Integration and System Qualification of the ATLAS Pixel Detector

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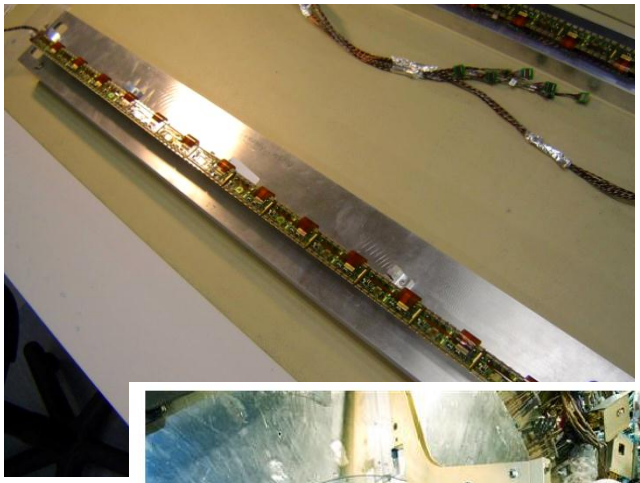
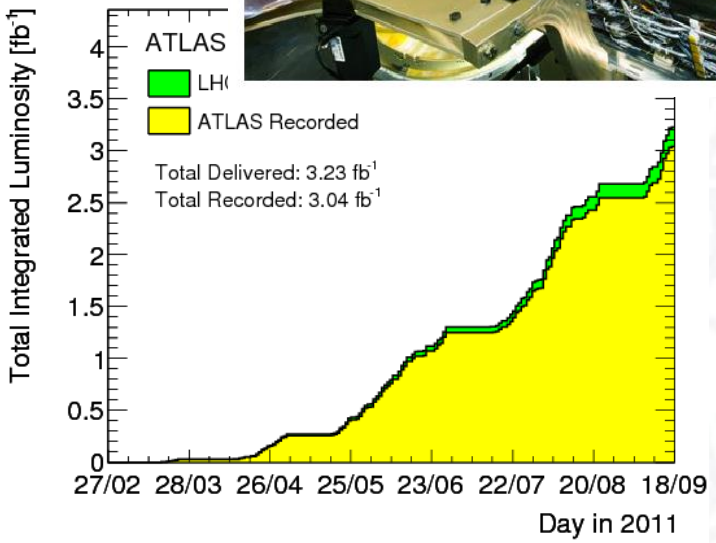
On behalf of the ATLAS Collaboration

Introduction

- Will cover the period from integration to operation
  - Mainly QC
- Will try to focus on lessons we have learned
  - Do not claim to have brand-new insights, but rather summarise the well-known pitfalls we encountered
  - Recommendations will be based on the assumption of infinite time; it is clear that in some cases the perfect QA might have to be sacrificed to the schedule
  - (I will also mention a few things that were successful ;-))





Outline

- Pixel Detector Integration
- Pixel Package Integration
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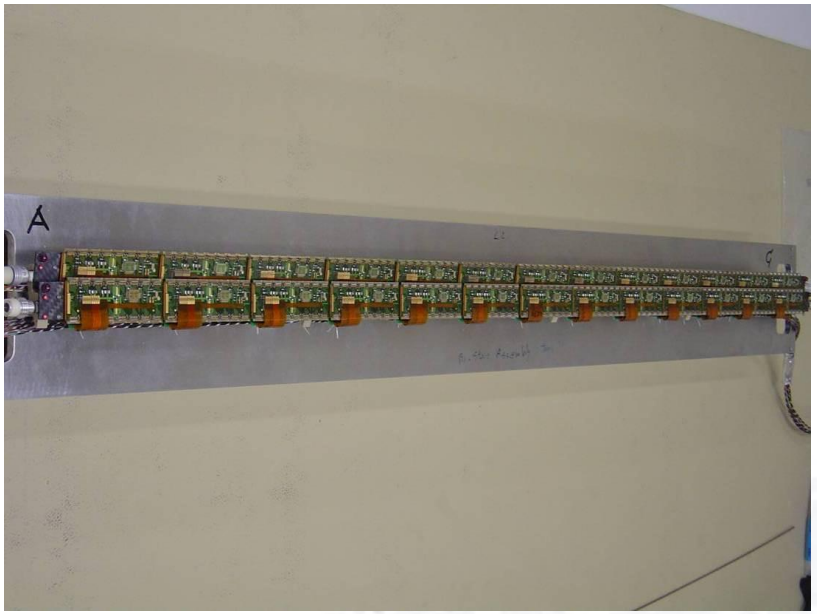
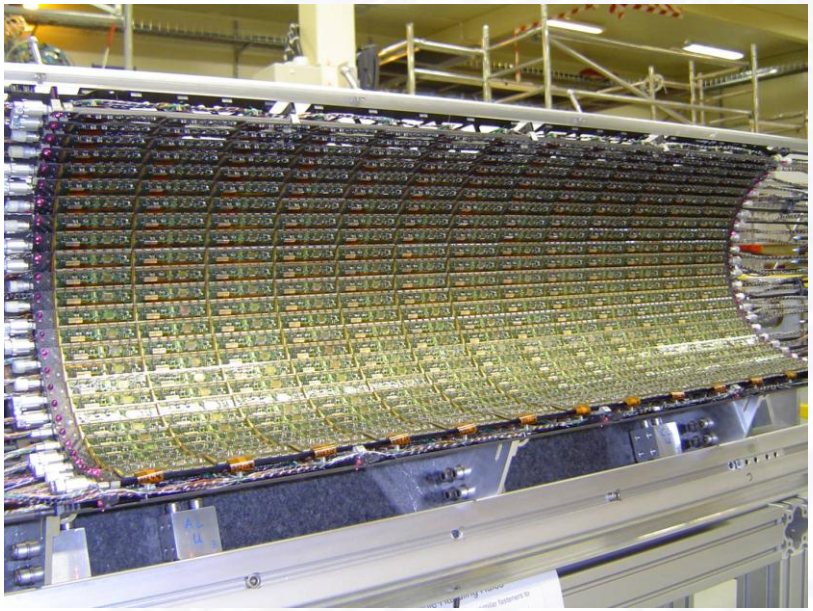
Pixel Barrel Integration

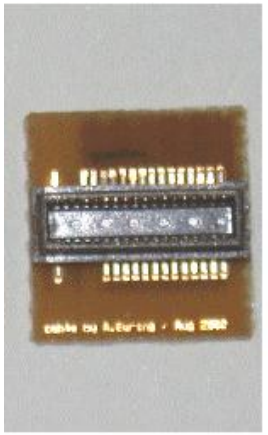
- Staves were mounted to bi-staves (cooling unit)
- Bi-staves were mounted into half-shells
- Half-shells were clamped together
- During bi-stave construction: Test of several modules at a time with dedicated test setup

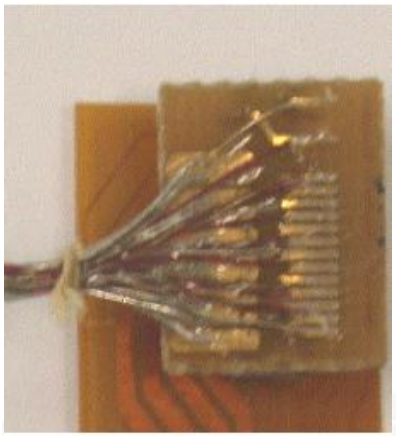




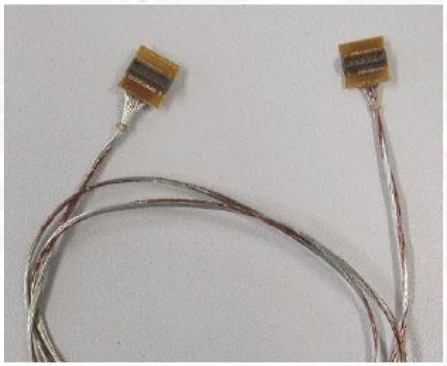
Problems During Integration

- Problems with connectors of micro-cables:
  - Soldering of the connector broke mainly on the outer pins
  - Had sporadically shown up before, but no systematic stress-tests done, only repair of defect connectors → continued to show-up





