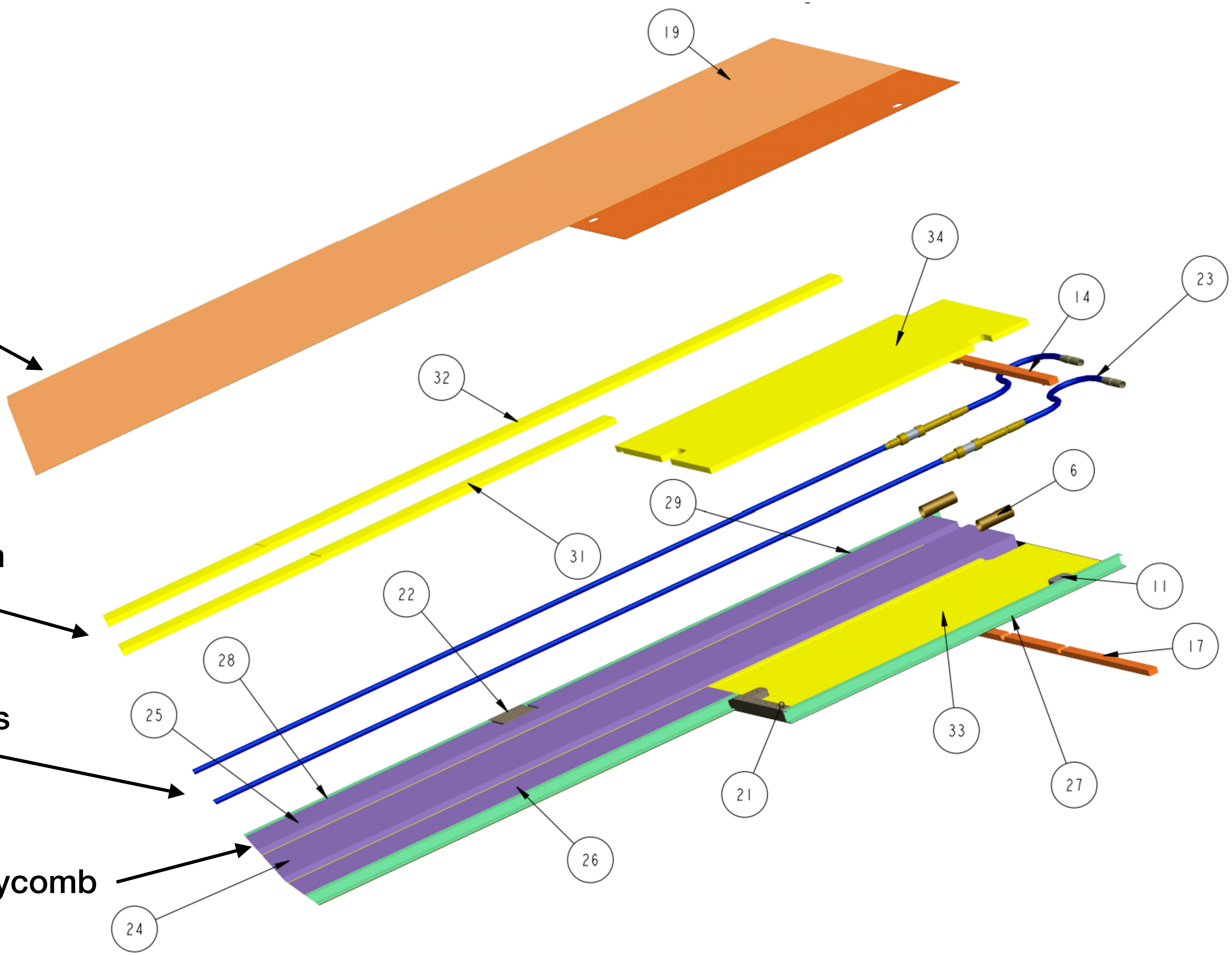
Strips module design

Local Support Structures

- Local support structures: stave cores (barrel) and petal cores (end cap)
  - Formed from two CF face-sheets, which sandwich a core that is made from cooling components and low-density CF honeycomb
  - Provide mechanical, thermal, and electrical support to modules
    - Electrical power and data transfer services carried by a copper/polyimide **bus-tape** mounted on both sides of structure and operated by EoS (End of Substructure) card
  - Modules adhesively attached to the two faces and electrical connections between the read-out hybrids and the bus-tape will be made via wire-bonding
  - 14 (9) modules mounted on each side of stave (petal)
- 392 stave cores and 384 petal cores to be installed in ITk



