The ATLAS Insertable B-Layer Detector (IBL)

D. Giugni / INFN Milano
H. Pernegger / CERN
on behalf of the IBL collaboration
Outline

- Motivations for IBL
- Insertion environment and geometrical constraints
- Baseline for the detector lay-out
- Sensors and FE electronics
- Mechanics, thermal performances and cooling
- Installation scenario
Atlas Pixel overview

Atlas Pixel is the innermost detector of the ATLAS tracker system.

- 3 tracking points up to $\eta<|2.5|$ layers barrel and 3+3 disks
- 1744 modules with 46080 pixel 50x400 $\mu$m$^2$
- 80millions channels total.
- 16.9 KW cooled via an evaporative C3F8 system.
Why does ATLAS need IBL…
**LHC/ sLHC Luminosity profile**

- The actual innermost layer (B-layer) cannot last up to the end of the Phase I. Radiation damage on the sensors will reduce the efficiency of the detector.

- The foreseen integrated luminosity ramp gives, in 10 years time, \(650 \text{ fb}^{-1}\)
- Actual B-Layer is designed for \(\sim 150 \text{ fb}^{-1} \) [\(7.1 \times 10^{14} n_{eq}/\text{cm}^2\) or 50MRad].
- IBL will be inserted when LHC has delivered already \(\sim 100 \text{ fb}^{-1}\) and it will see nominally \(550 \text{ fb}^{-1}\) [\(2.7 \times 10^{15} n_{eq}/\text{cm}^2\) or 190MRad]
- Due to the errors in the hadronic interaction cross-section the designing dose is: 
  \[1000 \text{ fb}^{-1}\] or \([5 \times 10^{15} n_{eq}/\text{cm}^2]\) or \([350\text{MRad}]\)
Not only irradiation

• Degradation of the sensor performances with the integrated dose is what is at the origin of the B-layer replacement in the Pixel detector. This affects:
  – The *depletion voltage* of the sensor that can rise above the 600V → lower charge collected.
  – *Charge trapping* → lower charge collected.
  – Increase of the leakage current → increase of the noise and increase of the power dissipated by the module. This could trigger a positive feedback effect that takes the module to a thermal run-away.

• But there are several other events that could degrade significantly the efficiency of the detector:
  – *High operational temperature of the modules.*
  – *Leaks in the detector that would force to shutoff cooling loops.*
  – *Failure in the opto-board and lost of a significant number of modules.*
Leaks

- A single cooling loop serves, in the barrel, 26 modules and, in the disk, 12. In case of a major leak with a significant loss of fluid the loop has to be turned off with the consequence *loss of 26 modules.*
- B-layer has 11 bi-staves with 286 module in total. A loss of 26 module due to a cooling loop is almost the ~10% of the B-Layer.
- Note that such a leak *won’t be repairable without removing the detector.*
- Estimates of the *probability of such an event are extremely unreliable.*
  Some leaks have already appeared and the aging will certainly worsen the situation.

OptoBoard failure

The read out is performed optically via an optoconverter. Modularity is high.

- In case an *optoboard fails we loose 6/7 module in one go:* half stave or a disk sector.
- It is a significant loss for the B-Layer.
IBL motivations summary

- Radiation damage on the sensor that will not survive at the end of LHC phase I.

- Leaks in the cooling loops that force to shutoff a large fraction of the detector.

- Failures in the on board read-out chain at the optoconverters.
Environment
Insertable rather than replaceable

- The Pixel detector went through a significant re-design after the insertion scenario had been changed.
- The detector became a ”package”, with the Beam Pipe embedded in it. The package could be inserted into the SCT detector at the very “last minute”.
- The aim was to postpone as much as possible the installation time without delaying the integration of the rest of ATLAS.
- In fact the “package” concept worked rather well and it allowed us to recover time and solve severe problem encountered during the production phase (stave pipe corrosion) without impacting on the overall ATLAS schedule.

The Pixel installation date, agreed with ATLAS, has in fact been met.

- The “con” was the difficult access to the B-layer with the tradeoff of inflating time required for the BL replacement is no longer feasible in the Winter 2013/2014.
Insertable rather than replaceable (2)

It turned out to be preferable to install a new layer at a smaller radius inside of the existing three.