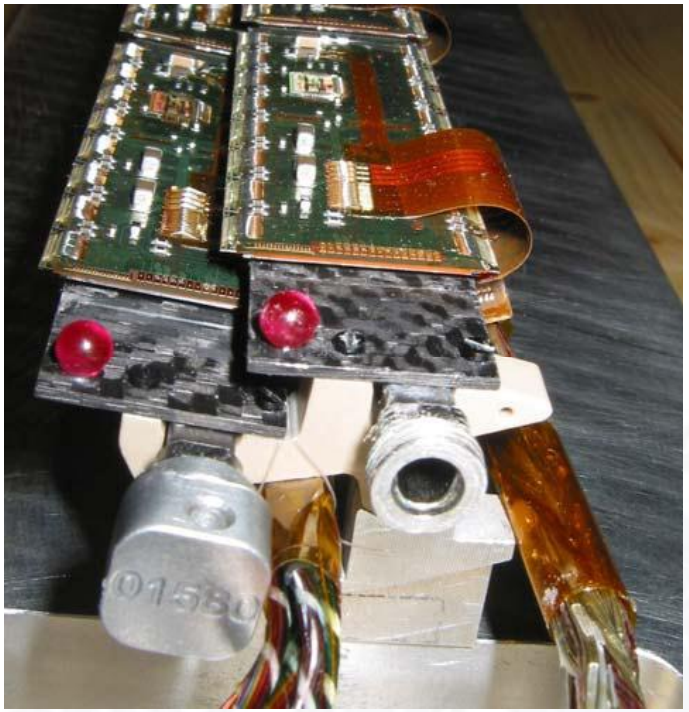
- Type-0 cable problems (barrel):
  - Discovered during integration
  - Went back to vendor for change of production sequence
  - Scrupulous test program for new cables

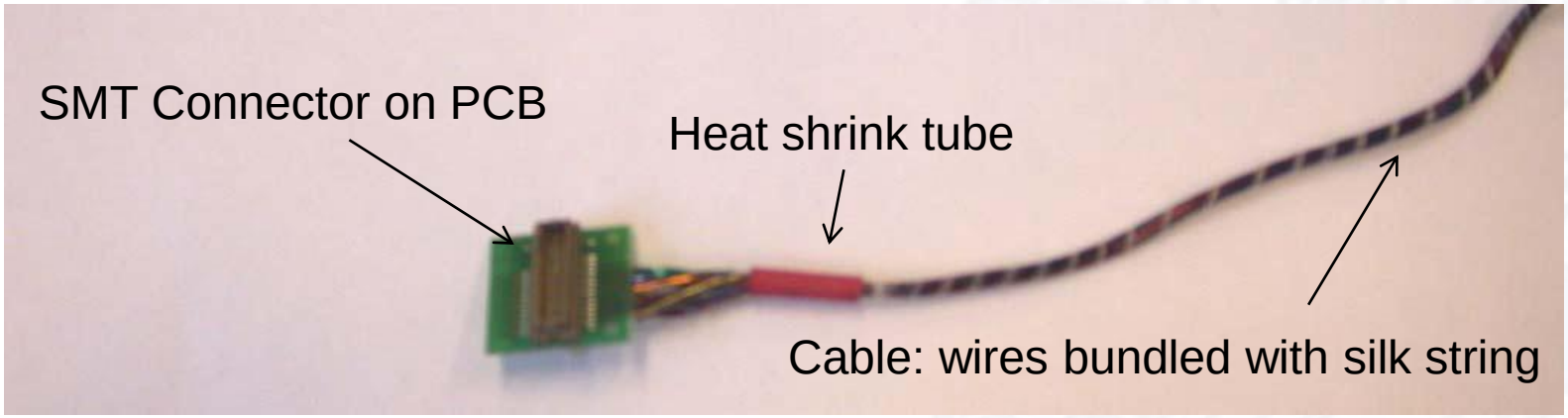


- HV return:
  - Tests were blind to a defect in the HV return due to parasitic current paths
  - Problems were found and had to be repaired during installation

Type-0 Cables

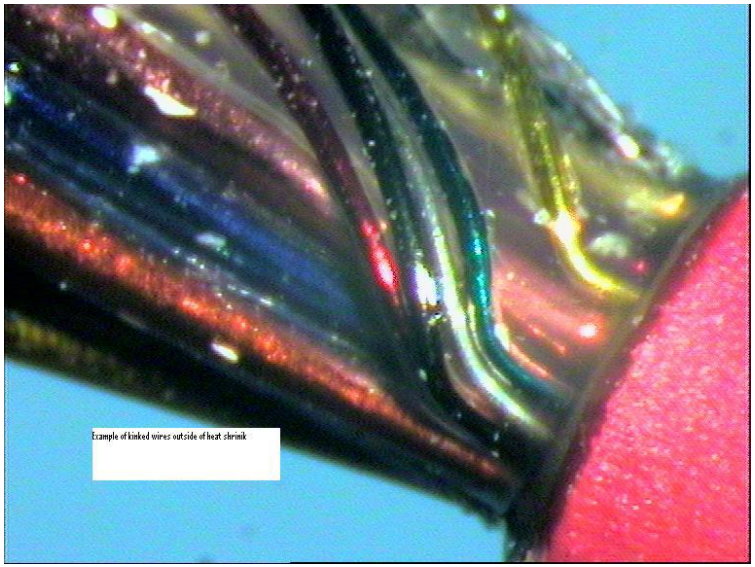
- Connectors at both ends (mounted on PCB board)
- Round Al conductors
  - 30 individual wires per cable
  - 16 x 100µm diameter
  - 14 x 300 µm diameter
  - Custom thickness polyurethane insulation

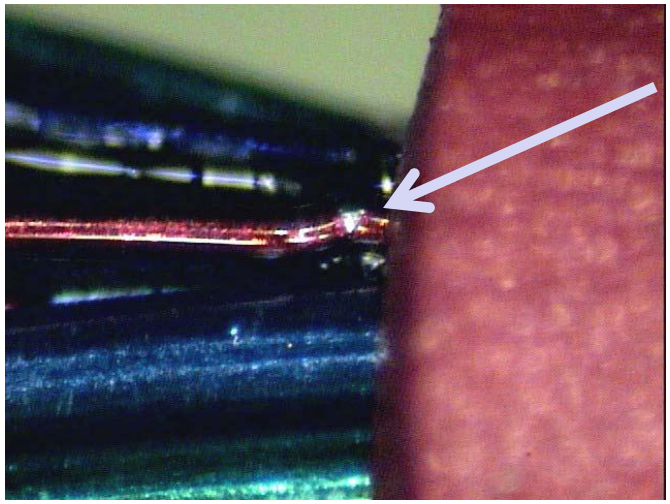




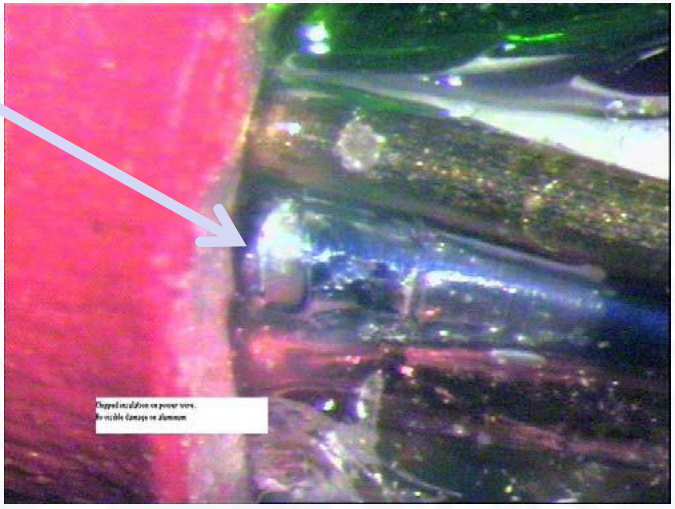
The Damage

Close-up of a typical cable
Close to heat shrink tube:

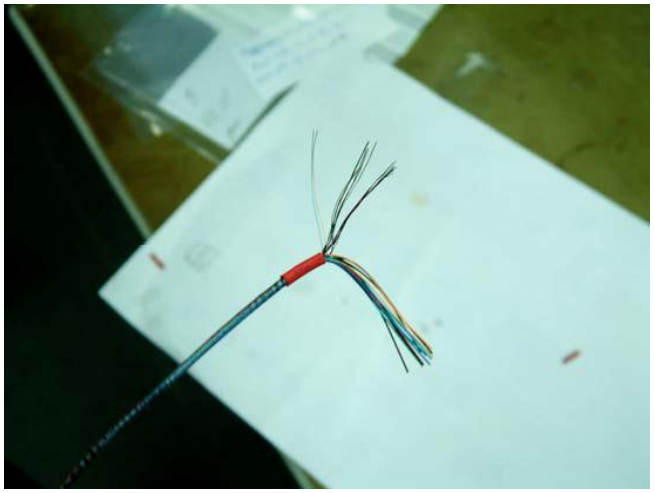




Example of damaged cables: the insulation is broken, leaving the cable very vulnerable to failure with even very delicate handling or with thermal cycling



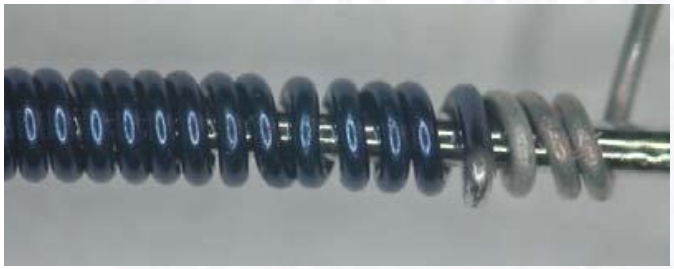
The Bad Process Step



- Wires were bent before stripping, separating thin and thick wires (to be stripped in two different phases)
- Stripping solution is molten NaOH (T ~ 400C)
- Pictures of insulation heated above 250C:

Bent then heated:

Heated then bent:



Type-0 Strategy

- Reproduced enough cables for layer-0, layer-1 and part of layer-2
- For rest of layer-2 accepted part of initial production after stricter quality control
  - Mechanical stress testing
  - Electrical test and visual inspection before and after stress testing
- After that only very few failures of type-0 cables and not clearly related to the old failure mode

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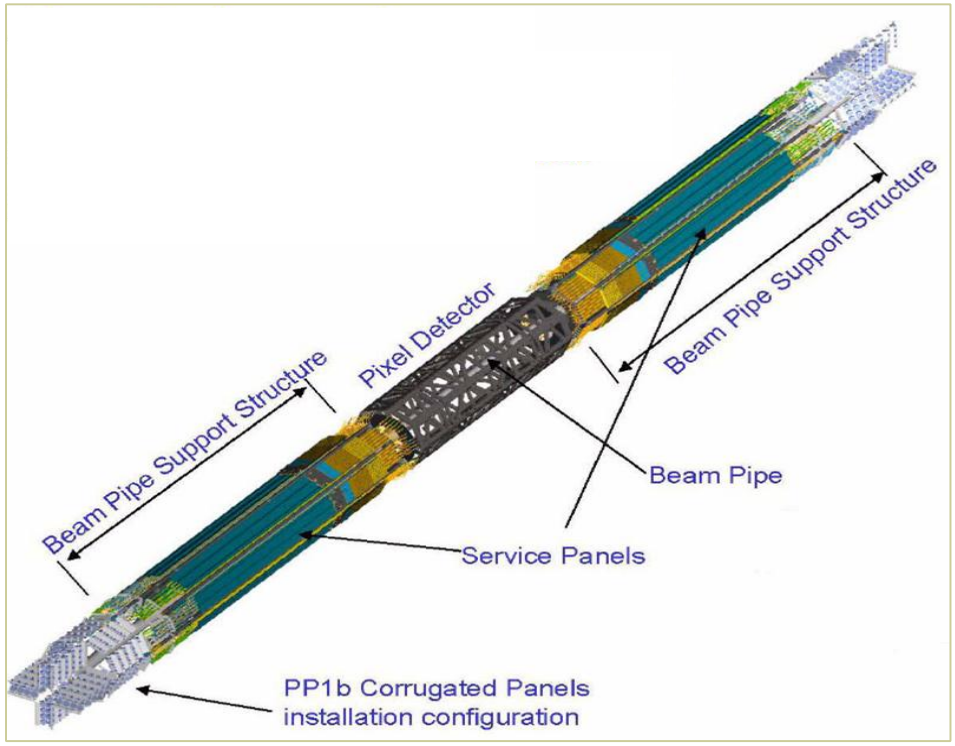
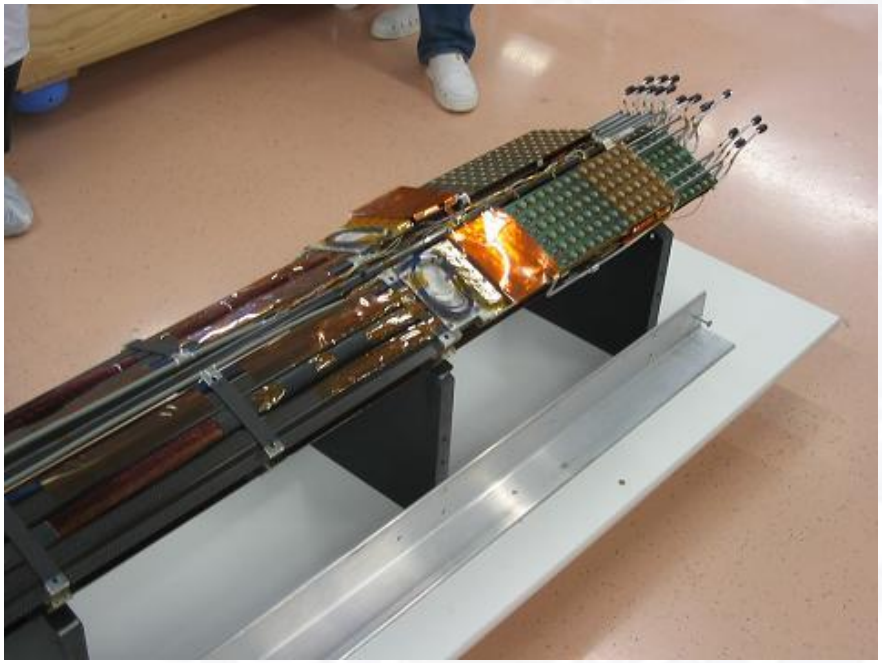
The ATLAS Pixel Package

