The ATLAS Insertable B-Layer: from construction to operation

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on behalf of the ATLAS Pixel Collaboration

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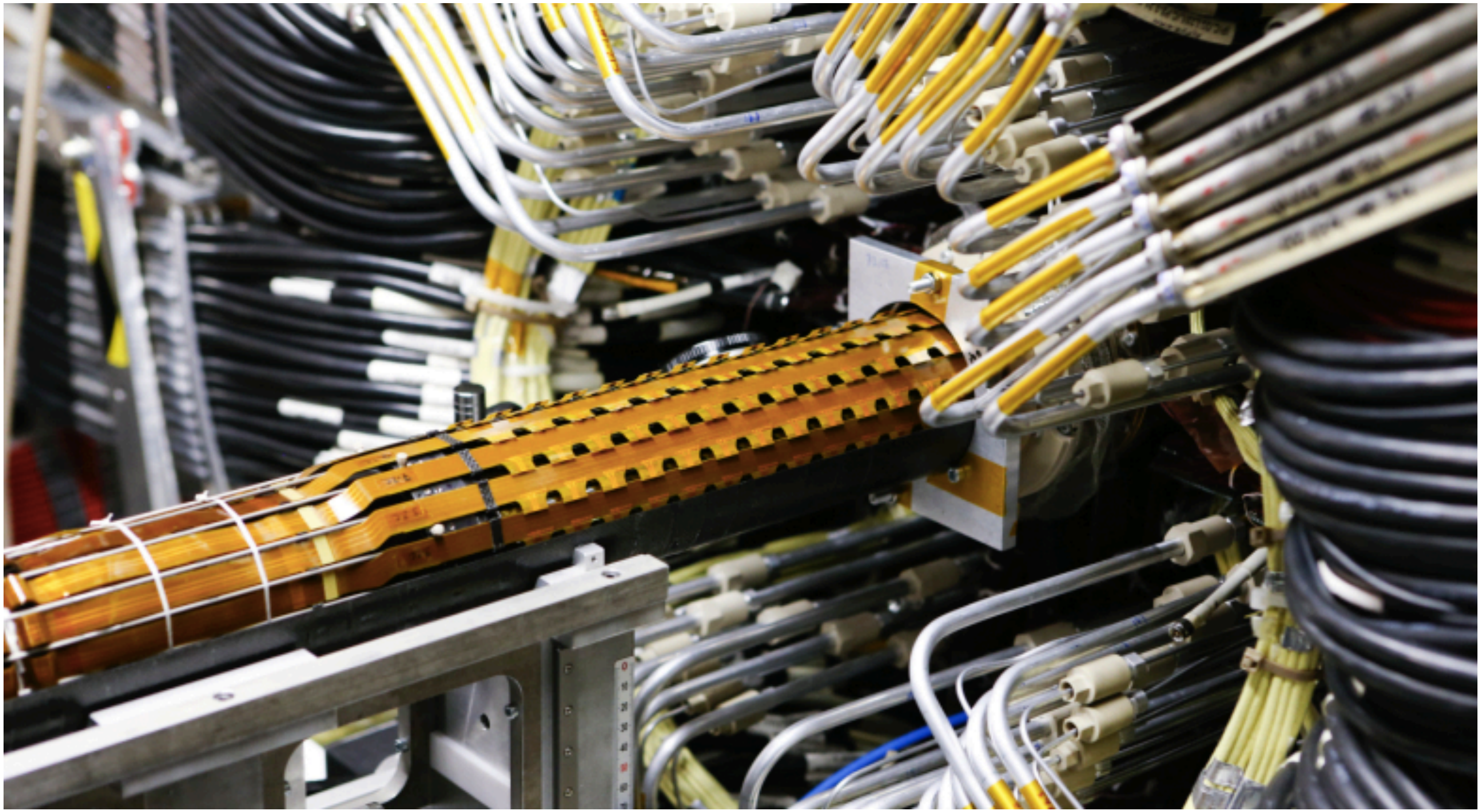
The ATLAS Insertable B-Layer (IBL)

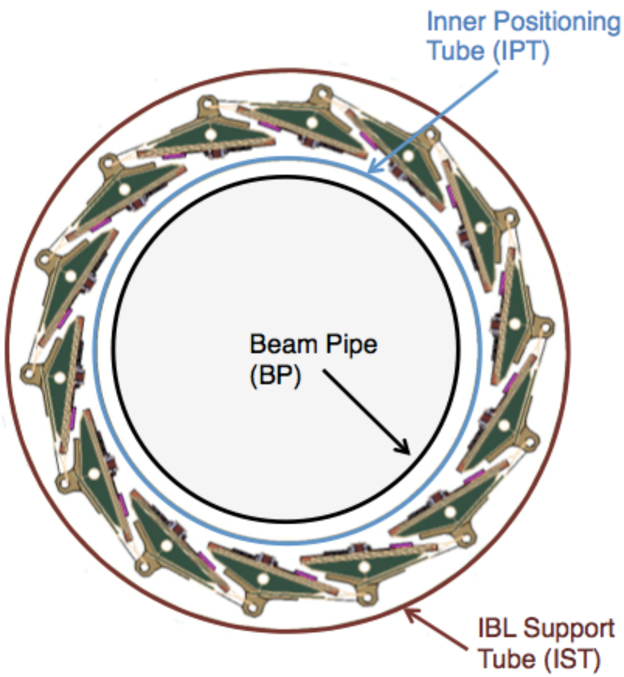


Module assembly & QA → Stave assembly & QA → Integration → Commissioning → Operation

The ATLAS Insertable B-Layer (IBL)

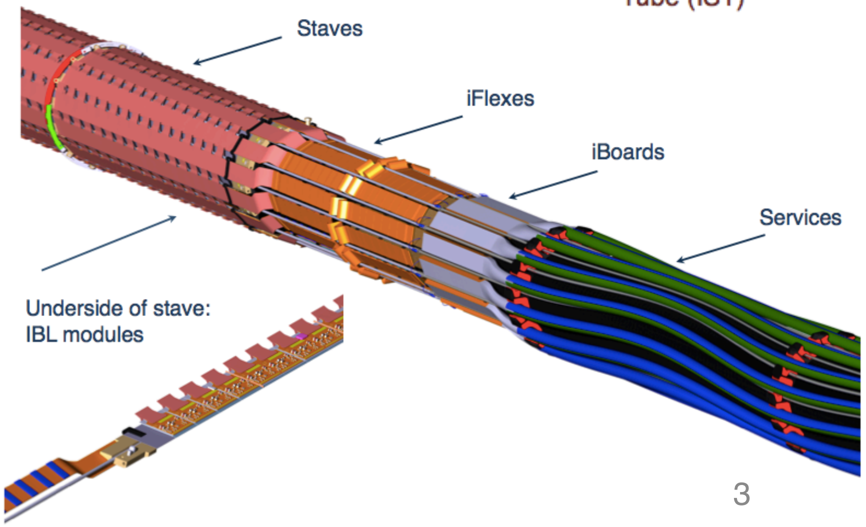
Motivation

- ✧ *Retain excellent vertex detector performance*
- ✧ *Improve heavy flavor tagging, primary and secondary vertex reconstruction/ separation*
- ✧ *Add additional redundancy of the detector in case of failures caused by radiation damage*



Detector overview

- Length: ~64cm (~7m including services in both sides)
- 14 local support structures (staves) at 3.27 cm overlapping in phi
- 32 R/O chips per stave
- New R/O chip: FE-I4 in IBM 130 nm CMOS
  - Cell size (50 x 250) μm^2
  - 80 columns x 336 rows = 26880 channels / FE
- Data transfer at 160 MHz
- CO_2 cooling integrated into the staves



