The ATLAS Insertable B-Layer project

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ABSTRACT: The ATLAS experiment will upgrade its pixel detector with the installation of a new pixel layer in 2013–14. The new sub-detector, named Insertable B-layer (IBL), will be installed between the existing pixel detector and a new smaller radius beam-pipe at a radius of 3.3 cm.

To cope with the high radiation and pixel occupancy due to the proximity to the interaction point, a new read-out chip and two different silicon sensor technologies (planar and 3D) have been developed. Furthermore, the physics performance should be improved through the reduction of pixel size while a low material budget should be imposed. A new mechanical support using lightweight staves and a CO₂ based cooling system is used.

An overview of the IBL project and the status of the production of staves and the qualification of the assembly procedure, the loaded module electrical integrity and the read-out chain will be presented.

KEYWORDS: Particle tracking detectors; Large detector systems for particle and astroparticle physics
1 Introduction

In 2014 the Large Hadron Collider (LHC) [1] will upgrade its energy to 14 TeV and its peak luminosity to \( \mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \), planning to reach \( \mathcal{L} \approx 2 - 3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) for 2020, and aiming an integrated luminosity of about \( L \approx 300 \text{ fb}^{-1} \) in that period.

The current ATLAS [2] pixel detector [3] was designed for a peak luminosity \( \mathcal{L} \approx 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \), so an upgrade of such detector is needed in order to avoid degradation of the ATLAS performance in tracking, vertex reconstruction and b-tagging due to the high number of interactions per bunch-crossing, the so called pile-up.

IBL (Insertable B-Layer [4]) will improve b-tagging by introducing a 4th, high granularity, pixel layer that will provide redundancy of the B-layer measurements and it will improve the tracking performances thanks to smaller pixel occupancy. Simulations show that, with the IBL inserted, the ATLAS tracker will be able to efficiently perform track pattern recognition with a peak luminosity \( \mathcal{L} \approx 3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \).

The IBL has been designed to withstand 250 MRad of ionizing dose and \( 5 \times 10^{15} \text{ neq/cm}^2 \) non-ionizing dose, these guarantee safety margin values of 40% with respect to the expected integrated luminosity in 2020.
2 IBL design and goals

The IBL consists of 14 staves arranged around the beam-pipe with a tilt of 14° allowing for an azimuthal overlap of the staves (Δφ = 0.18°) to ensure complete coverage in φ and to compensate for the Lorentz angle in the 2T solenoidal magnetic field of the ATLAS detector. No overlap in z is foreseen and so the design has to minimize the gap between sensors areas, which is about 250 µm. The average distance of the staves with respect the center of beam pipe is 33.25 mm. Figure 1 shows the IBL structure in the \( r - \phi \) plane.

Each IBL stave is 64 cm long and covers a pseudo-rapidity \(|\eta| \leq 2.9\), where \( \eta = -\ln[\tan(\theta/2)] \) and \( \theta \) is the angle of an out coming particle with respect to the beam axis.

The cooling pipes are made of titanium, to avoid corrosion of the pipes; permanent pipe joints will get rid of possible leakage at the fitting points.

The IBL is a very light detector with a material budget corresponding to only 1.9% of a radiation length.

A new beryllium beam pipe will be inserted together with the IBL, the new beryllium beam pipe will have a radius of 25 mm, 4 mm smaller than the old one.
3 Sensors and electronics

The main requirements for IBL regard the radiation hardness of the components. The sensors are more sensible to damage induced by neutral particles, while electronic components are mainly damaged by charged particles.

3.1 Front end technology

A new readout chip has been developed for the IBL, the FE-I4 [5]. The chip design has been developed in 130 nm CMOS technology, while the previous version of the chip, the FE-I3 used a 250 nm CMOS process.

The main features of this chip are:

- large dimension, $21 \times 19 \text{mm}^2$;
- pixel size $50 \times 250 \mu\text{m}^2$, smaller than FE-I3;
- 26880 pixels arranged in 80 columns and 336 rows;
- noise ≃ 100 equivalent electrons;

Each pixel cell contains an amplification stage, with adjustable shaping, followed by a discriminator, with adjustable threshold, which allows the measurement of the discriminator time and a time-over-threshold.

The pixel array is subdivided into a $2 \times 2$ pixels regions which share a common Pixel Digital Region (PDR) holding memory, hit logic and trigger processing. The PDR allows for high occupancy running. The FE-I4 has a maximum trigger rate of 200 kHz and a hit inefficiency less than 1% at occupancies of 400 MHz/cm$^2$. This local hit storage supports higher occupancy without saturation with respect to the FE-I3. The inefficiency of FE-I3 and FE-I4 as a function of luminosity is reported in figure 2.

3.2 Sensor technology

Two sensor technologies have been chosen for IBL: a conservative planar [6] technology and a novel 3D [7] technology introduced for the first time in one of the LHC experiments. The planar technology covers the innermost part of the detector for 75% of the active area, while the 3D one is used for the outermost part in $|\eta|$, covering the remaining 25%. The performances of unirradiated and irradiated IBL modules has been evaluated in test-beams [8] at DESY with a 4 GeV positron beam and at CERN with 120 GeV pions using the EUDET [9] telescope to reconstruct the beam trajectories with high resolution as the main external reference system.