Local Support Structures



Bus-Tape

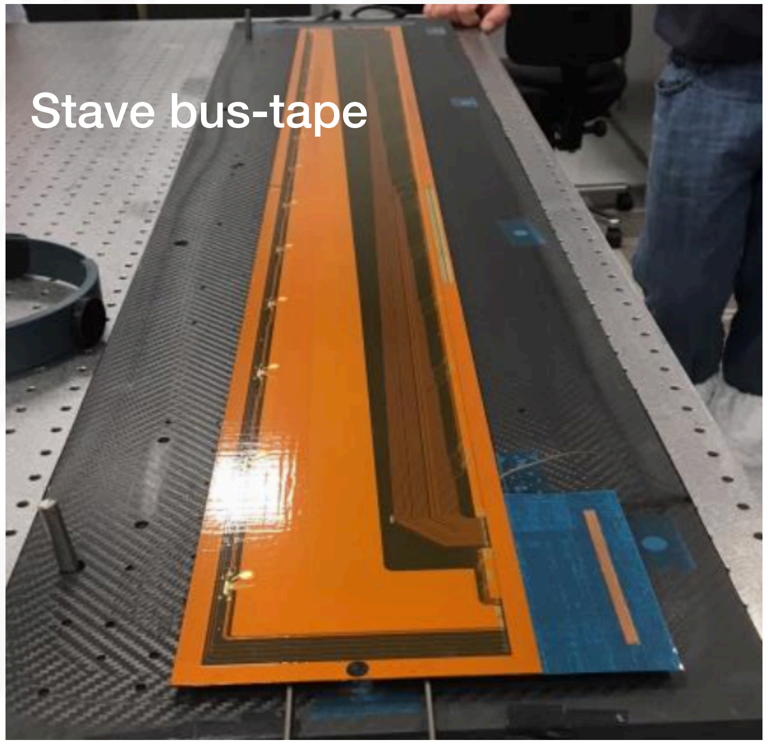
Carbon Foam

Cooling Tubes

Carbon Honeycomb

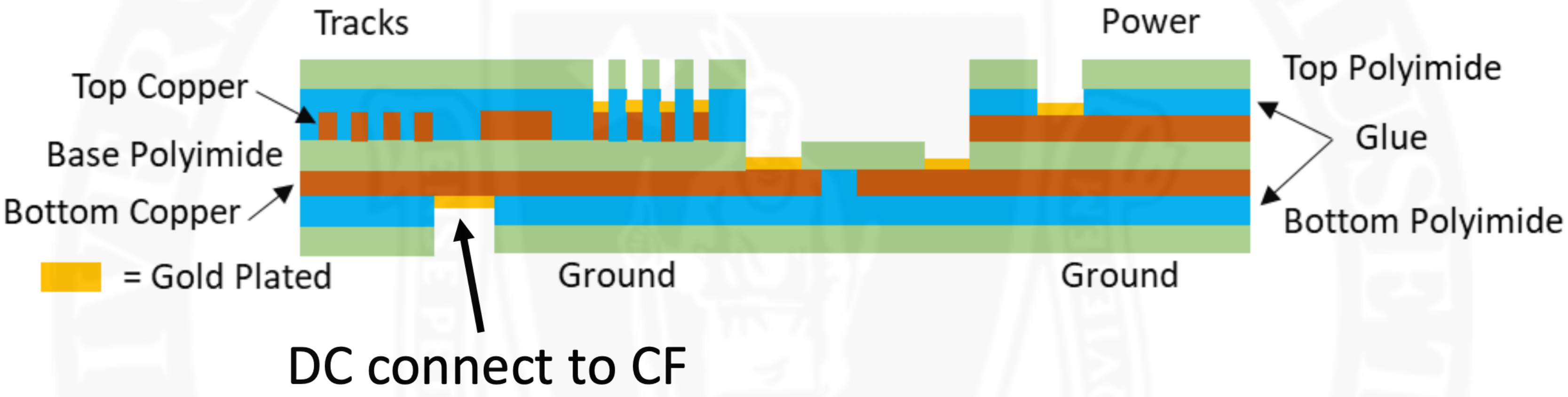
Bus-Tapes: Functionality

- The purpose of the bus tapes is to:
  - provide electrical power (low voltage DC (10-11V) and high voltage DC (up to 750V)) to the modules
  - transfer TTC (Timing, Trigger and Control) and measured data between the EoS and the hybrids
  - provide control data to the power boards
- Specifications:
  - Round-trip voltage drop for low-voltage lines < 1 V
  - High Voltage Insulation Resistance (HVIR) between neighboring HV lines > 1 GΩ
- Identical technologies will be used for the barrel stave and petal bus-tapes

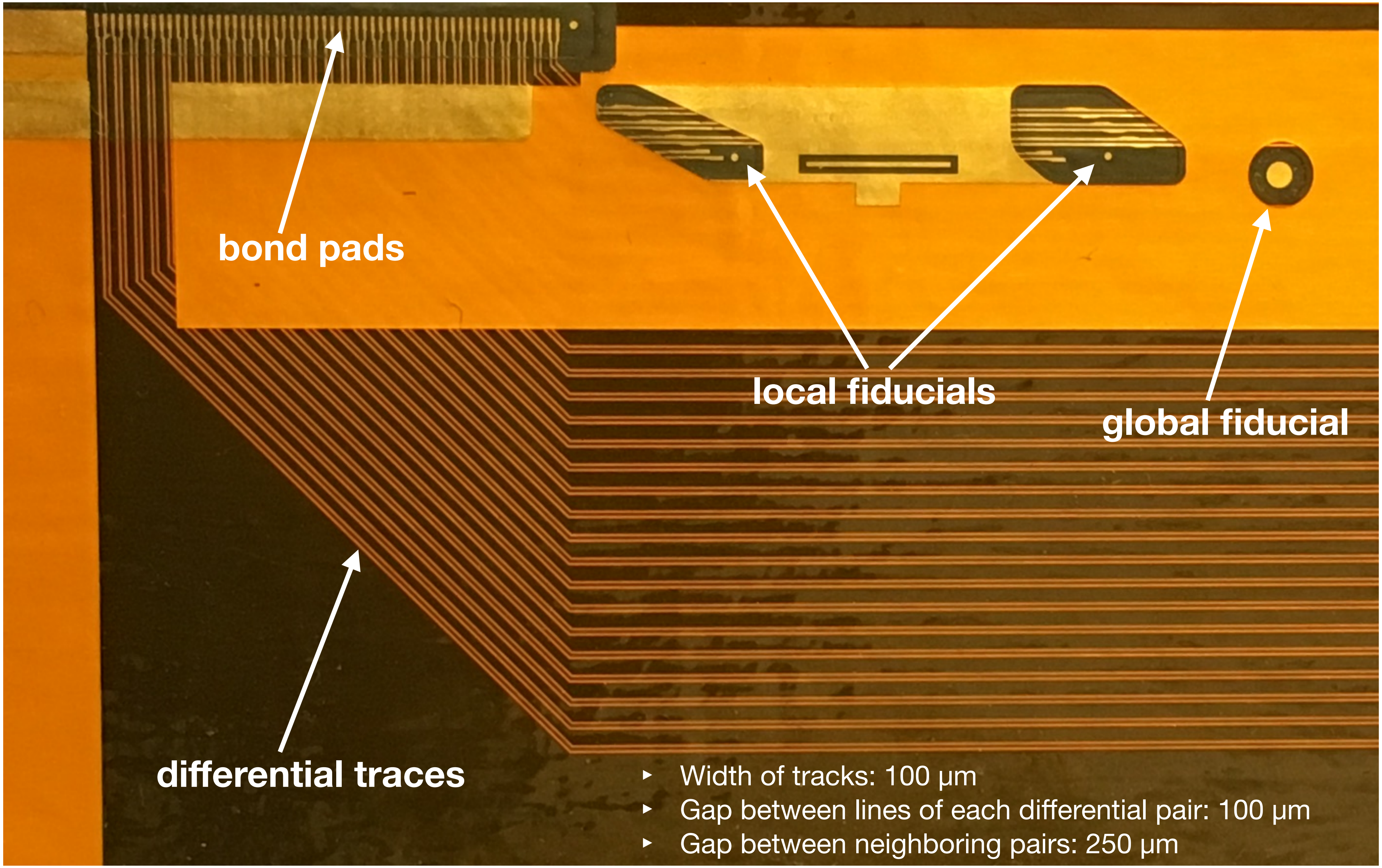


Bus-Tapes: Design

- Bus-tapes are made from two layers of adhesive-less copper/polyimide
- Differential lines to transfer high-speed (640 Mbps) data from the hybrids to the EoS
- Openings cut in cover layer around pads to allow standard nickel-gold plating for wire bonding hybrids to the tape
- Global and local fiducials included in tape design for QC testing