… seen as a first tech step to HL-LHC

- New **sensors** with higher radiation hardness
  - $5 \times 10^{15}\ n_{eq}\ cm^{-2}$ NIEL (improved radiation hardness by factor 5)

- New **readout chip** with finer segmentation, larger active fraction and increased hit-rate capability
  - New readout architecture and smaller cell size $(250 \times 50)\ \mu m^2$
  - Large single-chip $(20.2 \times 18.8)\ mm^2$

- Lighter detector: less radiation length of **support** and **cooling** structures
  - Improved radiation length per layer from 2.7% to 1.9% to minimize multiple scattering in innermost layer
  - High efficiency **CO_2** cooling at -40°C coolant temperature

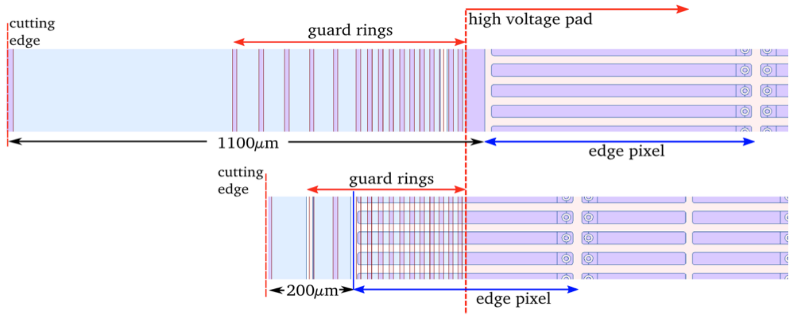
See dedicated talk by B. Veerlat on Friday

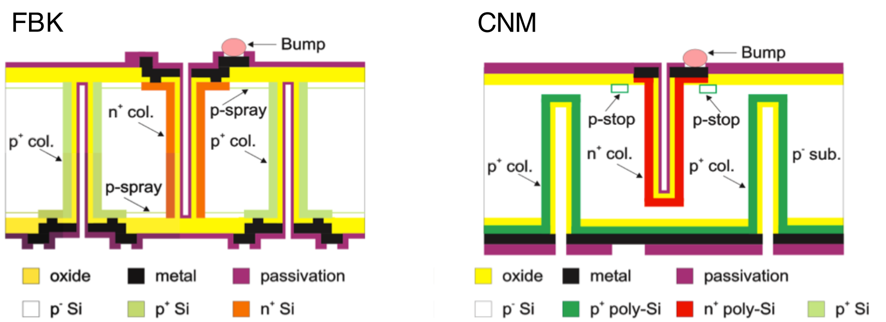
- New **off-detector** readout system
  - Increased readout speed by a factor 2

Sensor technologies

Two technologies chosen: **Planar** and **3D**

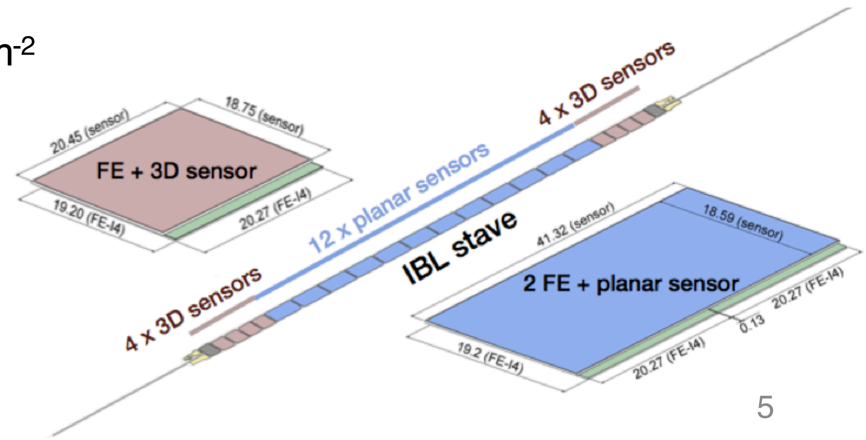
- **Planar** (produced by CiS)
  - 200 µm thick n^{+}-in-n sensor
  - Inactive edge minimized by shifting guard rings (13) underneath pixel region
- **3D** (produced by CNM and FBK)
  - 230 µm thick n^{+}-in-p sensor
  - Column through almost the full bulk with two electrodes per pixel



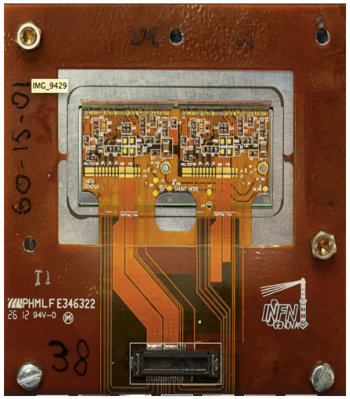


➢ **Sensor specification**:
  - Qualified up to 5 x 10^{15} $n_{eq}cm^{-2}$
  - Sensor max power dissipation: 200 mW cm^{-2} at -15°C
  - Single-hit efficiency > 97%

➢ **Population of sensors on the staves**:
  - 75% Planar (central)
  - 25% 3D (at both sides, i.e. large η)



Detector construction: flow chart



Sensor and FE production

↓

Bump bonding

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Module assembly and QA

Bare stave and flex production

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Stave and flex and QA

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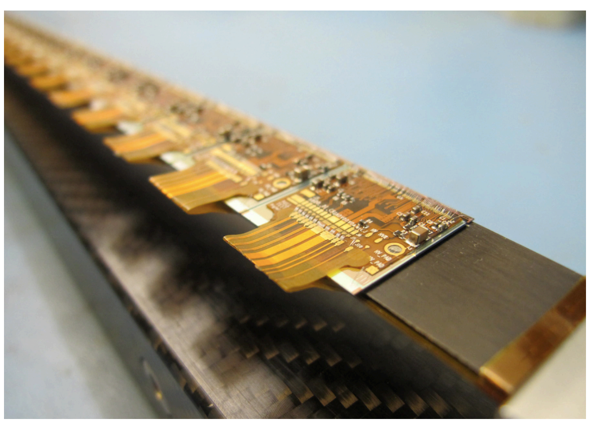
Stave-flex assembly and QA

Production of 20 staves



Module loading on stave

↓

Stave electrical and functional tests

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Stave burn-in and QA

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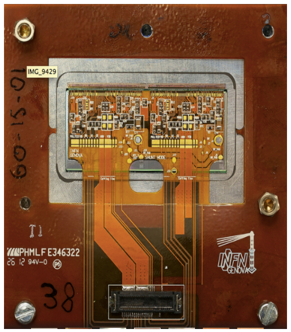
Stave to beam pipe integration

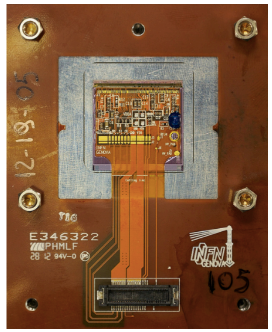
Selection & integration of the best 14 staves