3.2.1 Planar technology

The planar technology is already used for the current pixel detector. Some changes have been applied in order to improve radiation hardness and to reduce inactive area. The IBL planar sensors are built in n-in-n technology, 200 $\mu$m thick, $4 \times 2 \text{cm}^2$ wide.

The use of a novel slim edge concept reduces the inactive region to only 200 $\mu$m. This is possible by moving the 13 guard rings underneath the active region from the edge.
Figure 2. Readout chip inefficiency for FE-I3 and FE-I4 as a function of the luminosity.

After an irradiation campaign up to $5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ the noise of a planar module stays under 250$e^-$ while 90% of the charge collected before irradiation is measured. So radiation hardness has been fully proved to be within the IBL specifications.

The cell efficiency after irradiation at $5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ has been measured for planar sensors to be 96.9% when a particle hits the sensor with an angle of $0^\circ$ with respect to the normal to the silicon surface and 86.4% when such an angle is about $15^\circ$ [8].

3.2.2 3D technology

The 3D technology uses the innovative concept of electrodes that pass through the bulk and are not only on the surface of the silicon sensor. This allows to use lower bias voltage with respect
to the planar technology and improves the performances after irradiation of the sensor. The IBL 3D technology uses n-in-p silicon sensors, 230 $\mu$m thick, $2 \times 2$ cm$^2$ wide. The cell efficiency after irradiation at $5 \times 10^{15}$ n$_{eq}$/cm$^2$ has been measured to be 97.5% for tracks perpendicular to the silicon and 99% when such an angle is $15^\circ$ [8].

4 Support staves

IBL is using carbon fibre material as support stave for the modules. This is a very light material, allowing to have less than 0.6% $X_0$ as support stave material budget.

In order to minimize damages due to radiation, the modules on the stave need to be operated at $-20^\circ C$, so cooling is provided to the modules through the support stave. Carbon foam provides the thermal path to the cooling pipe, which is hard bonded and the thermal contact is provided by thermally conducting epoxy.

A CO$_2$ two phase system has been chosen as cooling service. This consists of 14 boiling channels, each for one stave, with a nominal cooling power of 100 W. The total power of the cooling plant has been chosen to be 2 kW, in order to have a safety margin of 40%. The system is able to provide a cooling up to $-40^\circ C$ and to work with pressure up to 100 bar.

5 Construction status

The construction of the IBL is currently underway. The module production step is close to the end, which is foreseen by December 2013; this step includes bump-bonding of the readout chip to the sensors, glueing of a kapton PCB to the sensor back-side, and wire bonding of the readout chip to this PCB.

The loading of modules onto the staves is on-going at University of Geneva, where several tests are performed at each loading step. These are:

- metrology tests, to check the envelop of staves at micro metric precision;
- thermal cycles, to check the survival of electrical and mechanical properties of the staves after cycles from $40^\circ C$ to $-40^\circ C$;
- two electrical tests during loading operation, to check the status of the staves before and after the thermal cycles.

A rework procedure has been set up in order to deal with mechanical problems and electrical failures of the modules; this procedure has been approved and applied to 7 staves so far.

Currently 17 staves out of 20 have been produced. The best 14 will be used for the IBL, while 2 of remaining ones will be used for the system test.

The integration of the IBL will proceed through brazing the titanium cooling pipe extension to the stave, mounting the staves around the beryllium beam-pipe using a multi-purpose-container (MPC) loading device, connecting the services. A final test before installation is also planned. The stave integration will finish in early 2014, to allow for IBL installation into the ATLAS cavern in spring 2014.
6 Quality assurance procedure

Dedicated test and Quality Assurance (QA) procedures have been setup at each construction step in order to fully qualify the IBL production.

Modules QA is on-going at the University of Bonn and University of Genova, that are also taking care of the module assembly, while staves QA is on-going at CERN and University of Geneva.

The tests consist of warm ($\simeq 15^\circ C$) and cold ($\simeq -20^\circ C$) temperature operation of modules and staves. Modules and staves go through the following checks:

- I-V curves, shown in figure 3: to check integrity of the sensors and their breakdown behavior
- FE-I4 power consumption: to check front-end operation
- Module characterization: this includes radioactive source scans and tuning performances (figure 4(a) and (b)) at different thresholds in order to check the module features and estimate the number of bad pixels.

7 Summary and outlook

The first upgrade of the ATLAS pixel detector, the Insertable B-Layer (IBL), consists of a 4th layer of pixels that will be installed on smaller radius beryllium beam-pipe during the 2013–14 shutdown of the LHC.

The IBL will use both slim-edge planar and 3D sensors with a new front-end chip, the FE-I4, to cope with the expected high occupancies and radiation levels. Test-beams show excellent results. The first IBL staves have shown excellent behavior on a dedicated QA test-stand at CERN. Stave production will finish by the end of 2013, and the integration of the staves onto the beam-pipe should finish by early 2014. The IBL will be installed inside the ATLAS experiment by spring 2014.
Figure 4. Examples of tests performed in stave Q.A. assurance site at CERN: (a) Stave Threshold distributions for different targeted tunings; (b) Stave Noise distribution for different targeted tunings.

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