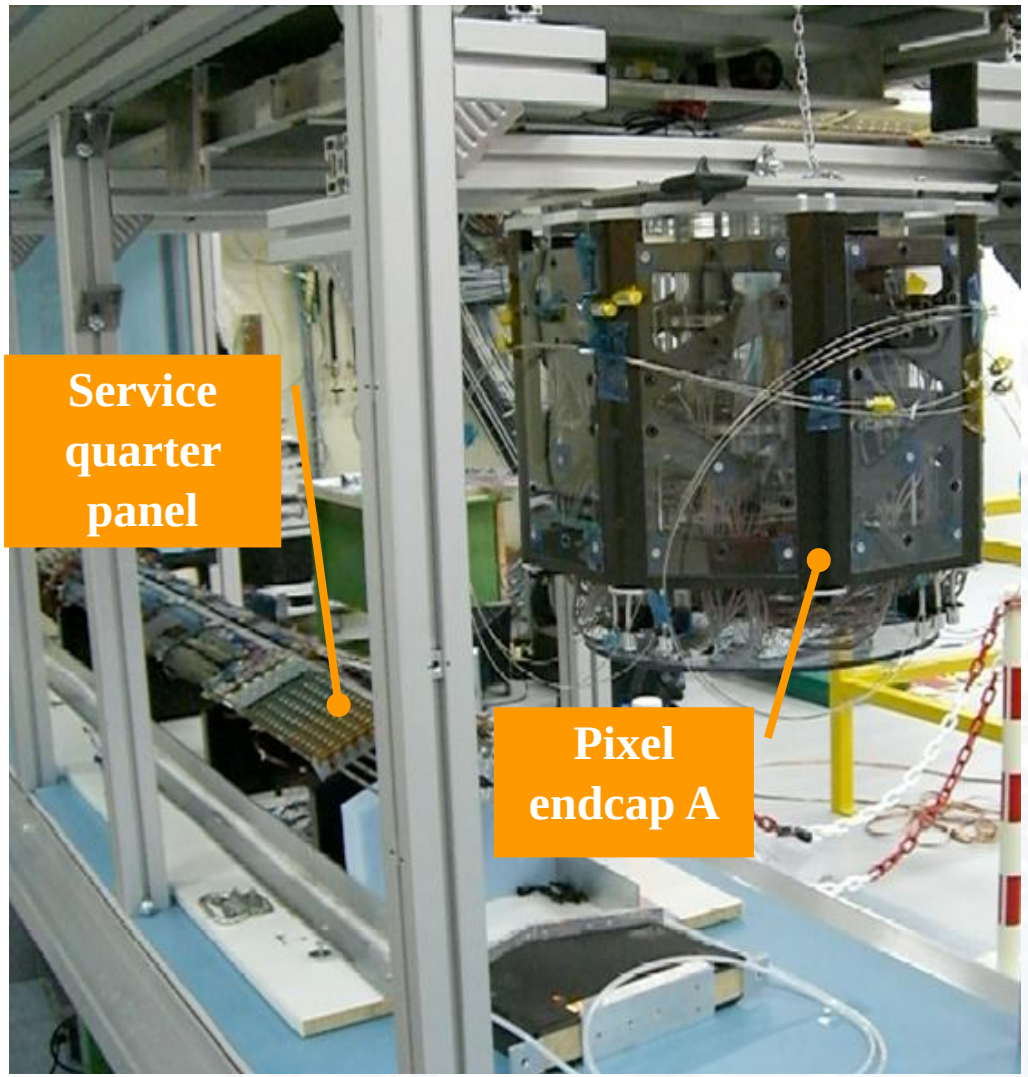
- Service Panels bring services out of inner detector volume (cryostat)
- 7-m-long pixel package integrated on the surface
- Detector plus 8 service quarter panels





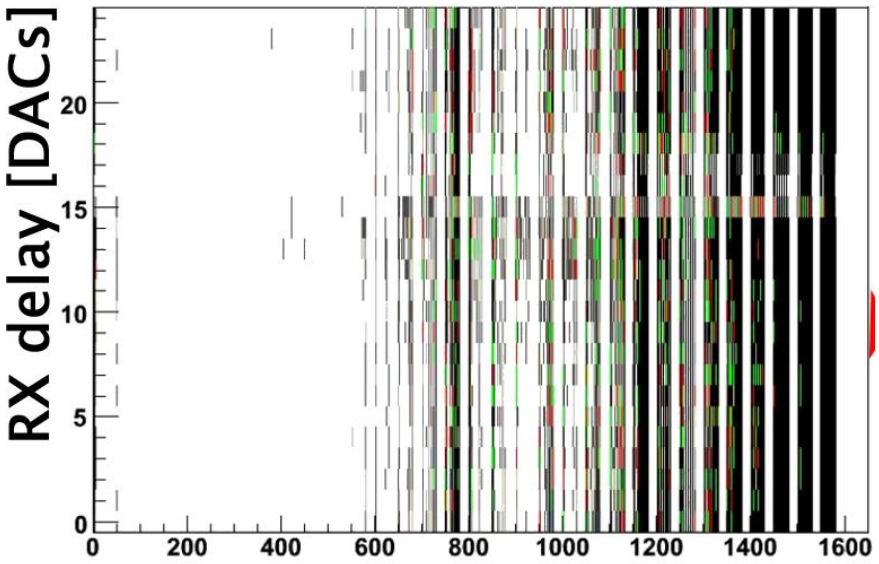
System Test (Fall 2006)

- In fall 2006 – before final detector integration: performed a 10% system test
  - One end-cap (144 modules)
  - One prototype service panel
  - Services and readout close to final version
  - operation at -10 ºC, using evaporative cooling;
- Achievements:
  - Commission services
  - Commission DAQ and offline with cosmic and random triggers.
  - Caught several important problems (next slides)

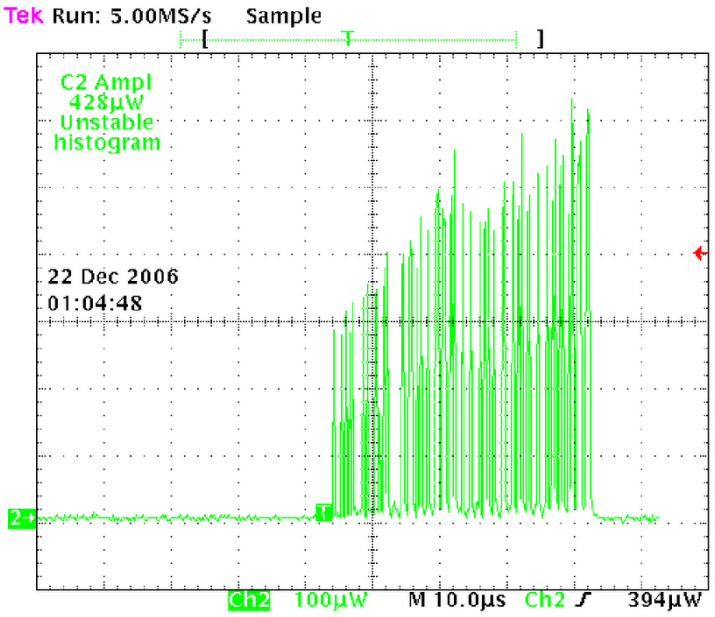


Opto-board Slow Turn-On

Decoded data-stream:

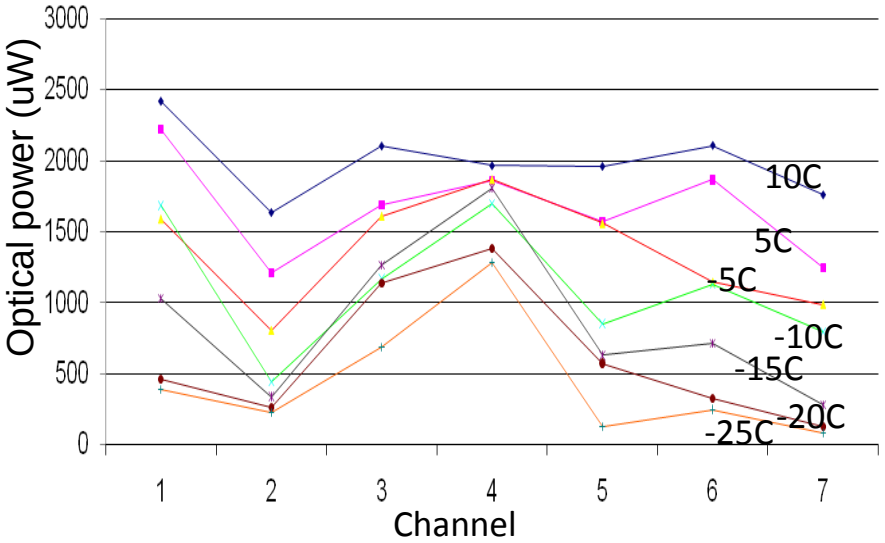


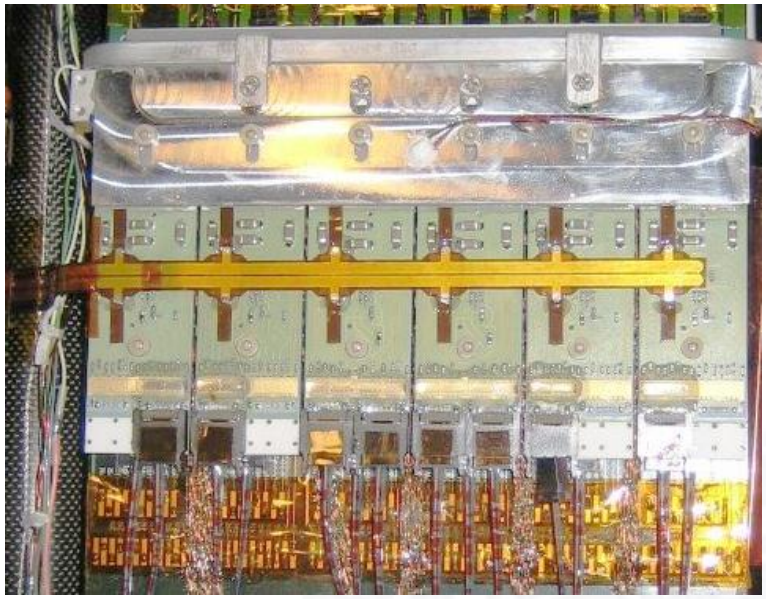
Scope picture:



- Problem I: Discovered opto-board channels with slow turn-on
  - Would have led to data corruption during operation
  - Added additional QA step for the opto-boards in the final service quarter panels
  - Several opto-boards with slow turn-on found and exchanged

Opto-board Temperature Dependence



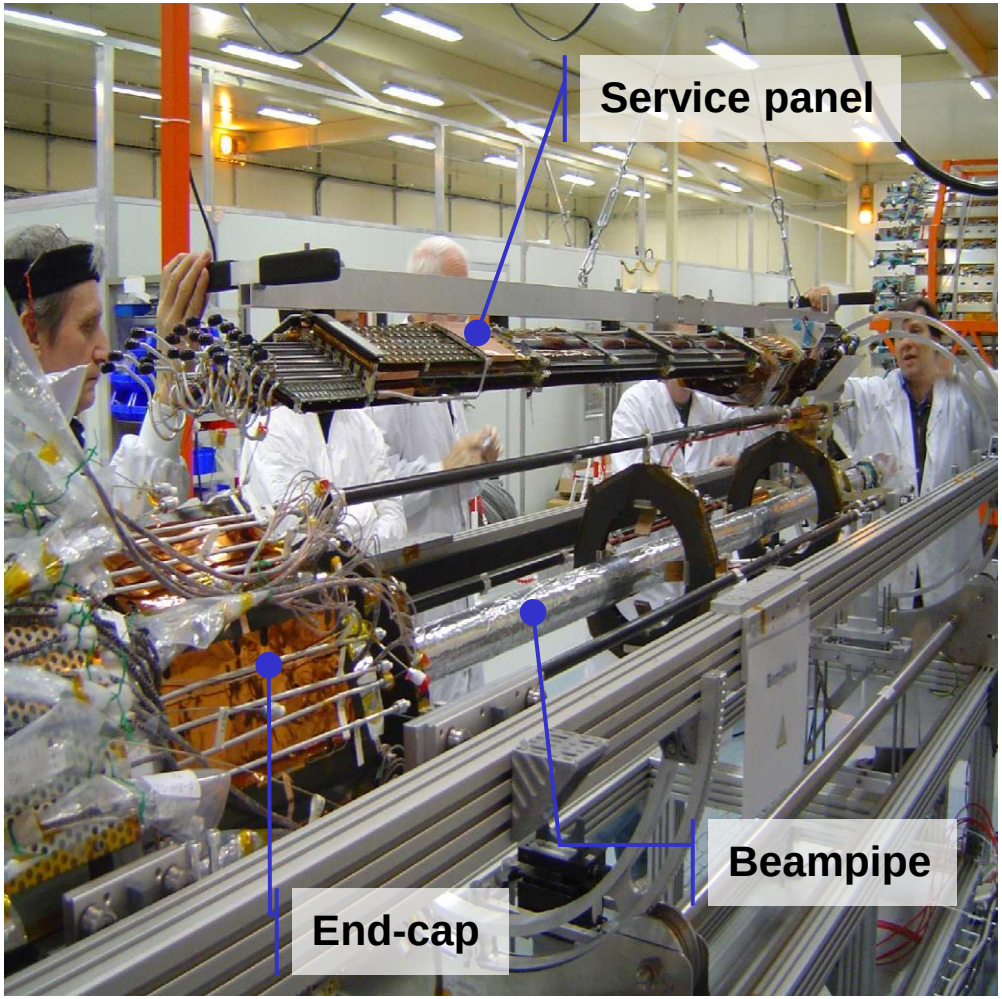


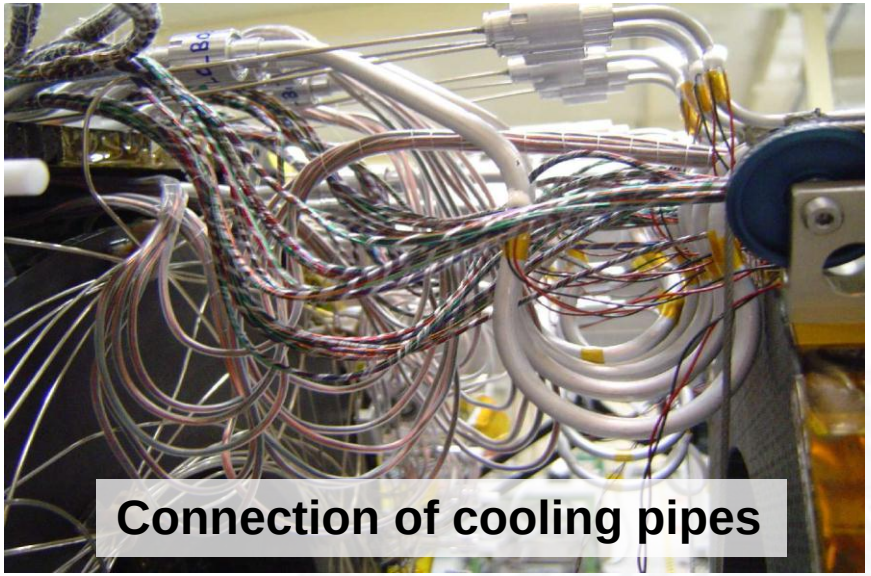
- Problem II: VCSEL array power and uniformity are temperature dependent
  - One VCSEL array serves 6/7 modules; no single-channel adjustment possible
  - Opto-boards coupled to cooling → added resistive heaters to actively control temperature; now opto-boards are operated at 20degC, all links are tunable
  - Without heaters this problem would have had the potential to make several links in the detector untunable (1 link = 1 module)