Module assembly, production and QA

Planar/ Double-chip



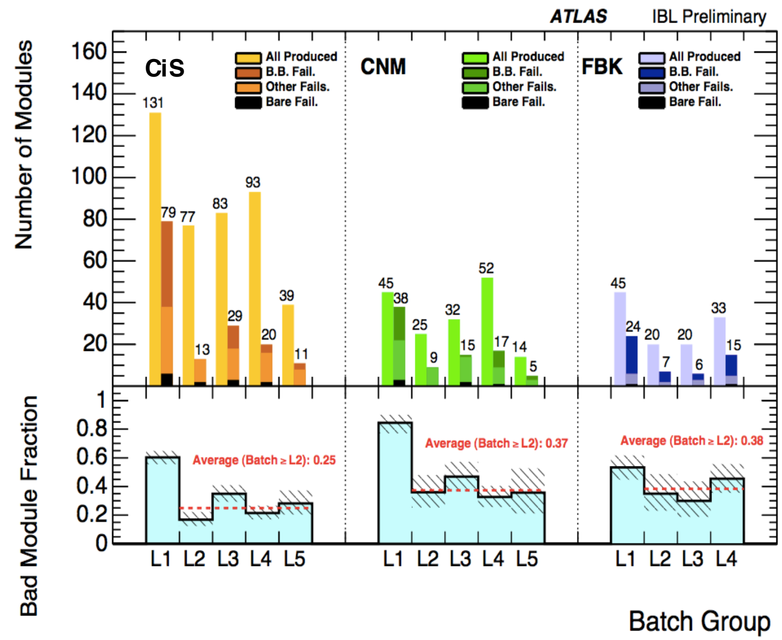
3D/ Single-chip

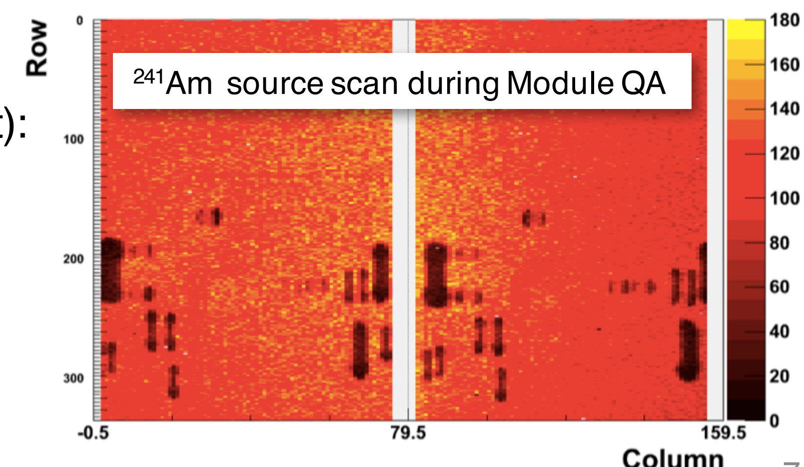


~710 modules produced in total (in ~1-year)

- Verification of basic functionality at 15°C after the assemblage
- Thermal stress: 10x (-40°C to +40°C)
- Final qualification at -15°C
- Module yields (lower than expected, see next):
  - Planar (double-chip: CiS) ~75%
  - 3D (single-chip: FBK and CNM) ~ 62%
- Ranking and module selection

  IBL spec < 1% pixel defects/FE





Bump bonding

Two kind of defects observed on the first batches

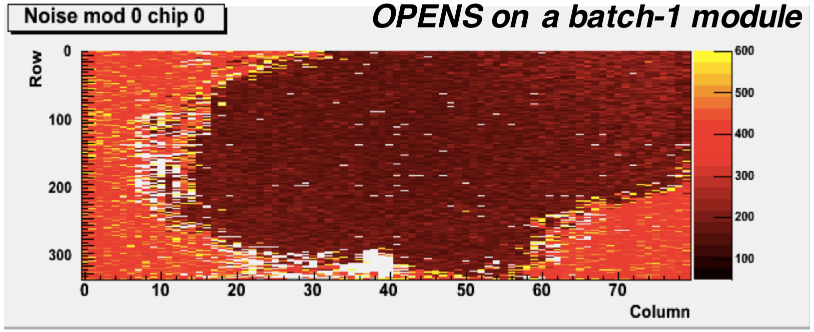
- Large area of unconnected bumps (**opens**)
- Areas or single bump defects distributed over the module (**shorts**)

➢ Stopped production in late September 2012

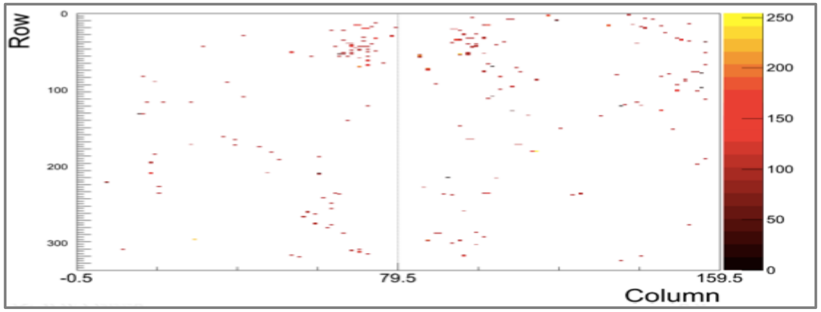
➢ Intense investigation program
  - ✧ Open bumps traced back to excessive flux in flip-chip process
  - ✧ Lack a convincing explanation of the opens origin but problem vanished switching to flux-free flip-chip