- The shut down time is significantly reduced.
- Can benefit from the technological step: sensor, electronics and mechanics.
- The physics performances are enhanced due to the smaller radius.

Difficult thing is to find out the required space in the gap between the first layer and the beam pipe. Beam pipe diameter reduction looks to be the natural way to explore.
Reduced diameter beam-pipe

- Beam stay-clear 14mm
  - Composed of beam size, beam separation, closed orbit and crossing, angle components
  - within the tracker region (±5 m) at injection.
- Survey Precision ~ 2.6mm
- Mechanical construction ~ 2.6mm
  - Tolerances on straightness, circularity, wall thickness, sag under selfweight and construction of survey targets
- Instabilities ~ 9.8mm
  - Stability of the cavern, detector movements due to electro-magnetic forces and thermal expansion

**TOTAL beam pipe aperture R29mm**
Reduced diameter beam pipe

- Cavern stopped *lifting* since 2005.
- The *beam pipe aperture* can be revisited and reduced to 25mm.
- The min outer radius is *R29 mm*, includes
  - Beryllium wall thickness,
  - Bake-out heaters
  - Insulation

*It might look marginal but this is what makes the insertion of the new layer possible.*

<table>
<thead>
<tr>
<th></th>
<th>Current Design (mm)</th>
<th>Phase I (proposed) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam aperture (10σ)</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Alignment</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Construction and deflection</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Stability during run, and between alignments</td>
<td>9.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Physical radius of pipe</td>
<td>29</td>
<td>25</td>
</tr>
</tbody>
</table>
Lay-out
Basic requirements for the IBL lay-out

The *beam geometrical parameters* are not expected to change (at least before the upgrade time):

- One pixel hits over the full rapidity range covered by the actual Inner Detector (|h|<2.5), for all tracks generated within |z| < 11.2 cm (2σ) of the beam crossing point.
- 1 GeV min transverse momentum full coverage [R=1.6m].
- Coverage to infinite momentum tracks up to a max beam offset of 7 mm

Some key numbers of the layer:

- 14 composite supports (staves)
- R32 mm mean sensor radius
- Sensor surface only ~0.2m2
- 1.5KW power cooled @ ~ -20°C via an evaporative cooling system.
Electronics and Sensor
New Front End Chip: FEI4

- Why a new FE design
  - Radiation hardness has to be increased from 50MRad → 350MRad
  - New architecture to reduce the inefficiencies.

- Parameters of the new FE
  - Pixel size = 250 x 50 µm²
  - Pixels = 80 x 336
  - Technology = 0.13 µm² (on the way to 90nm)
  - Power = 0.5 W/cm² (max) , 0.25 W/cm² (nominal)

- FE-I4 Design Status
  - Contribution from 5 laboratories: Bonn, CPPM, INFN Genova, LBNL, Nikhef
  - Main blocks MPW submitted in Spring 2008 and under test now
  - Working on Full-Size FE-I4 ready for submission to build IBL prototype modules next year
**Readout links**

- **Try to minimize changes from present system:**
  - Down link (TTC) stay the same 40Mb/s
  - Uplink use 160 Mb/s data+clock (8b/10b encode) – Single FE-I4
  - Need new BOC design
  - Use GRIN fibers (under rad-test for SLHC, or new Ericsson)
  - Opto-board at PP1 – test on going for the electrical signal transmission at 6m on a twisted pair.
Sensors: 3D silicon

- Approved ATLAS upgrade R&D
- pro’s:
  - Good charge collection but more power in the FE for same time-walk
  - Active edge
  - Lower bvolatge (<150 V), power after irradiation lower than planar
- Con’s:
  - column Inefficiency at 90°
  - Higher $C_{det}$
  - Need to establish yield in “scale” production
- See Poster by Andrea Zoboli/Trento on FBK 3D-DDTC sensors and Cinzia DaVia on 3D detectors for LHC upgrade

3DC Fabricated at Stanford and tested with Atlas pixel and SLHC fluences
3DC SINTEF
FE-I3 n-on-n Bum-bonded, n-on-p with FE-I4 run started. Should be ready by spring 09