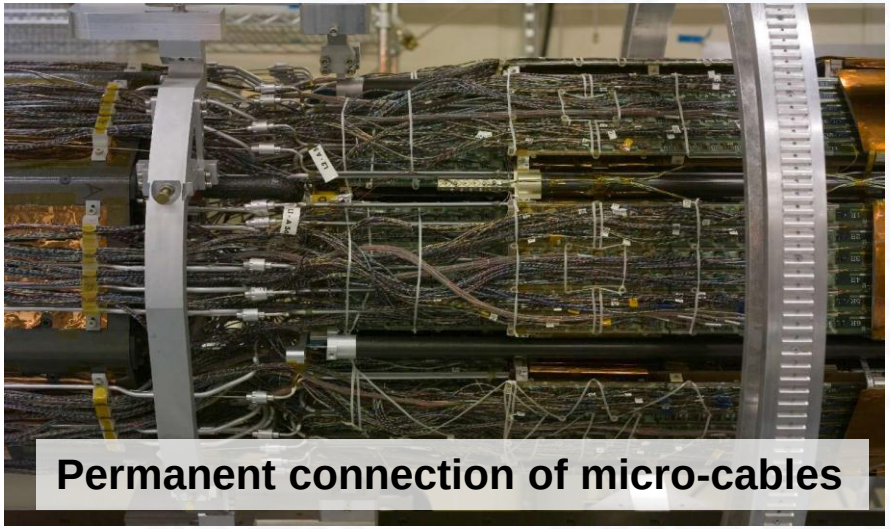
LEMO-F Connectors

- While setting up system test: Found problem with LEMO-F connectors at PP1 (end of cryostat, point of final connection in the pit)
  - Not exactly the usual cm/inch problem but nearly
  - All components had passed QC but …
  - Male Lemo-F connectors on the upstream cables (made in collaboration with LEMO-Europe) have movable pins to allow for self-alignment
  - Female Lemo-F connectors in the pixel package (made in collaboration with LEMO-US) were backfilled and thence had fixed pin-receptacles
  - In case of misalignment the receptacle would push the pin back
  - Developed special tool with LEMO to check for vulnerable pins
  - Find, repair and reinforce those pins
  - Check each single pin during service tests
  - Introduce procedure in power-up that checks for open sense lines

Package Integration (Mar – Jun 2007)







Connectivity Test

- During integration: connectivity test
  - No module cooling available
  - Develop test procedure that allows to test all connections in the integrated package without overheating the modules
    - Electrical Services (low voltage, high voltage, NTCs)
    - Optical Links (TTC links, data links)
    - Module Functionality and Identity (from threshold dispersion in short threshold scan)
  - Test was performed after connection of each SQP
  - One dead PiN diode channel and one dead VCSEL channel were not followed up; now there are a few more ☹
  - Test was repeated in the pit after the final connection at PP1

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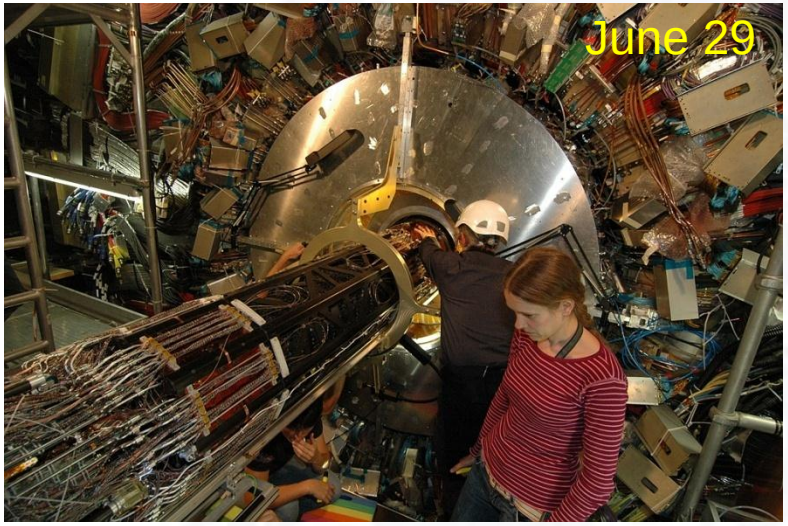
Into the Cavern …



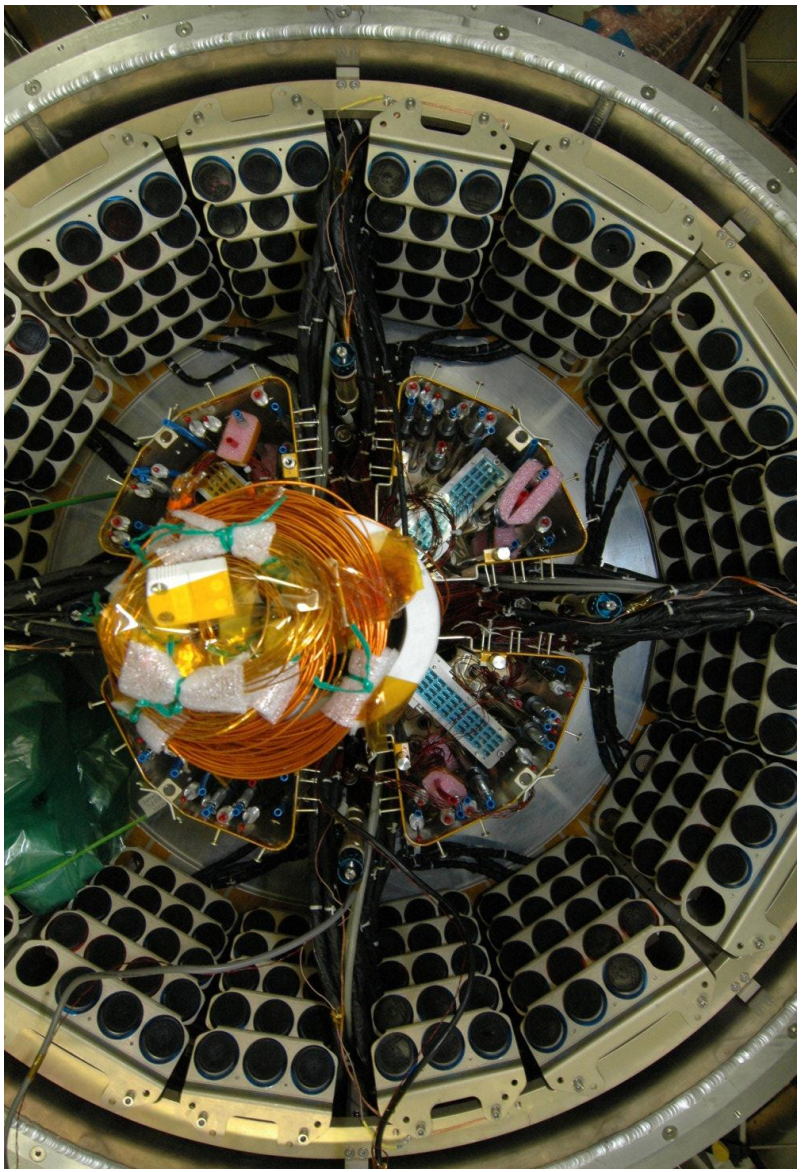
ATLAS Pixel Services

- Different possibilities to address reliability question
  - In ATLAS: high granularity of services and control
  - 25000 electrical contacts in more than 400 64-pin connectors at PP1
  - 88 independent cooling circuits
  - 588 optical fibre ribbons
  - Large effort spent on testing the services before doing the final connections and verifying the correct connection afterwards
    - → Service tests
    - → Connectivity test