➢ Restarted production with **flux-free flip-chip process** in February 2013

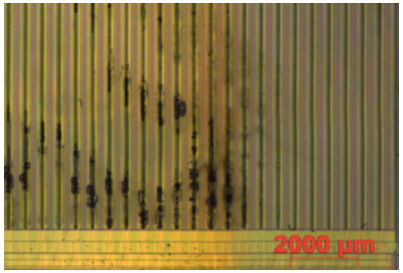
OPENS on a batch-1 module



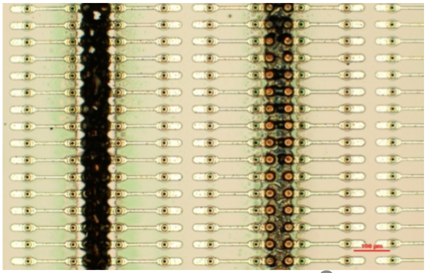
Crosstalk of a batch-3 module



FE chip after de-soldering

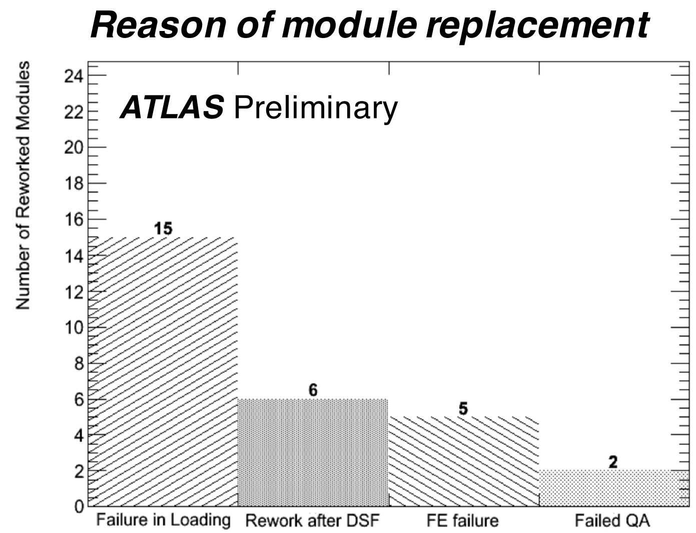


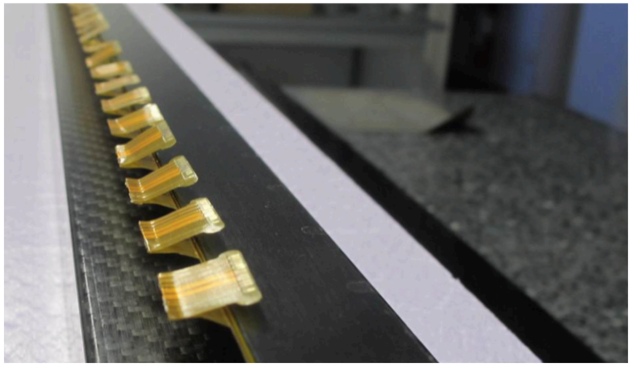
Sensor after de-soldering

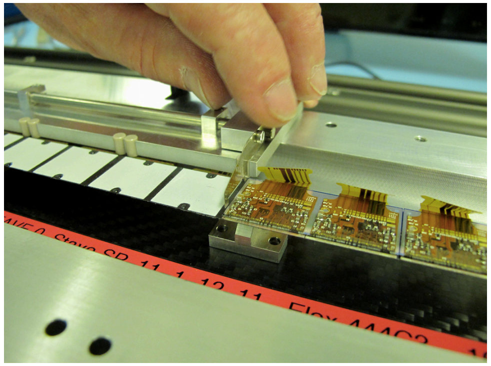


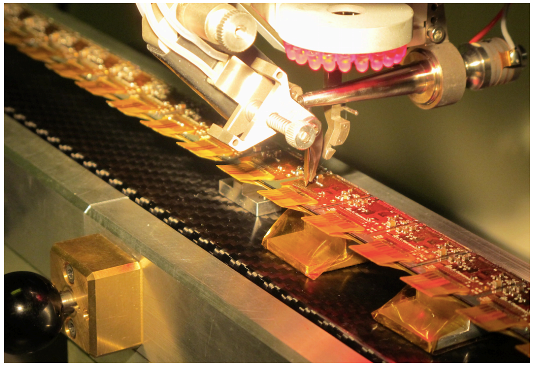
Stave loading

- **20 production staves built in ~1-year**
- 428 modules loaded in total
  - Including module replacement (28)
    challenging and risky operation for nearby modules but possible!





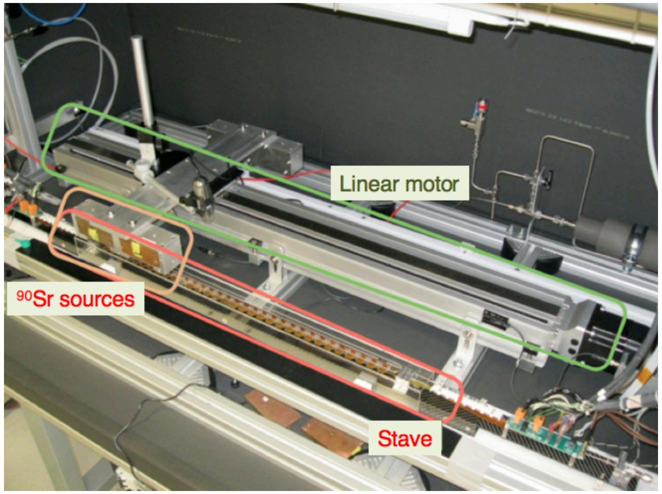




- First stave quality check at the loading site
  - Optical inspection and basic electrical/functional tests

Stave quality assurance

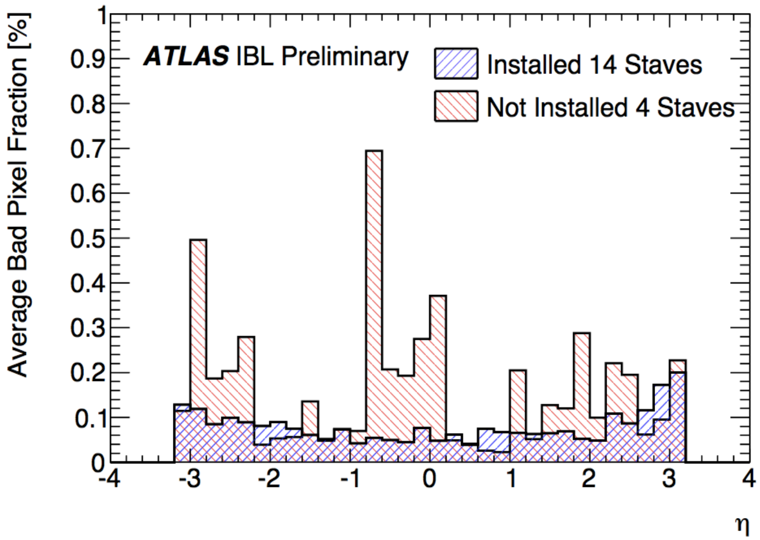
- **Tuning at different temperature** and Source (^{90}Sr) scans on the full stave
  - Mimic real detector operation in clean-room
- **Pixel defects**
  - Classified as related to sensor, FE or bump bonding
  - 73% of all chips loaded onto staves have less than 0.1% bad pixel
  - Percentage of disconnected bumps is less than 0.06% for the produced staves



Selection of the best 14 staves

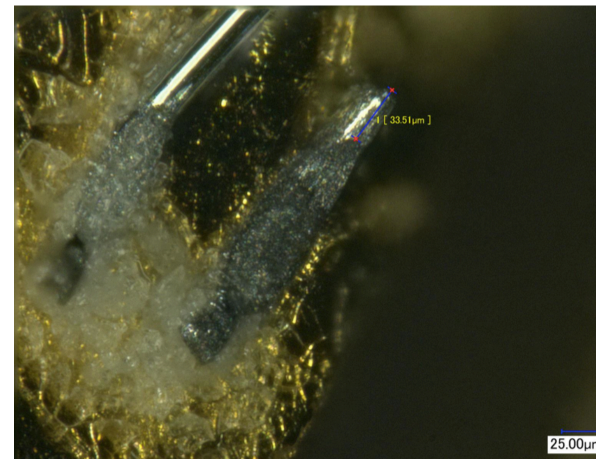
➢ Arranged modules & staves in final IBL for uniform low $\eta-\phi$ distribution of dead pixels for $\eta < 2$

➢ **Total bad pixel ratio for the integrated staves is < 0.1%**

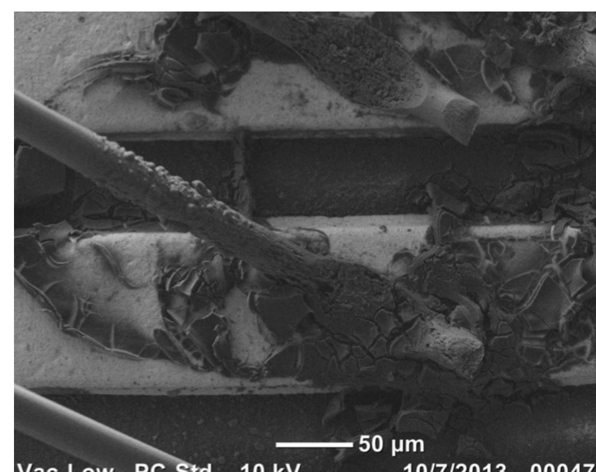


Wire bonds corrosion

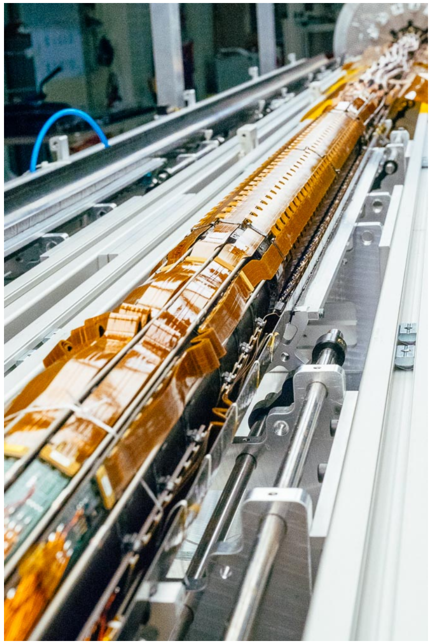
- Two staves were accidentally exposed to a severe condensation during QA
- Observed corroded wire bonds which triggered a detailed inspection of all staves



