Nuclear Instruments and Methods in Physics Research A 699 (2013) 67–71

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Irradiation and beam tests qualification for ATLAS IBL Pixel Modules

Igor. Rubinskiy

DESY, Notkestrasse 85, 22607, Hamburg, Germany

On behalf of the ATLAS Collaboration

ARTICLE INFO

Available online 22 May 2012

Keywords:
ATLAS upgrade
Insertable B-Layer
IBL
FE-I4
Radiation hard sensors
NIEL
Planar pixel
3D pixel

ABSTRACT

The upgrade for the ATLAS detector will have different steps towards HL-LHC. The first upgrade for the Pixel Detector will consist in the construction of a new pixel layer which will be installed during the first shutdown of the LHC machine (foreseen for 2013–2014). The new detector, called Insertable B-Layer (IBL), will be inserted between the existing Pixel Detector and a new (smaller radius) beam-pipe at a radius of 33 mm. The IBL will require the development of several new technologies to cope with the increase in the radiation damage and the pixel occupancy and also to improve the physics performance, which will be achieved by reduction of the pixel size and of the material budget. Two different promising silicon sensor technologies (Planar n-in-n and 3D) are currently under investigation for the Pixel Detector. An overview of the sensor technologies' qualification with particular emphasis on irradiation and beam tests is presented.

1. Introduction

The ATLAS detector is a general purpose detector [1] at the Large Hadron Collider at CERN, which was designed to be sensitive to a wide range of physics signatures to fully exploit the physics potential of the LHC collider at a nominal luminosity of $1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. After the successful commissioning and operation in the last 2 years, it is planned to extend the LHC physics program into the High-Luminosity LHC (HL-LHC) by increasing the instantaneous luminosity by a factor of five. A three-phase upgrade of the LHC will be followed along by the upgrade of the ATLAS detector. The first phase (Phase-0) will take place during the 20-months long shutdown in 2013–2014 and will include the LHC magnets' repair to achieve the designed 14 TeV in the center-of-mass proton–proton colliding system. The instantaneous luminosity will reach $1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and an integrated luminosity of $50\,\mathrm{fb}^{-1}$. The second phase (Phase-1) will take place during the second 12-months long shutdown in 2017–2018 and will aim at a further increase in the instantaneous luminosity up to $2\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and an integrated luminosity of – $300\,\mathrm{fb}^{-1}$. The third phase (Phase-2) will take place after 2022 and will initiate the HL-LHC era aiming at $3000\,\mathrm{fb}^{-1}$ integrated luminosity to be collected during the following years.

During the Phase-0 shutdown the ATLAS Pixel Detector [2] will be extended with an additional layer inside of the existing detector system. The so-called Insertable B-Layer (IBL) [3] will be installed together with a new beam pipe to maintain an excellent vertex detector performance and compensate possible inefficiency of the current Pixel Detector, which may arise during the luminosity increase after the Phase-0 and Phase-1 machine upgrade.

This report is a follow up to [4–7].

2. ATLAS IBL requirements

The ATLAS IBL will be the fourth pixel layer mounted on a new beam pipe inside of the current innermost Pixel Detector layer (*B*-Layer). It is designed [3] to have 14 staves equipped with 32 sensor-chip assemblies with the sensor side of the assemblies closer to the beam pipe. The distance to the collision axis of the IBL modules is to be 31 mm in the closest and 40 mm in the outermost points with a mean distance of 33 mm.

The IBL Technical Design Report (TDR) [3] assumptions and module related characteristics are:

- The detector will operate until the Phase-2 upgrade, which implies a peak instantaneous luminosity of $2\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and an integrated luminosity of $550\,\mathrm{fb}^{-1}$, or in terms of a total fluence of $5\times10^{15}\,\mathrm{n}_{eq}/\mathrm{cm}^2$ including safety factors.
- A hit efficiency in the active area of the sensors is greater than 97% until after the total dose.
- Angular coverage: high p_T tracks hit the sensors in IBL with a phi angle between 0° and 28° and an $\eta<2.58$.
- A geometrical inefficiency $<2.6\%$.