IRST - FBK Trento
Run n-on-p completed FE-I3 bump-bonded. Active edge being included in layout CNM
n-on-p completed and FE-I3 waiting for bump-bonding

Double column design

Test beam $\epsilon = 99\%$
Sensors: New planar silicon

- Approved ATLAS upgrade R&D
- Pro’s
  - n-on-n is a proven technology with minor changes for IBL (pad size)
  - n-on-p single sided process (costs) is being studied
  - Lower $C_{\text{det}}$ → lower noise, lower in-time threshold for same power settings in the FE.
  - Partially depleted sensors collect charge
- Con’s
  - Need for slim edges → reduce dead area in Z
  - Need high bias voltage (~1000V$_{\text{bias}}$?)
  - N-on-p need high voltage insulation on chip side
- Study n-in-n and n-in-p structures with DOFZ and MCz wafers
- Develop “slim” edges (reduce guard ring width)
- Submitted prototype run at CiS (Erfurt)
Sensors: CVD diamond

- Approved ATLAS upgrade R&D
- pro’s:
  - No leakage current increase with radiation
  - Lower capacitance, therefore less threshold required for in-time efficiency
  - Can operate at any temperature, no cooling issues
- Con’s:
  - Smaller signal (with poly-crystal CVD)
  - Need to establish yield in “scale” production
  - Higher cost & number of vendors (?)

- Single-chip and 16-chip modules bump-bonded at IZM (Berlin), constructed and tested in Bonn
- Operating parameters (FE-I3): Peaking Time 22ns, Noise 140e, Threshold 1450-1550e, Threshold Spread 25e, Overdrive 800e

Spatial resolution with TOT information: 8.9µm
Mechanics and Thermal management
Stave design

Main parameters
- 32 FE chips/ stave. Single or 2 chips module
- Stave power: 100W (32FE chips + sensor bias)
- $X/X_0$ target (only mechanics) < 0.5%
- Low cool down induced deformation < 100um
- Mechanical stability at the micron level
- MDP (Max Design Pressure) 100bar

Design
- Based on light carbon foams
- Cooled by evaporative system
- Mechanics has 2 options:
  - Homogeneous Stave with the carbon Fiber Pipe.
  - Titanium pipe based stave.
What is an homogenous stave?

The homogenous stave is a carbon based stave that has all the parts made of composite. Specifically the cooling pipe, i.e. the boiling channel, is made of carbon fiber.

- **The stiffness is provided by a CF laminate:**
  
  Fiber YS-80A; resin EX-1515; lay-up \((0/60/-60)_{S2}\)

- **Carbon foam diffuses the heat from the module to the cooling pipe**
  
  Poco Foam \(\rho=0.55\text{g/cm}^3;\) \(K=135/45\) W/mK  
  Kopers KFOAM L1-250 \(\rho=0.245\text{g/cm}^3;\) \(K=40\) W/mK  

- **The CF pipes is the boiling channel made through an over-braiding and RTM/extrusion process.**

  Fiber: T-300 1k rowing-24 rows;  
  Matrix: Aralidite 5052  
  Lay-up: BRAID \([\pm 45^\circ]\)  
  Fiber v. ratio: 0.4\(\rightarrow\)0.6 in volume
Why? What are the benefits

1) **Much better X/X₀:**
Significantly lighter than the metal pipe.

2) **Substantially unaffected by the deformation**
induced by the temperature drop. Practically, playing with the lay-up, it is possible to tune and match the pipe longitudinal CTE to those of the surrounding parts.

3) **It has no corrosion issue!**
Our experience with aluminum piping was characterized by *recursive corrosion events*. Pixel detector Alu piping has suffered extensively of corrosion both on the detector and off detector. Aluminum is *far in the galvanic series from any material used in the detectors structures (Cu, Ni, C) and the risk of destructive corrosion can never be excluded.*

Aluminum is particularly worrisome becomes in case of galvanic corrosion it becomes *the sacrificial anode and large parts of its volume can be “digested” by the process.*