- ➢ Stopped production in earlier September 2013
- ➢ Intensive investigation program & solution:
  - ❖ Found Halogen (Cl or F) associated with corrosion product (residue)
  - ❖ Aggressive cleaning helped but also weakened the gold metallization
  - ❖ Coating with Uretan showed a very good protection (too late for being applied in the production)
  - ➢ **Rework of the affected staves already produced**
    1) **Wire bonds removal and cleaning**
    2) **Re-boning all FE and wings pads**
    3) **Keep the detector dry as much as possible**



Stave integration onto IPT

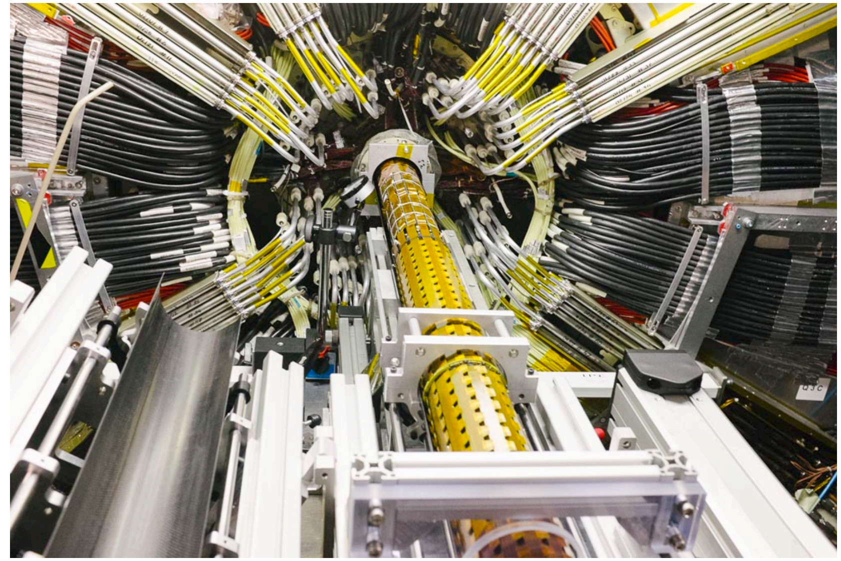


Integrated staves on support tube (IPT) within one month

- Stave was mounted with a support structure onto the IPT (clearance less than 0.8mm between IPT and stave) after cooling pipe extensions were made by brazing
- Staves were connected on both ends to power and readout services and then tested

➢ **Tests confirmed the results obtained during stave QA**

Installed, connected and tested

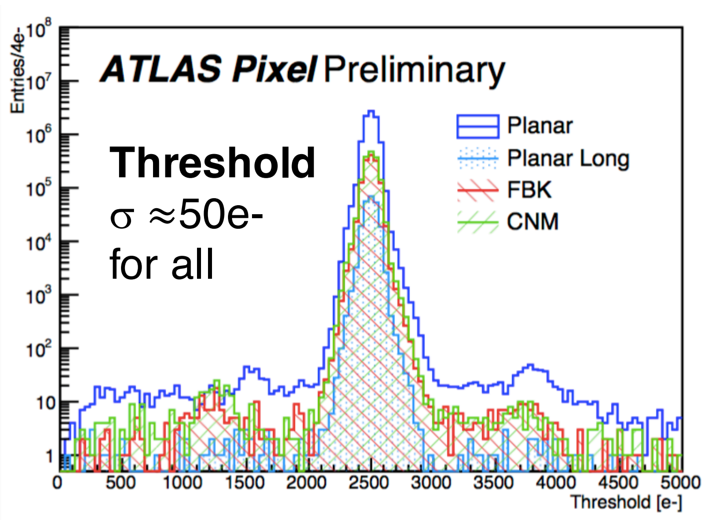


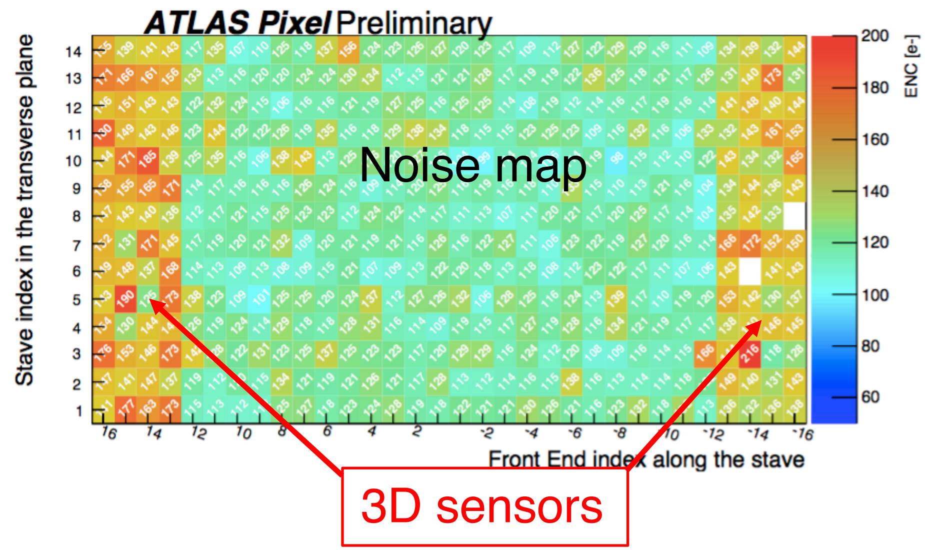
- May 2014: the detector was completed and installed
- End of June 2014: the detector was connected to power, readout and cooling, and then the detector commissioning started

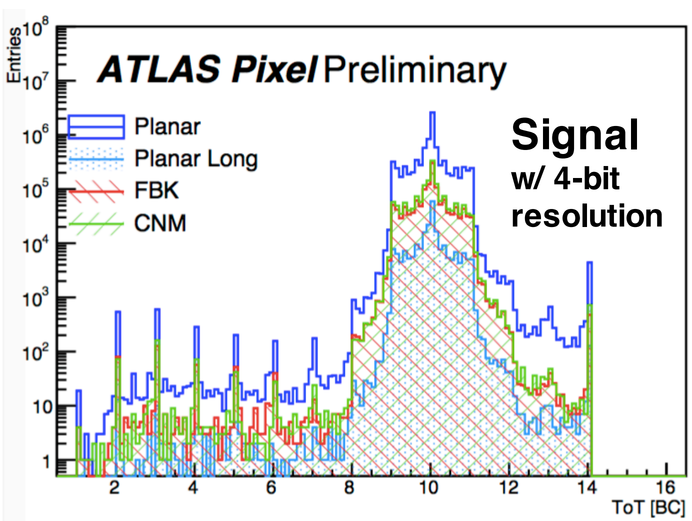
  - **From electrical/ functional-tests no deterioration observed**

Calibration

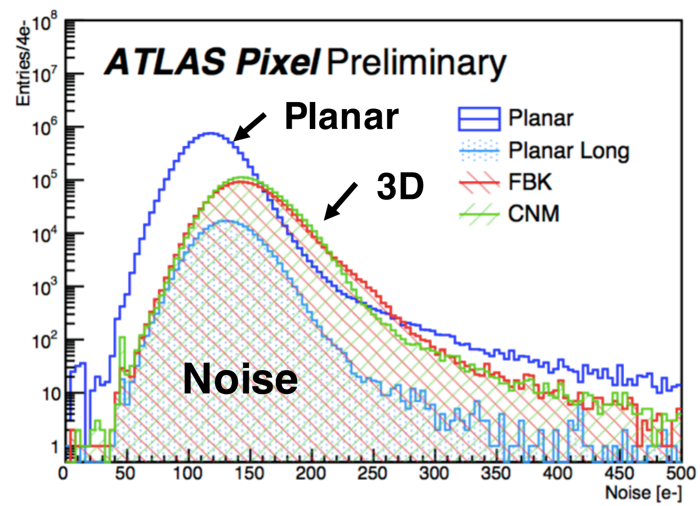
Tuning: Threshold at 2500e- and TOT of 10 at 16000e- (Temp= -15 ^{o}C)