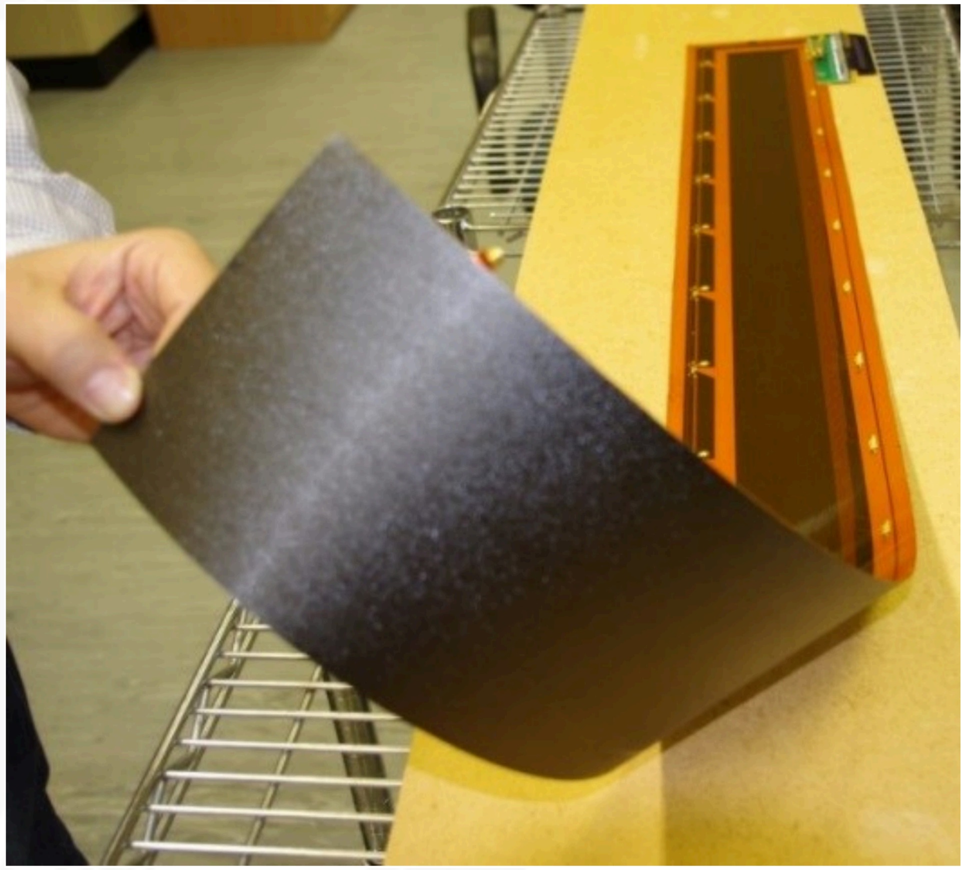
EoS Region on Bus-Tape



- Width of tracks: 100 µm
- Gap between lines of each differential pair: 100 µm
- Gap between neighboring pairs: 250 µm

Co-curing

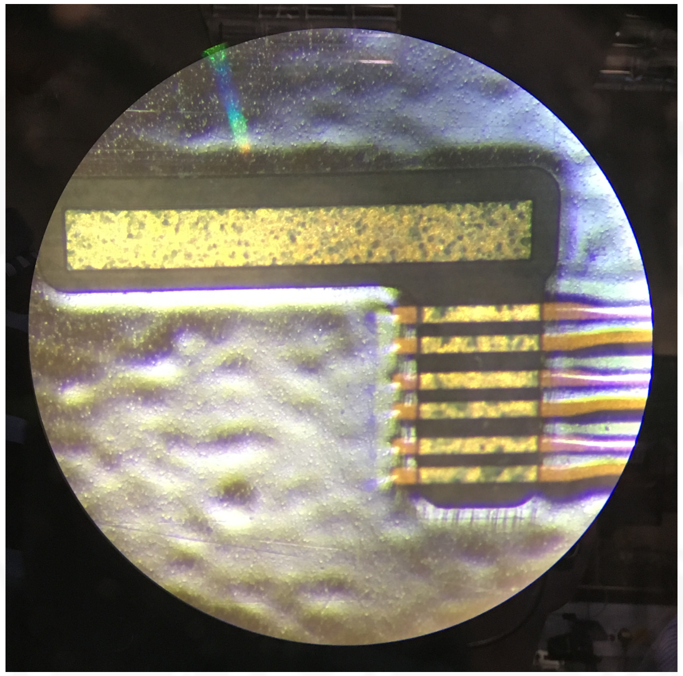
- The bus tapes will be co-cured with three layers of carbon fibre to produce the face sheets which are then mounted on both faces of the local support sandwich
- Co-curing the tape provides:
  - mechanical stability
  - thermal dissipation
  - electrical grounding
- Co-curing done in an autoclave at 120°C and 7 bar
- Bus-tape for the stave expands by as much as 0.5 mm after co-cure

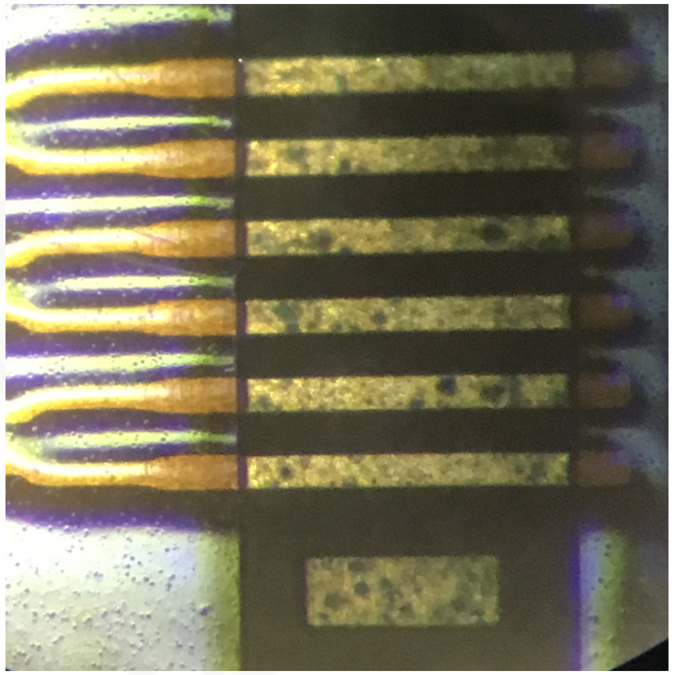


- Tapes are cut with a 10 mm sacrificial rim to prevent resin from creeping around the edge of the tape and onto sensitive areas (bond pads)