<table>
<thead>
<tr>
<th>IBL Monopipe layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Alu</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>PipeID_Radius</td>
</tr>
<tr>
<td>PipeOD_Radius</td>
</tr>
<tr>
<td>Pipe Cross Section</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>weight/length</td>
</tr>
<tr>
<td>Number of pipe in IBL</td>
</tr>
<tr>
<td>IBL pipe radius</td>
</tr>
<tr>
<td>cylindrical density</td>
</tr>
<tr>
<td>X₀</td>
</tr>
<tr>
<td>X/X₀</td>
</tr>
</tbody>
</table>
The Homogeneous stave

- Here is the first prototype of the stave. The critical aspect is the *thermal contact* between the carbon pipe and the foam.
- The X-ray tomography taken during the qualification of the thermal bond shows how the resin “impregnates” the pores of the foam as if it were a sandwich core.
- Preliminary thermal measurements dedicated to quantify the thermal impedance due to the interface *did not reveal measurable contributions*.

- *Thermal tests are actually ongoing.*
Titanium pipe stave

A valuable alternative is to substitute the composite pipe with a metal titanium pipe:

- Corrosion resistant and compatible with composites.
- Low CTE (compared to the other metals): 8.6 ppm/°K
- High thermal conductivity: 16.4 W/mK
- High strength: yield at 340MPa
- Weldable:
  Laser, Electron Beam, TIG welding… and brazing

- Rather light: 4.52 g/cm³
- Available at wall thickness of ~100μm

Prototypes are already available
Cooling
Thermal run-away

The cooling is hinging around the “so called” thermal run-away effect:

- Radiation increases the sensor leakage current
- Sensor Power dissipation increases
- Temperature increases
- Sensor current increases accordingly to →
- ... and so on
- Power and temperature diverge

\[
\frac{I(T)}{I(T_0)} = \left(\frac{T}{T_0}\right)^2 \exp \left(-\frac{E_s}{2k_B}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right)
\]
Thermal management

- Thermal performance of the stave depends upon the choice of the boiling channel material: CF or Titanium.
- The conductive part is significantly different and it ranges between \( \sim 17 \, ^\circ\text{C} \cdot \text{cm}^2/\text{W} \) (CF) and 2.4 \( ^\circ\text{C} \cdot \text{cm}^2/\text{W} \) (Ti).
- For the thermal run-away the stave thermal performance is not the only variable; another key parameter is the evaporation temperature.
- For IBL we want to consider both the C3F8 (min \( T_{\text{evap}} = -30^\circ\text{C} \)) and CO2 (min \( T_{\text{evap}} = -40^\circ\text{C} \)) option.
- The low irradiation level (with respect to the upgrade phase two) allows to consider both fluids.
Thermal run-away

Assumption:
• Sensor power for planar @ 1000fb⁻¹:
  • 70mW/cm² @ -25°C OR
  • 200mW/cm² @ -15°C
• -30°C as max evaporation temperature (compatible with C3F8 evaporation system).

Considered
• Carbon Fiber Stave (1 or 2pipes)
• Titanium stave.

The thermal performances are still adequate to cool the sensors but marginal if the sensor bias voltage is increased.

→ CO2 system cooling?
Detector installation
How to remove the current beam pipe

- The beam pipe flange on A-side is too close to the B-layer envelope. Need to be cut on the aluminum section.
- A structural pipe is inserted inside the Beam Pipe and supported at both sides.
- The support collar at PP0 A-side is disassembled and extracted with wires at PP1.
- Beam pipe is extracted from the C-side and it pulls the wire at PP1.
- New cable supports are inserted inside PST at PP0.
- A support carbon tube is pushed inside the PST along the structural pipe.
Installing the detector

- The support carbon tube is fixed in 2 point of PP0 and on PP1 walls on side C and A.
- The structural pipe with a support system is removed from the support composite tube.
- The new beam pipe is inserted from C-side.
Summary

- The Insertable B-Layer will be a new, 4th pixel layer to be added for the high-luminosity in the present ATLAS Pixel system
  - Smaller radius and lighter to further improve pixel performance
  - Compensate for gradual inefficiency of existing B-Layer
- The IBL is the “technology” bridge to sLHC
  - Its specification requires us to develop and use new technologies, which are directly relevant to sLHC
  - Construct a full detector system with those technologies on the time scale of 4-5 years
  - Development of Radiation hard sensors
  - New architecture and process for Pixel Front-End Chip
  - Lighter Support structures to minimize X0
  - More efficient cooling