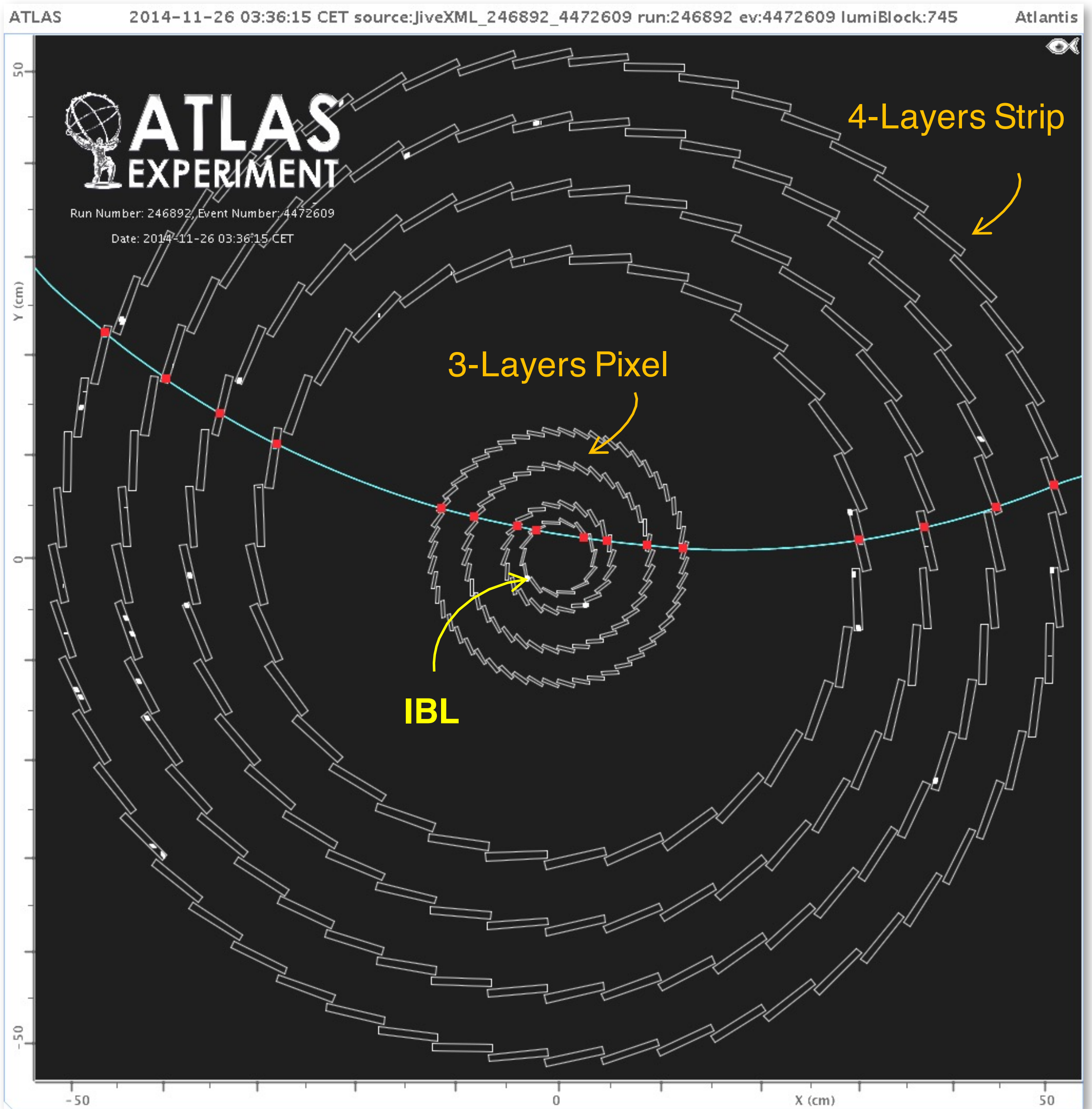




Vbias:
3D=20V
Planar=80V



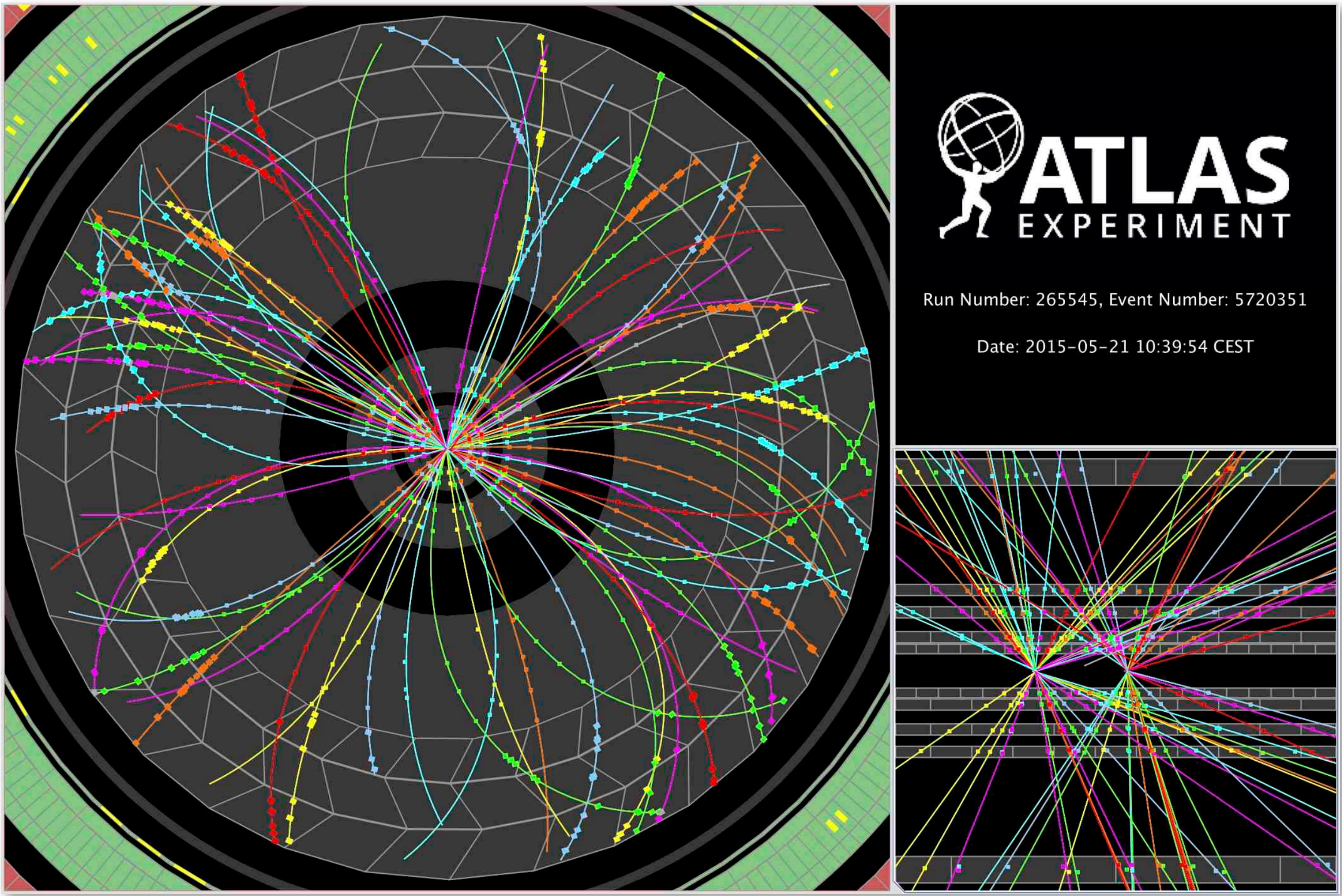
Commissioning with cosmic rays



November 2014:

First track with **IBL** integrated into the ATLAS data-taking

First tracks with the **4-Layer Pixel** detector **included** into ATLAS data-taking collisions at 13 TeV, May 2015.