Bus-Tape Defects & Consequences

- Several failure modes have been observed in the bus-tapes:
  - Open circuits
  - Short circuits
  - Poor pad quality

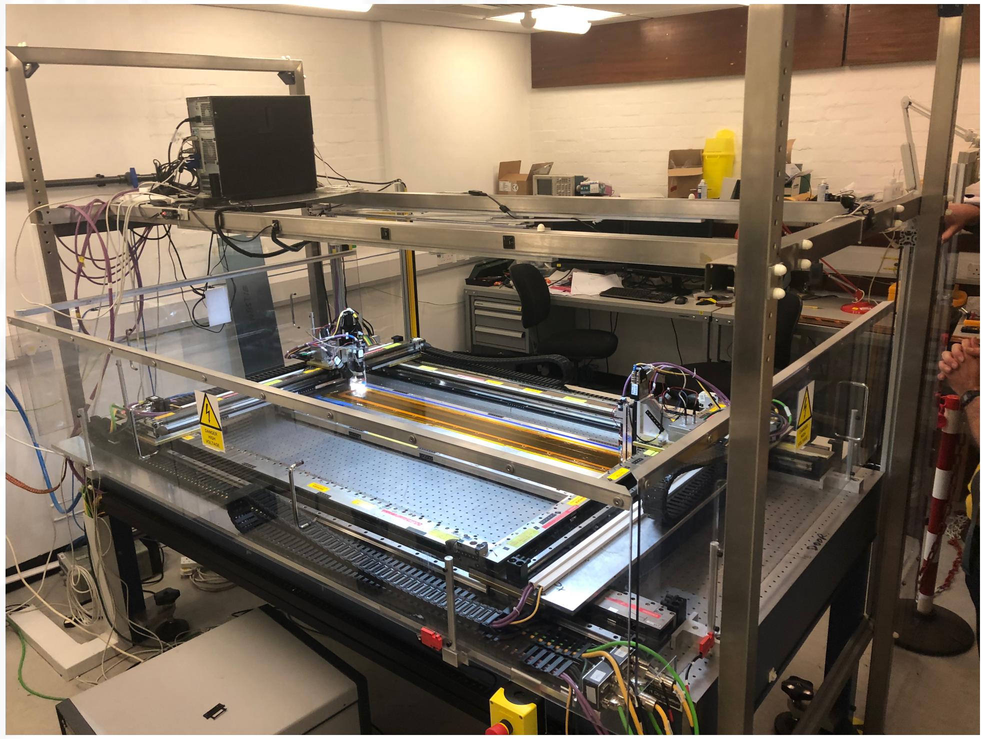




- Consequences:
  - A crack on a TTC line would result in the loss of physics data from up to 10 hybrids
  - In the worst case, this could make one side of a stave/petal inoperable
- Co-curing can introduce defects due to different thermal expansion between the tape material and the carbon fiber
  - Important to test all tapes at multiple stages during production

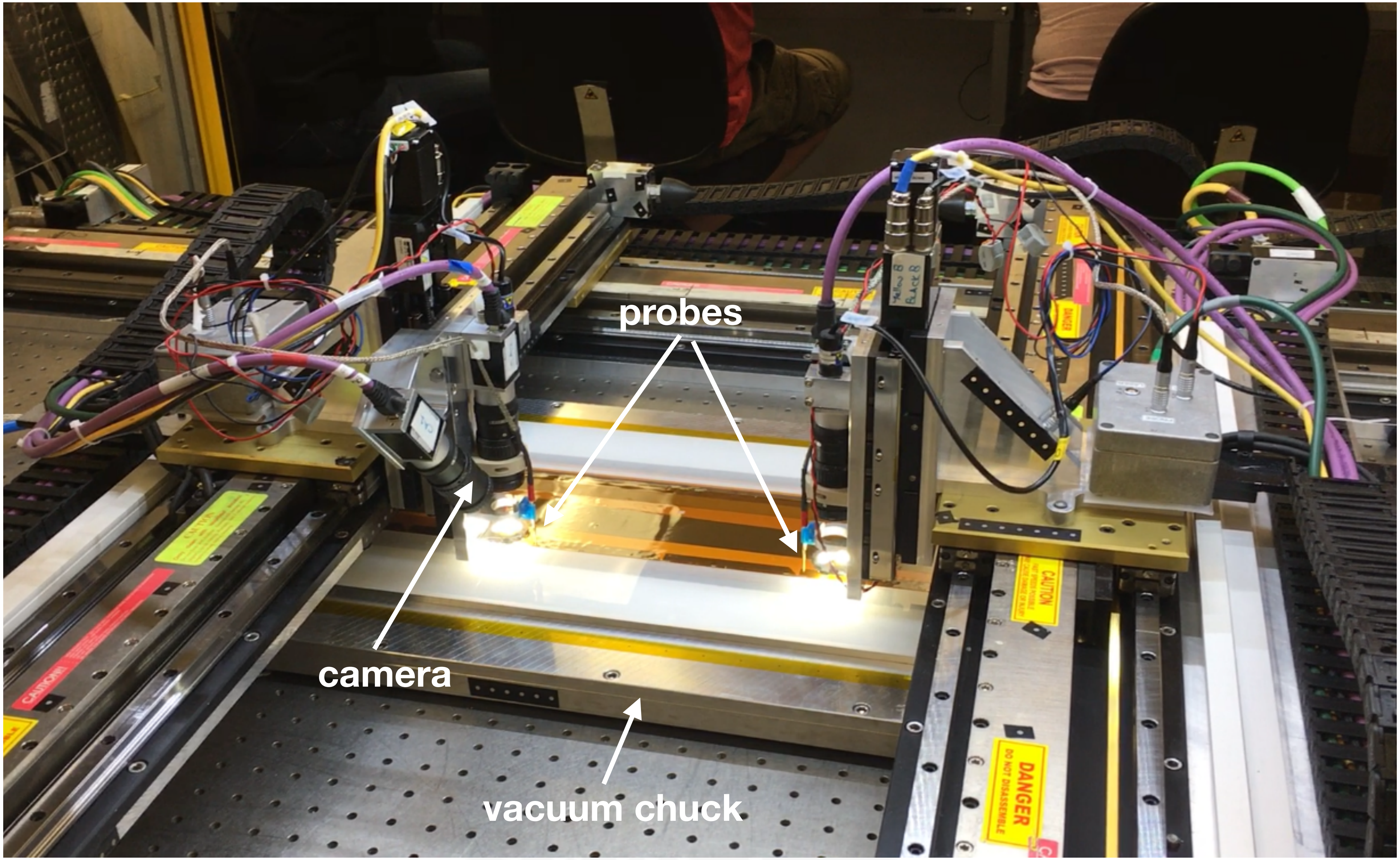
Tape Testing Robot

- A fully automated system has been developed by Roy Wastie at Oxford to perform QC testing of all bus-tapes
  - Due to distributed stave/petal core production, identical systems being built at UMass Amherst, DESY, and Ljubljana
  - Staves: Oxford/Yale, Petals: DESY/Ljubljana
- Design:
  - 2 independent probe heads on a gantry system with cameras for alignment
  - XY position control by linear stages, 5 μm resolution
  - Z position controlled by stepper motor, 1 μm resolution
  - Tape held down by vacuum chuck
- Test performed in multiple production stages:
  - Bare tape
  - After co-cure to carbon-fibre skin
  - After assembly into full mechanical stave/petal