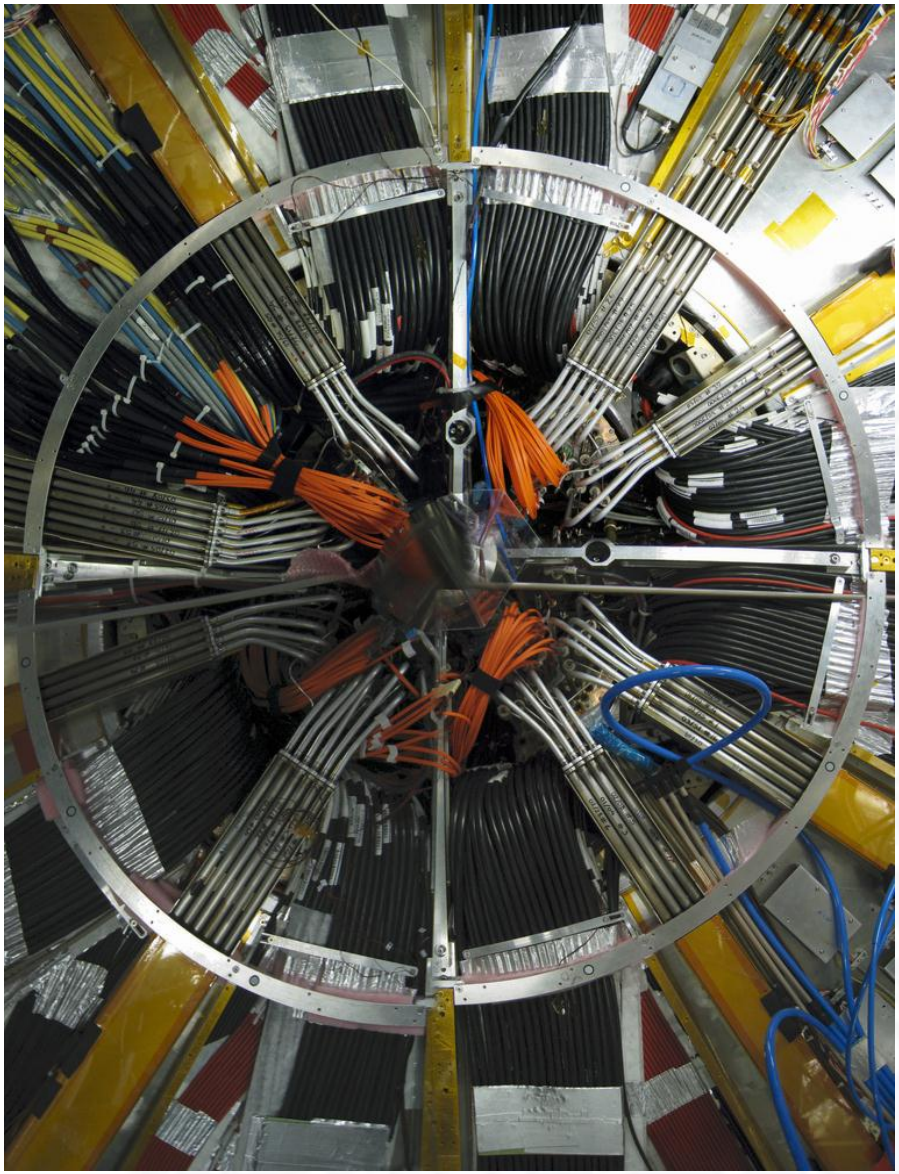
Service Tests

- Service tests:
  - Automated test setup using a switching matrix and a programmable load
  - Connects to services at PP1 (point of final connection)
  - Mimics a group of pixel detector modules and tests
    - Correct connection of all electrical services
    - Correct functioning of hardware interlocks
    - Robustness against sense line breaking (i.e. no dangerous voltages)
    - Correct mapping in the FSM
  - Fibre integrity checked with OTDR measurements
  - Leak tests done on all cooling pipes
  - Guaranteed that services were perfect when connecting the detector
    - Had to exchange parts that had been tested OK before transport and installation

Final Connection

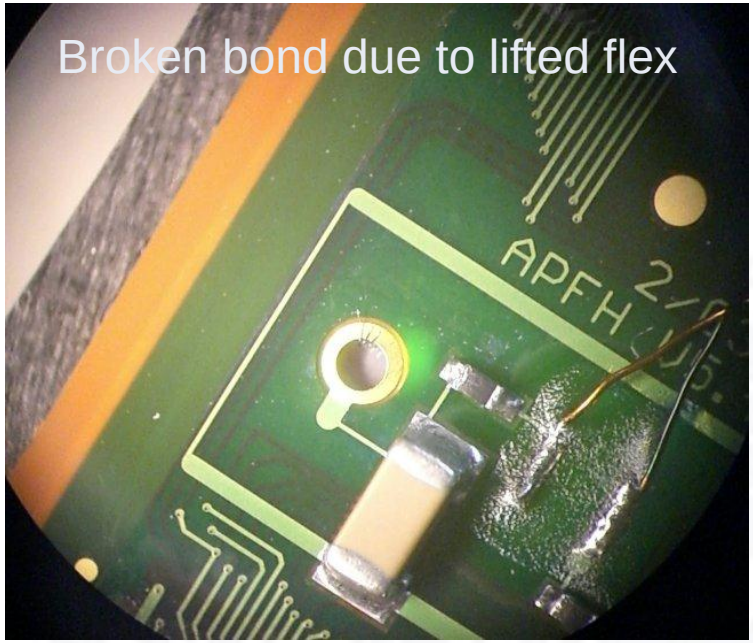


~ 8 wks



HV Opens

- Connectivity test after installation found
  - Aforementioned problem with HV return; could be bypassed
  - 11 unrecoverable modules
- HV Opens are responsible for majority of unrecoverable modules after installation
- At this point not possible to distinguish between cable and wire-bond problem
- Wire-bonds had low intrinsic reliability so that even after QA some weak parts got through
- Might argue that QC was not strict enough



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The Tx-Saga

- During operation in 2008 and early 2009 single laser channels transmitting clock and commands to the detector failed
- Evidence pointed to ESD damage and a new batch with stronger precautions was ordered and installed
- Lasers started to fail again in 2010; most likely cause humidity in the counting room air
- Standard 85/85 test (85C, 85% RH) would probably have revealed the problem
- Luckily no serious problem for operation as laser-plugins can be promptly replaced

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Conclusions

- Quality control during integration and installation revealed several problems which otherwise might have cost us dear
- As a result currently ~97% of the ATLAS Pixel Detector are working and behaving as expected
- Will try to summarise a few lessons we have learned
  - Part of them created some nuisance in getting to the 97%
  - Part of them might be responsible for (at least a fraction of) the 3%

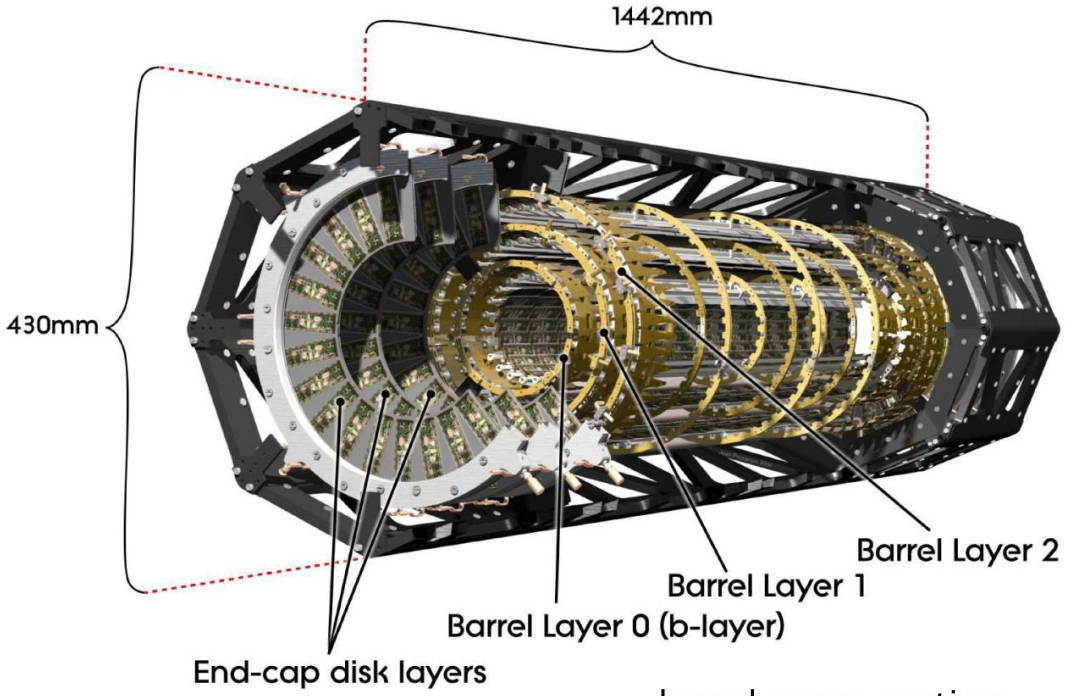
Lessons

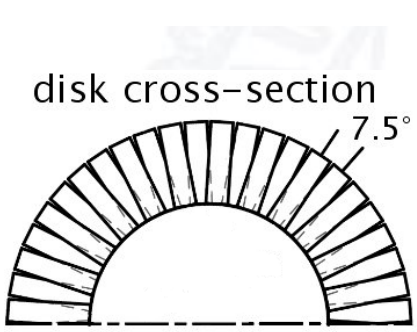
- (Not necessarily new) Lessons we learned:
  - Very often it is the less “sexy” things that fail most
  - In systems built at the extreme limits of material budget etc. there hardly is any component too simple to fail
  - In a large scale system operated over many years, there are hardly any one-time failures; even problems that seem “singular” during production and testing might be worth being followed up
  - Test each piece as long as possible under as realistic conditions as possible; a system test is an invaluable instrument to spot problems that occur only when the different pieces have to work together
  - In areas where expertise within the HEP community is limited: be conservative in design, adopt standard test procedures