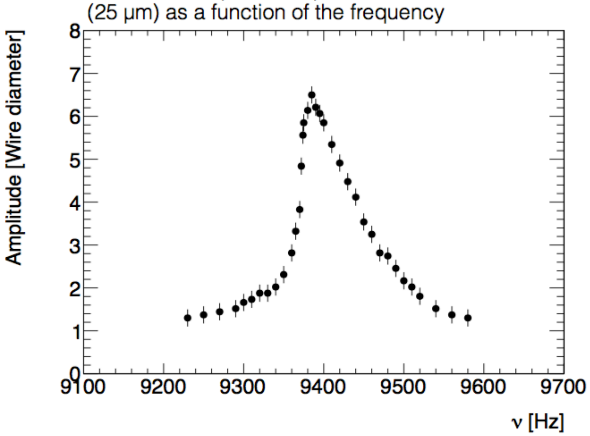
See next talk by S. Tsuno

Wire bonds oscillation

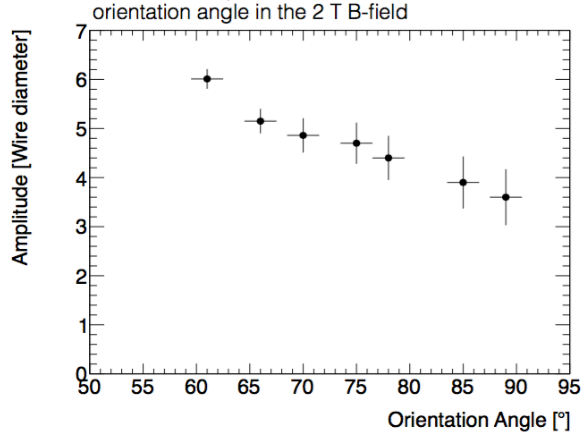
Wire bonds operate in the 2 T B-field and most of them at low currents except for voltage regulator connections

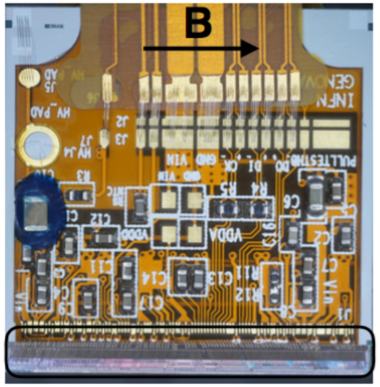
- High currents can be caused by consecutive triggers or calibration scans (max possible AC current is ~ 100 mA)
- Test and simulation showed that wires can break at the resonance frequency or in one harmonic
  - Digital supply lines are susceptible to current fluctuation when receiving triggers

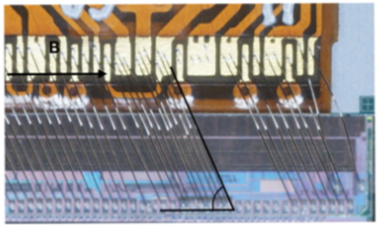
Oscillation amplitude expressed in wire diameter (25 µm) as a function of the frequency

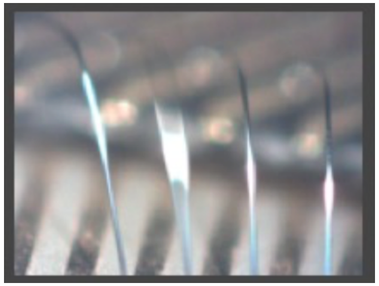


Oscillation amplitude as a function of the orientation angle in the 2 T B-field







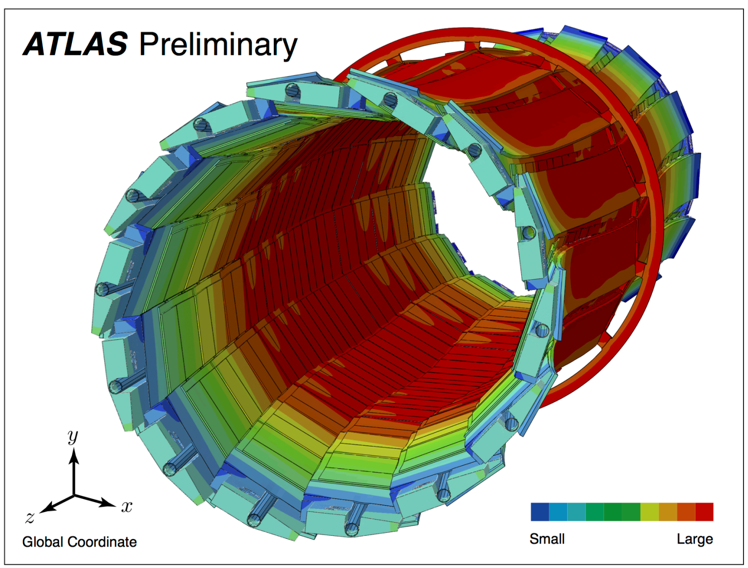


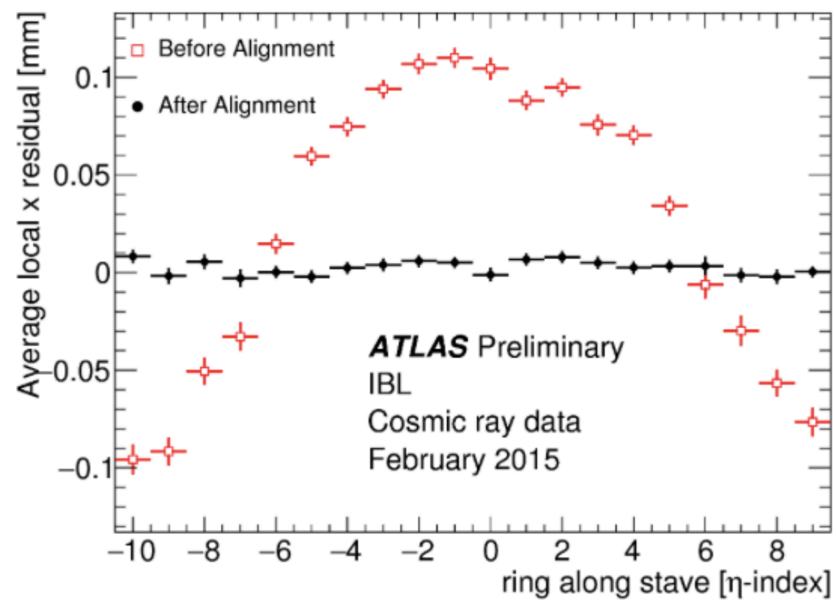
➢ **Fixed Frequency Trigger Veto** (FFTV) **implemented** into the readout chain to limit the number of trigger in resonance region

Mechanical distortion

- Observed in early 2015 during cosmic runs at the level of few µm/K
  - Origin: **CTE mismatch** between service buses and staves that manifests itself in a r-ϕ **twisting** of staves at the level of few µm/K