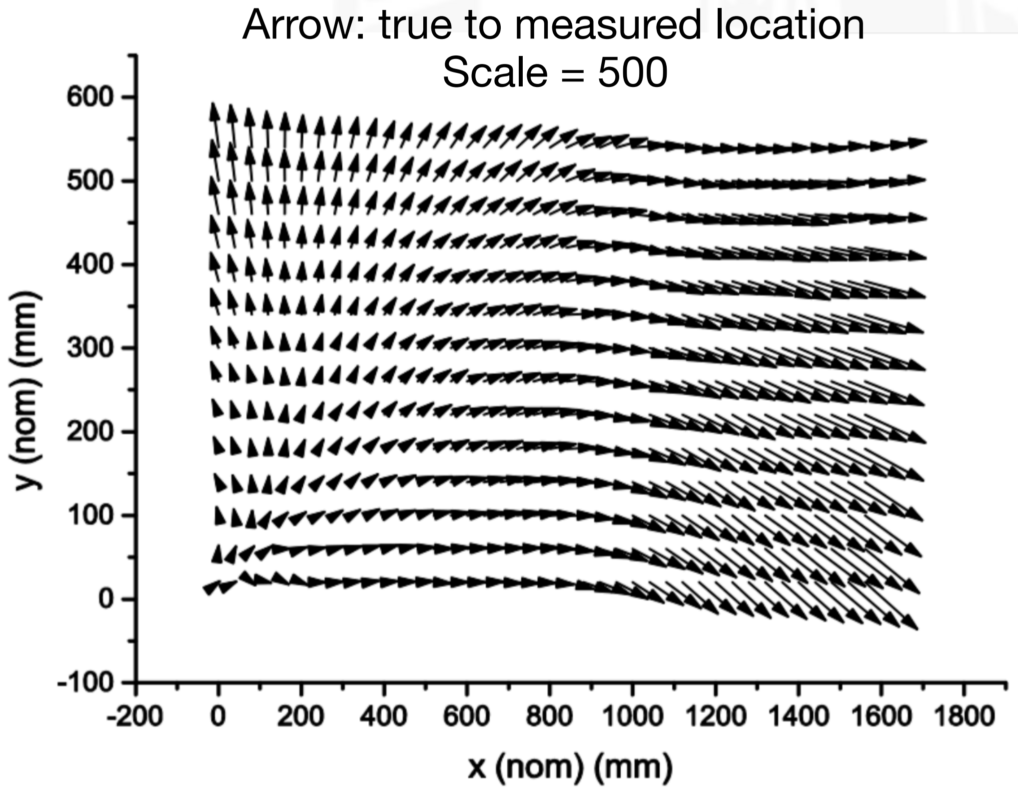
Oxford robot

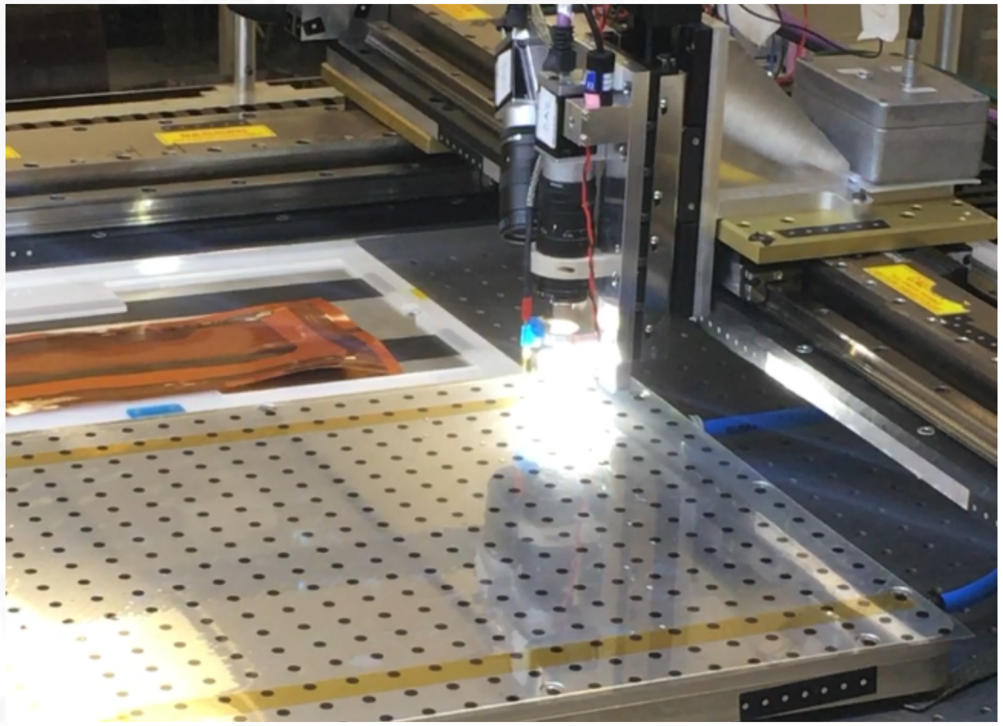
Oxford Tape Testing Robot



Stage Calibration

- Need to calibrate stages to achieve sufficient probe positioning precision
- Procedure:
  - Use a calibration plate with 2cm×2cm grid of black dots in regular pattern covering the full area of the vacuum chuck
  - Measure positions of circles in nominal stage coordinates using image finding software
  - Generate look up table of corrections from stage to real coordinates using linear interpolation
- Offsets between robot position and real coordinates up to ~200μm
  - larger than the size of the bond-pads, so calibration is necessary