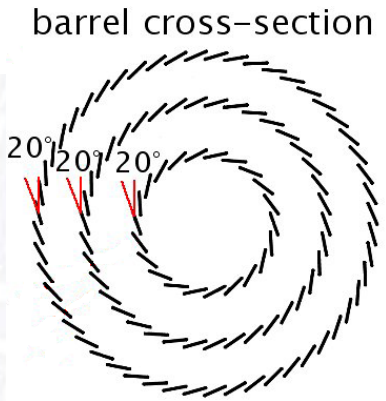
- Backup

The ATLAS Pixel Detector

- 3 hit-system for $|\eta| < 2.5$
  - 3 barrel layers
  - 2 x 3 endcap discs
- 1744 modules,
  80M readout channels
- Innermost barrel layer at 5 cm
  - Radiation tolerance
    500 kGy / 10^{15} 1MeV n_{eq} cm^{-2}
- Evaporative C3F8 cooling integrated in local support structures
  → Module temperatures < 0°C
  (Average temperature -13°C,
  warmest module at -5 °C)

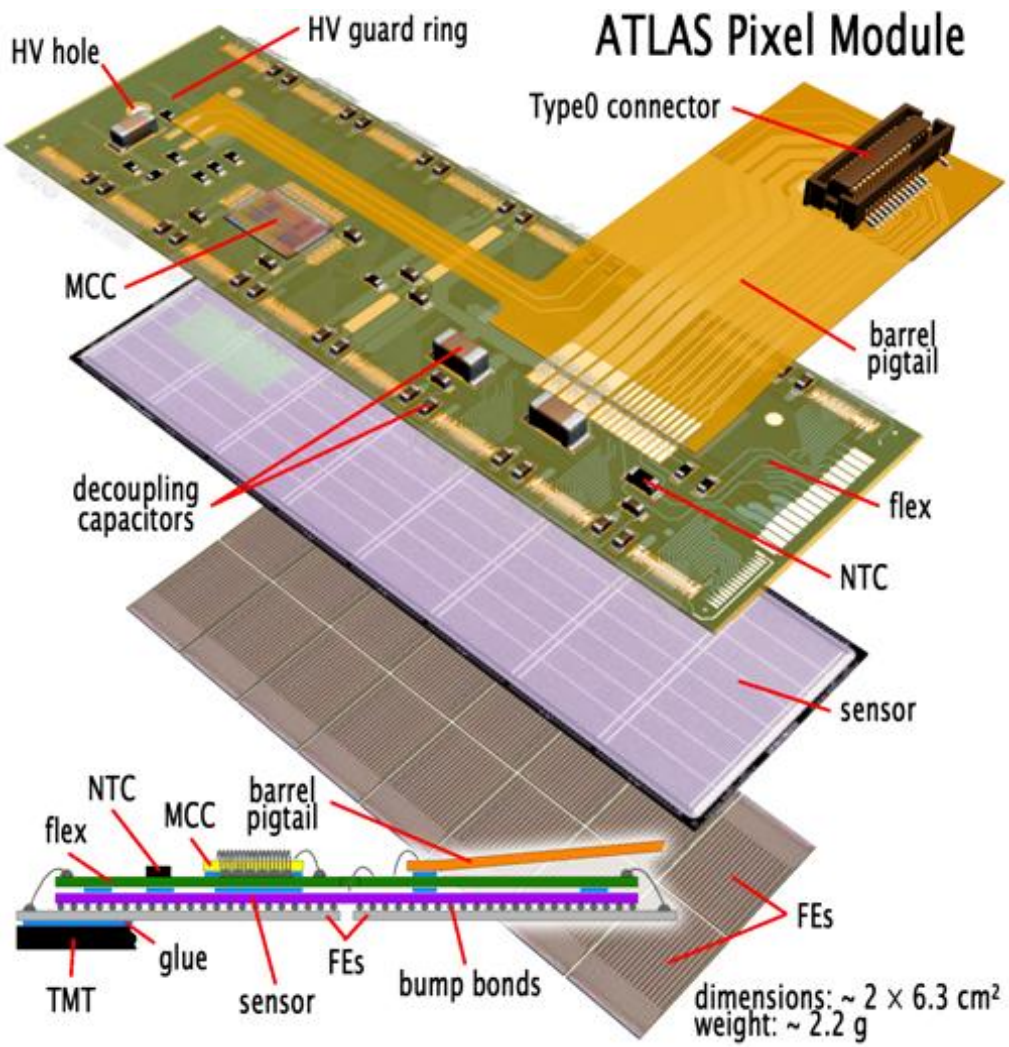




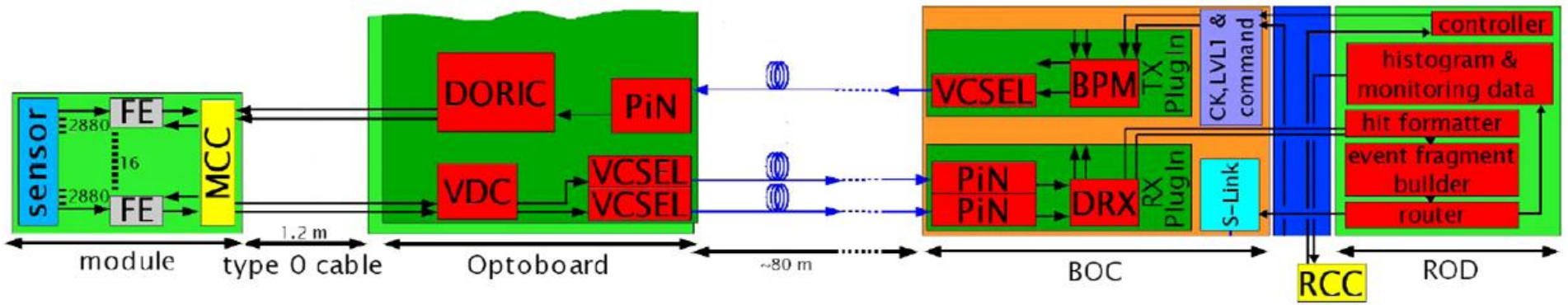


The ATLAS Pixel Detector Module

- Sensor:
  - 250 µm thick n-on-n sensor
  - 47232 (328 x 144) pixels
  - Typical pixel size 50 x 400 µm^2 (50 x 600 µm^2 pixels in gaps between FE chips)
  - Bias voltage 150 – 600 V
- Readout:
  - 16 FE chips, 2880 pixels each
  - Zero suppression in the FE chip, MCC builds module event
  - Pulse height measured by means of Time over Threshold
  - Data transfer 40 – 160 MHz depending on layer



ATLAS Pixel Optical Links



- Data to and from the detector is transmitted over optical links
- Electro-optical conversion is done
  - On-detector in the optoboards, ~ 1m from the IP
  - Off-detector in the readout crates (back-of-crate cards)
- Optical link tuning:
  - Mainly adjustment of the parameters of the Rx(data)-link