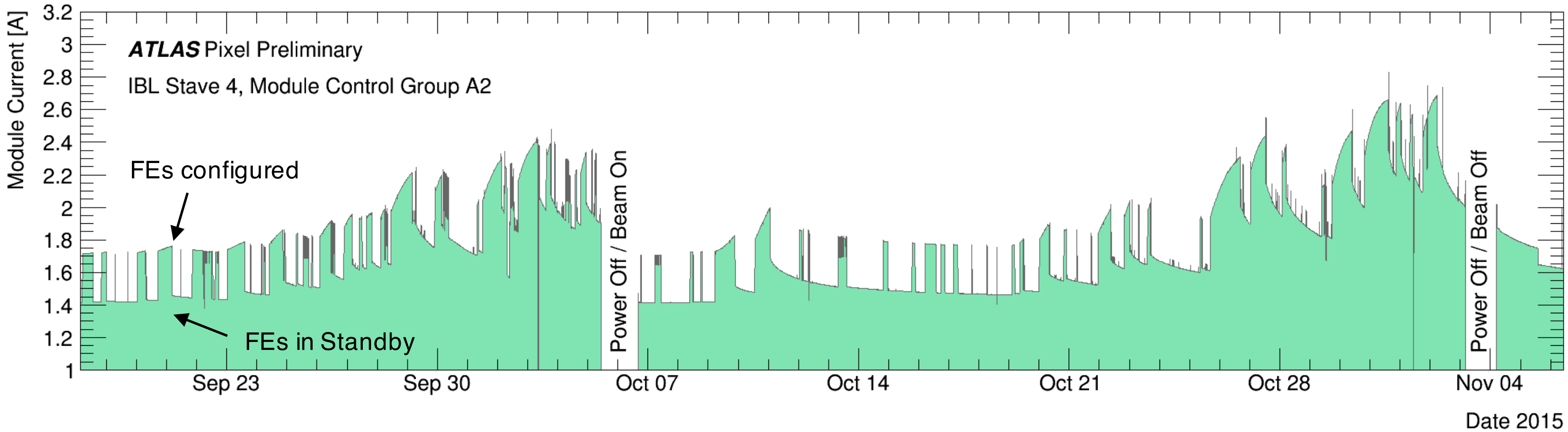
➢ The impact of this effect is **manageable** by a careful temperature control **at the level of ~0.2K** (alignment correction every 100 luminosity block)





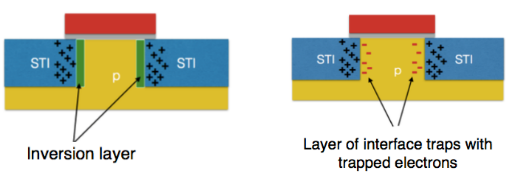
See dedicated poster on alignment by J. Pena

FE-I4 low voltage current drift



FE **low voltage current** and parameters (**threshold**, **ToT**) **drifted with integrated luminosity** in 2015

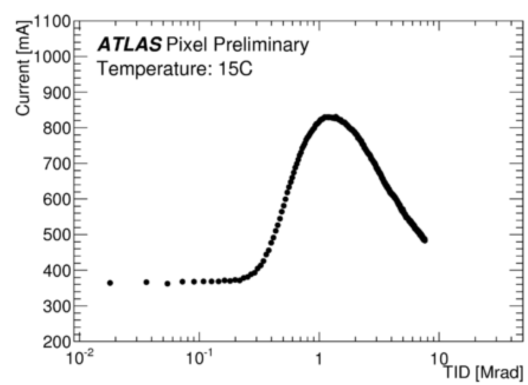
Consequences: Temperature increase and electrical failures



- Understood to be caused by a N-MOS transistor leakage current due to defects built-up at the silicon oxide interface (STI) and accumulated with increasing by the total ionization dose (TID)

- Parametrization of the leakage current was computed

➢ **Using special detector operation procedures, a successful data taking was possible**



See dedicated talk by K. Dette on Thursday

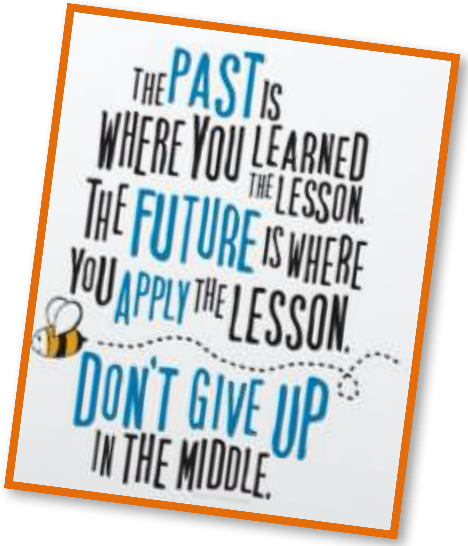
Lessons for the future

- **IBL** is a new detector **built relatively quickly** and with a short R&D time
- **Major issues discovered** late in the production, during commissioning and data-taking but **no showstoppers**.

Lessons learned:

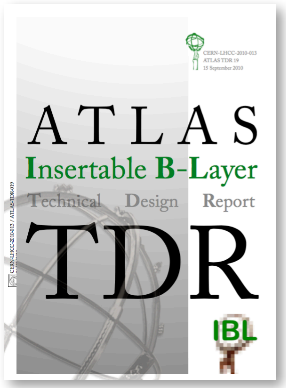
A new detector even if built by experts needs time for R&D, review and extensive qualification in all its domains.

- Mechanical distortion → stiff structure low susceptibly to temperature variation (low CTE).
- Wire bonds oscillation → potting, thick wires or no wires at all (TSV + RDL + Laser soldering).
- FE chip (NMOS transistor leakage current) → qualification to radiation should not be done only for intermediate and high doses.

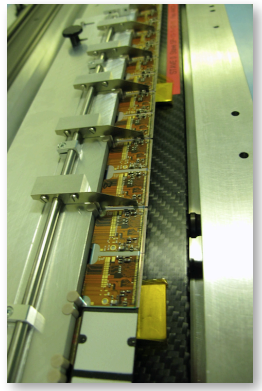


Summary

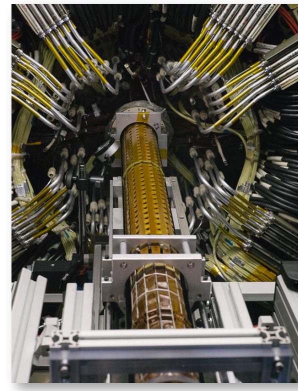
September 2010



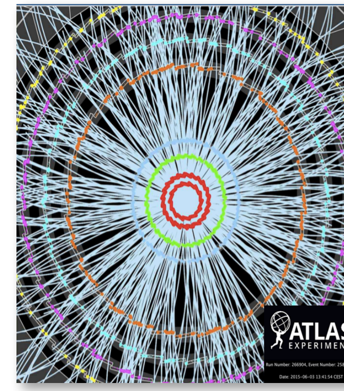
Mid 2012



May 2014



Since May 2015



The Long-Shutdown-1 was realized as an opportunity and finally a great success for the Pixel Detector upgrade:

- **4th Layer Pixel (IBL) successfully installed and in operation with good performance**
- **First** and **successful use-case** of **3D-Si** sensors in HEP experiment !

References

- ATLAS Insertable B-Layer Technical Design Report.
  CERN-LHCC-2010-013.
- ATLAS Insertable B-Layer Technical Design Report Addendum.
  CERN-LHCC-2012-009.
- Prototype ATLAS IBL Modules using the FE-I4A front-end readout chip.
  JINST (2012) 7 P11010.
- IBL Module Loading onto Stave and Quality Check
  ATL-INDET-PUB-2015-003.
- ATLAS Pixel IBL: Stave Quality Assurance
  ATL-INDET-PUB-2014-006.
- Cluster Properties and Lorentz Angle Measurement in the 4-Layer Pixel Detector Using Cosmic Rays.
  ATL-PHYS-PUB-2015-012.
- Studies of IBL wire bonds operation in a ATLAS-like magnetic field.
  PH-EP-Tech-Note-2015-002.
- Study of the mechanical stability of the ATLAS Insertable B-Layer.
  ATL-INDET-PUB-2015-001.