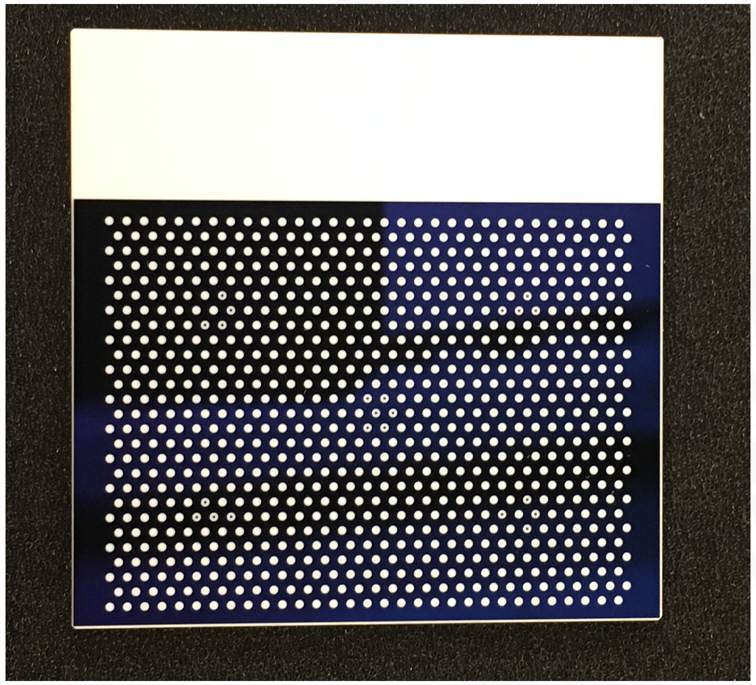




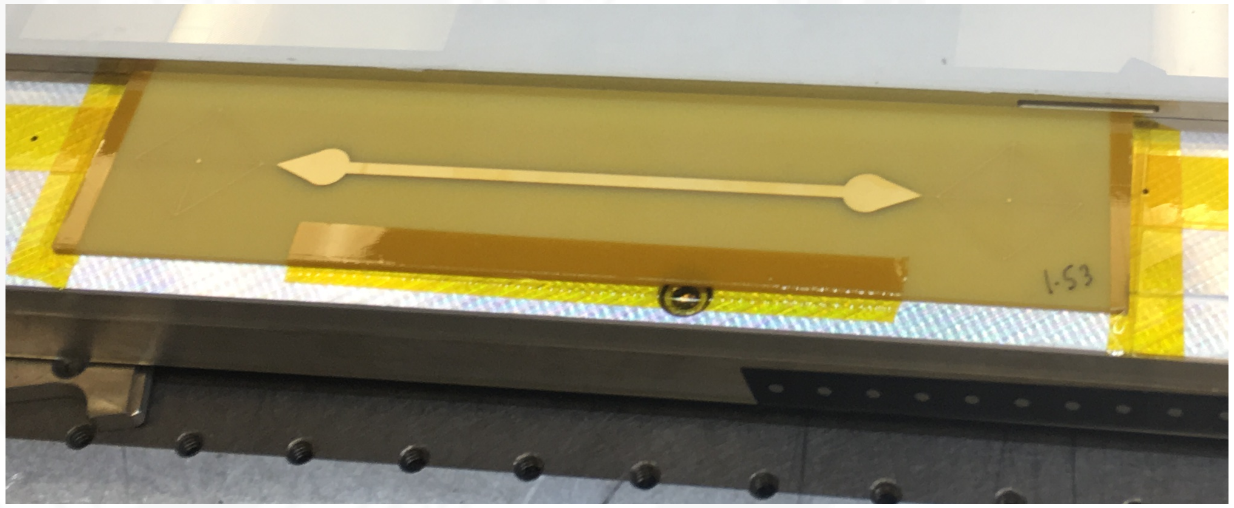
Roy Wastie, Oxford

Camera Calibration

- Need to calibrate camera to transform pixels into world coordinates
  - Uses calibration plate and image recognition software
- Need to calculate offset of the probe position from the camera image center
  - Uses a custom PCB with fiducials and copper traces



Camera calibration plate



Camera to probe calibration PCB

Probe Positioning

- Position of features on tape can vary from nominal location by more than 100µm
  - caused by the flexibility of the Kapton material during the lamination process or expansion during co-curing
  - Displacements are same size as the bond pads, would make probing impossible
- Local fiducials necessary for positioning the probes
- Probe positioning procedure:
  - Map nominal pads locations (from CAD file) to stage coordinates
  - Additional correction using local fiducials to allow for tape distortions
  - Include camera-probe offset

Tape Testing Robot: Probe View

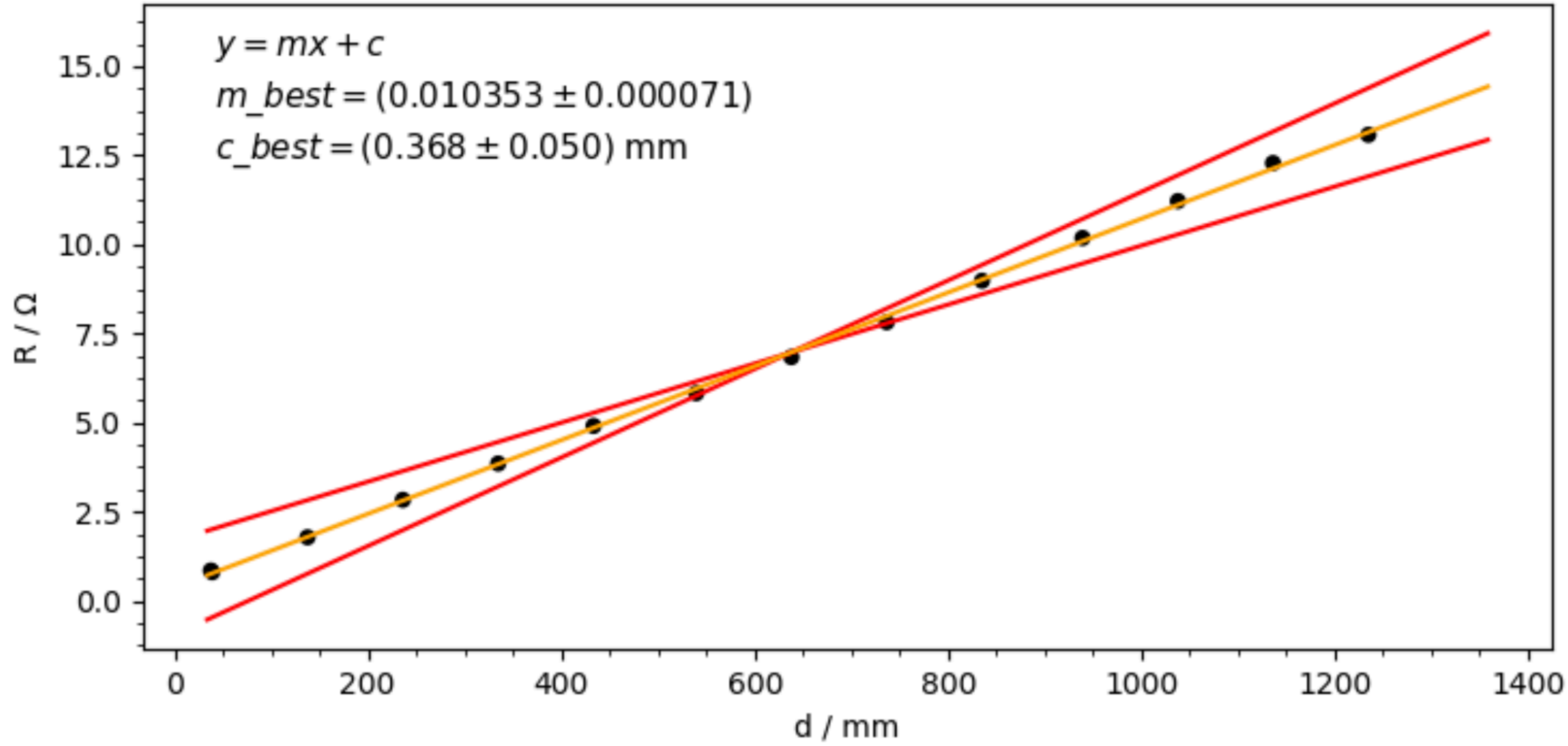
Testing Procedure

1. Find tape position on table using robot cameras and global tape fiducials
2. Measure local fiducials to determine tape deformations
   - Location of bond pads with respect to bus tape center should be within 300 µm of the nominal locations
3. Position probe heads on tape
4. Perform electrical tests
   - Measures resistance between pads on all networks of the tape
   - Checks for open/short circuits
   - HV insulation resistance testing >1GΩ
     - voltage equal to twice the maximum voltage required in operation
5. Repeat from step 3 for all networks

Tests each tape in less than 1 hour

Test Results

- For each network of LV lines a fit of resistance versus length will be made and an upper limit on the slope will be used as part of the QC
- For the power lines, the QC will simply use an upper limit on the resistance measured



Test Results: Open Circuits

- Hairline cracks in networks can cause open circuits
- Test results show very high resistance in affected areas

No Defect

Net	X [mm]	Y [mm]	Distance [mm]	Reading [Ω]
+DATA27	46.145	108.388	16.032	0.3
+DATA26	57.895	108.388	28.382	0.4
+DATA25	144.145	108.388	55.077	0.7
+DATA24	155.895	108.388	67.427	0.9
+DATA23	242.145	108.388	154.277	1.8
+DATA22	253.895	108.388	166.627	1.9
+DATA21	340.145	108.388	253.477	2.8
+DATA20	351.895	108.388	265.577	3.0
+DATA19	438.145	108.388	352.427	3.9
+DATA18	449.895	108.388	364.777	4.0
+DATA17	536.145	108.388	451.877	4.8
+DATA16	547.895	108.388	464.227	5.0
+DATA15	634.145	108.388	555.677	6.0
+DATA14	645.895	108.388	567.777	6.1
+DATA13	732.145	108.388	654.627	7.0
+DATA12	743.895	108.388	666.977	7.1
+DATA11	830.145	108.388	754.077	7.9
+DATA10	841.895	108.388	766.427	8.2
+DATA9	928.145	108.388	853.277	9.2
+DATA8	939.895	108.388	865.627	9.1
+DATA7	1026.145	108.388	955.177	10.1
+DATA6	1037.895	108.388	967.527	10.3
+DATA5	1124.145	108.388	1054.127	11.2
+DATA4	1135.895	108.388	1066.477	11.6
+DATA3	1222.145	108.388	1153.327	12.1
+DATA2	1233.895	108.388	1165.927	12.3
+DATA1	1320.145	108.388	1252.777	13.5
+DATA0	1331.895	108.388	1265.127	14.0

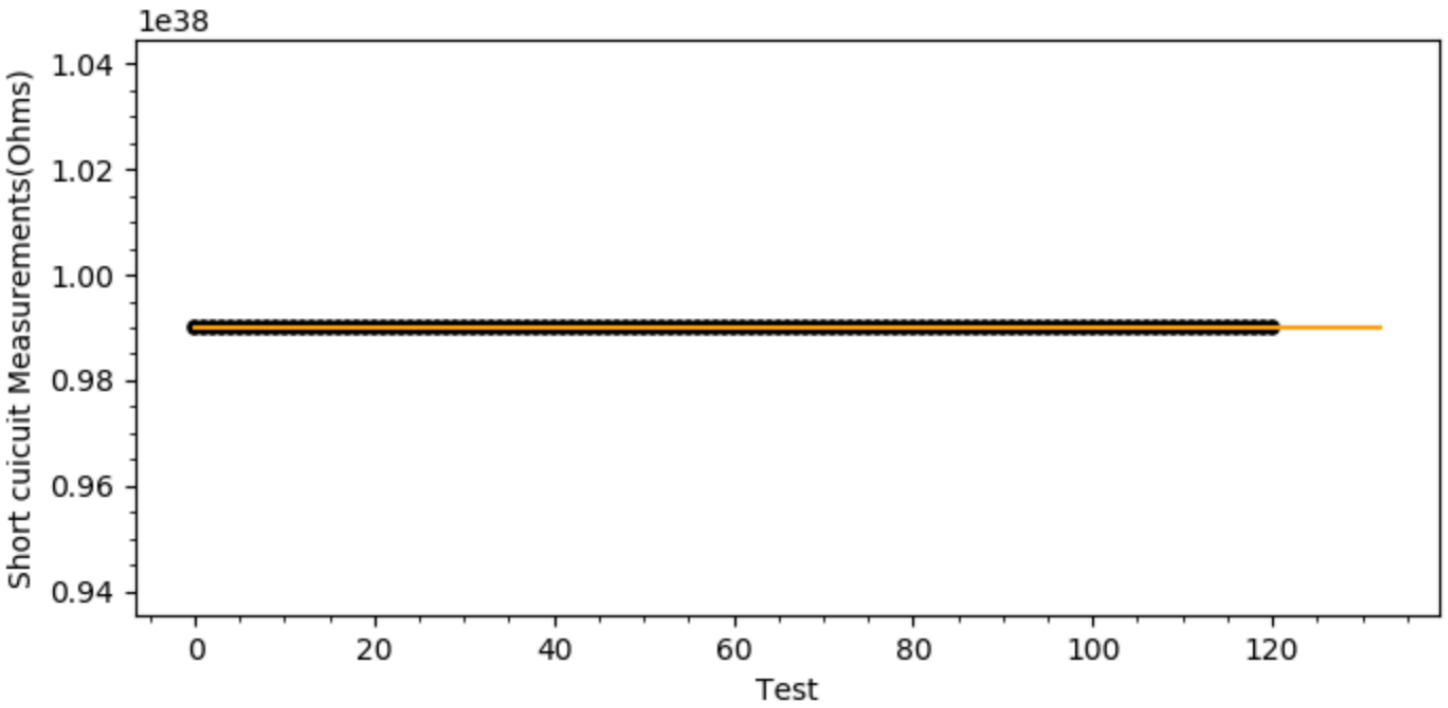
Defect

Net	X [mm]	Y [mm]	Distance [mm]	Reading [Ω]
-DATA26	-12.395	1.625	12.025	0.4
-DATA27	-11.795	1.625	24.375	0.6
-DATA25	66.617	6.412	52.049	0.9
-DATA24	78.367	6.412	64.399	1.0
-DATA23	164.617	6.412	151.249	1.7
-DATA22	176.367	6.412	163.599	2.0
-DATA21	262.617	6.412	250.449	2.7
-DATA20	274.367	6.412	262.549	2.9
-DATA19	360.617	6.412	349.399	3.8
-DATA18	372.367	6.412	361.749	3.9
-DATA17	458.617	6.412	448.849	4.8
-DATA16	470.367	6.412	461.199	5.0
-DATA15	556.617	6.412	552.649	5.9
-DATA14	568.367	6.412	564.749	6.1
-DATA13	654.617	6.412	651.599	6.9
-DATA12	666.367	6.412	663.949	7.1
-DATA11	752.617	6.412	751.049	7.9
-DATA10	764.367	6.412	763.399	8.2
-DATA9	850.617	6.412	850.249	8.9
-DATA8	862.367	6.412	862.599	9.0
-DATA7	948.617	6.412	952.149	10.0
-DATA6	960.367	6.412	964.499	10.2
-DATA5	1046.617	6.412	1051.099	989999999999999993426744560981400092672.0
-DATA4	1058.367	6.412	1063.449	11.2
-DATA3	1144.617	6.412	1150.299	12.2
-DATA2	1156.367	6.412	1162.899	12.3
-DATA1	1242.617	6.412	1249.749	13.3
-DATA0	1254.367	6.412	1262.099	13.3

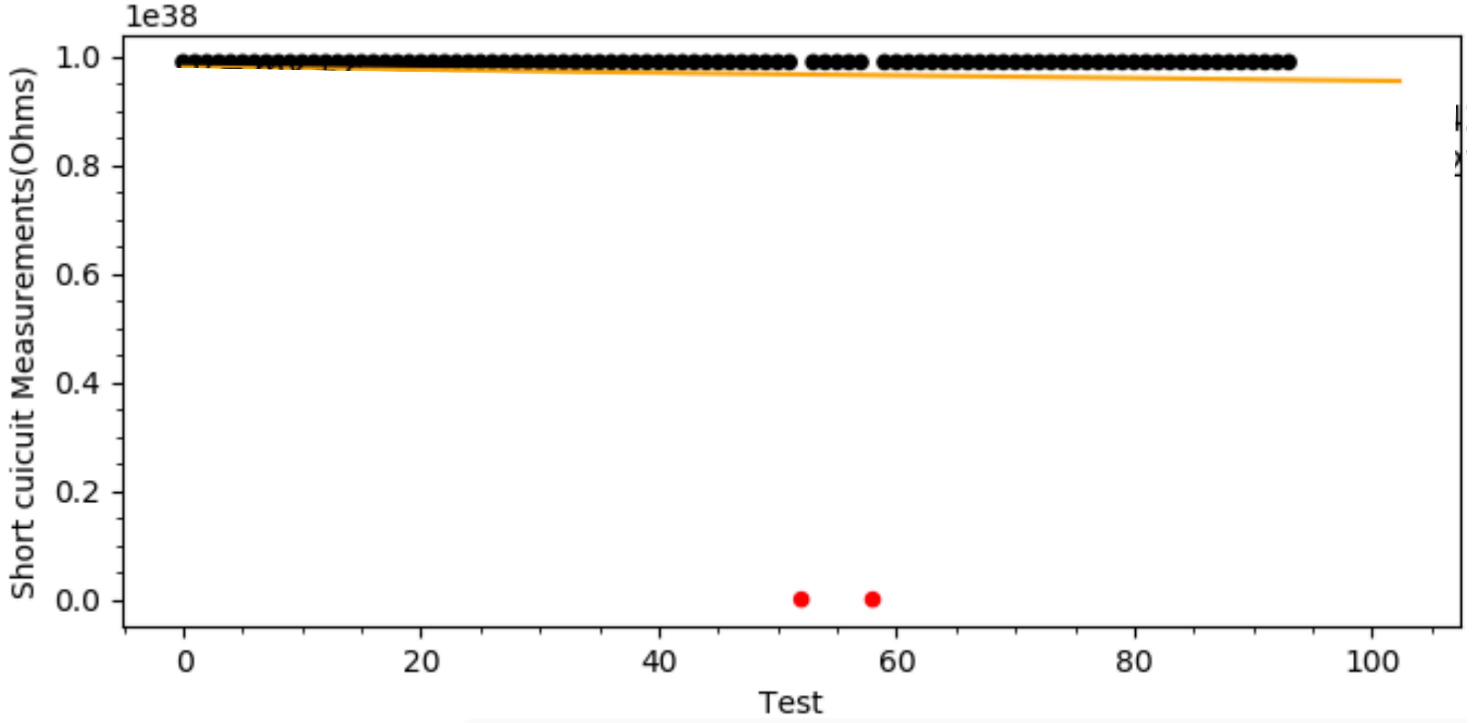
Test Results: Short Circuits

- Poor insulation between neighboring lines can lead to short circuits

No Defect



Defect



Summary + Outlook

- A robotic system has been developed to perform automated QC of all bus tapes for the ATLAS ITk strips detector
- The system has effectively identified several types of bus tape defects
- The techniques developed can be used for QC of general high-density bus tapes for detectors that use similar strategies for data extraction.

Acknowledgments

- **Oxford**: Roy Wastie, Tony Weidberg
    - Bus-tape design, robot design, development, and testing, Bus-tape co-curing
- **LBNL**: Carl Haber
    - Bus-tape co-curing
- **Yale:** Jeff Ashenfelter, Tom Barker, Will Emmet
    - Stave core assembly, UMass robot electronics
- **The ATLAS Collaboration**