E-mail addresses: igor.rubinskiy@desy.de, igorrubinsky@gmail.com

0168-9002/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2012.04.078

- The target temperature for operating the IBL sensors is approximately $-15\,^{\circ}$C, in order to minimize effects of reverse annealing on the sensors and to avoid thermal runaway. This also implies: an expected power dissipation of <200 mW/cm^2 at -15°, a sensor maximum bias at 1000 V, a leakage current of <100 nA/pixel.
- Technology driven engineering parameters: sensor thickness 225 ± 25 μm, small inactive edge <450 μm (this implies a sensor having a slim or active edge).

For the IBL a new front-end chip, called FE-I4 [8], was designed in 130 nm CMOS technology and consists of 26,880 pixel cells organised in a matrix of 80 columns (250 μm pitch) by 336 rows (50 μm pitch). The chip is using a 40 MHz clock and provides a digital readout with cell-wide adjustable threshold and internal 4-bit counter for the signal amplitude as Time over Threshold (ToT) measurement.

There are two different sensor design technologies which were chosen for the module construction. Depending on the technology, the modules consist either of one or of two sensor-chip assemblies. The planar pixel sensors (PPS) are manufactured by CiS (Erfurt, Germany) in n-in-n technology (200 μm thick) and are going to be mounted by two assemblies per module (Fig. 1a). The 3D sensors with double-sided column structure (230 μm thick) are manufactured by FBK (Trento, Italy) and CNM (Barcelona, Spain) and have only one assembly per module (Fig. 1b). Shingling in z is not foreseen for the IBL modules due to radial space constraints. This results in slightly different geometric acceptance for two-chip and one-chip assemblies. For one-chip (two-chip) assemblies the nominal acceptance for particles normal to the beam was estimated to be 98.8% (97.4%) for 450 μm inactive edges. An air gap of 200 μm (100 μm) between two-chip (single-chip) modules has been assumed to take into account the higher bias voltages needed by PPS with respect to 3D sensor-chip assemblies.

The final IBL design for the Planar n-in-n technology by CiS employs:

- guard rings on p-side are shifted underneath the outermost pixels,
- inactive edge reached at 200 μm,
- less homogeneous electric field, but charge collection after irradiation dominated by region directly underneath the pixel implant.

The final IBL design for the 3D sensors produced by FBK and CNM is based on a similar process:

- FBK full pass-through columns stopped by membrane, using p-spray for pixel isolation, 200 μm inactive edge,
- CNM stop etching before reaching opposite end, columns 210 μm deep (out of 230 μm p-bulk thickness),
- same layout and column geometry in both designs,
- 10 μm column diameter.

3. Irradiation and beam tests

In 2011 four testbeam campaigns were carried out. The first two took place at the DESY II synchrotron with a 4 GeV positron beam. In the beginning the beam time was dedicated to understand the FE-I4 chip, which became available only shortly before the first testbeam at DESY. In the second DESY testbeam the first irradiated samples were tested. The beam tests of the sensor-chip assemblies in the magnetic field in the CERN Morpurgo [9] magnet at 1.2 T were performed in June with 180 GeV pions. However the beam time was reduced (from 5 weeks to 5 days) due to machine problems. The IBL Review Committee took place in July for an inspection of the sensor development and readiness of the PPS and 3D sensor technologies for the IBL modules production. The IBL Review decision allowed both technologies to proceed. At the moment a dual-technology IBL is being evaluated so that both the PPS and 3D best features are used. The testbeam period in September at CERN in the beam of 120 GeV pions was dedicated to clarify questions raised by the Review Committee regarding the performance of the sensors.

The beam tests both at DESY and CERN were done using the EUDET telescope [10]. The EUDET telescope is based on 50 μm thick Mimosa26 sensors, which are Monolitic Active Pixel Sensors (MAPS) with 18.4×18.4 μm^2 pixel area. The EUDET telescope track pointing resolution is <2 μm, which is vital for single pixel

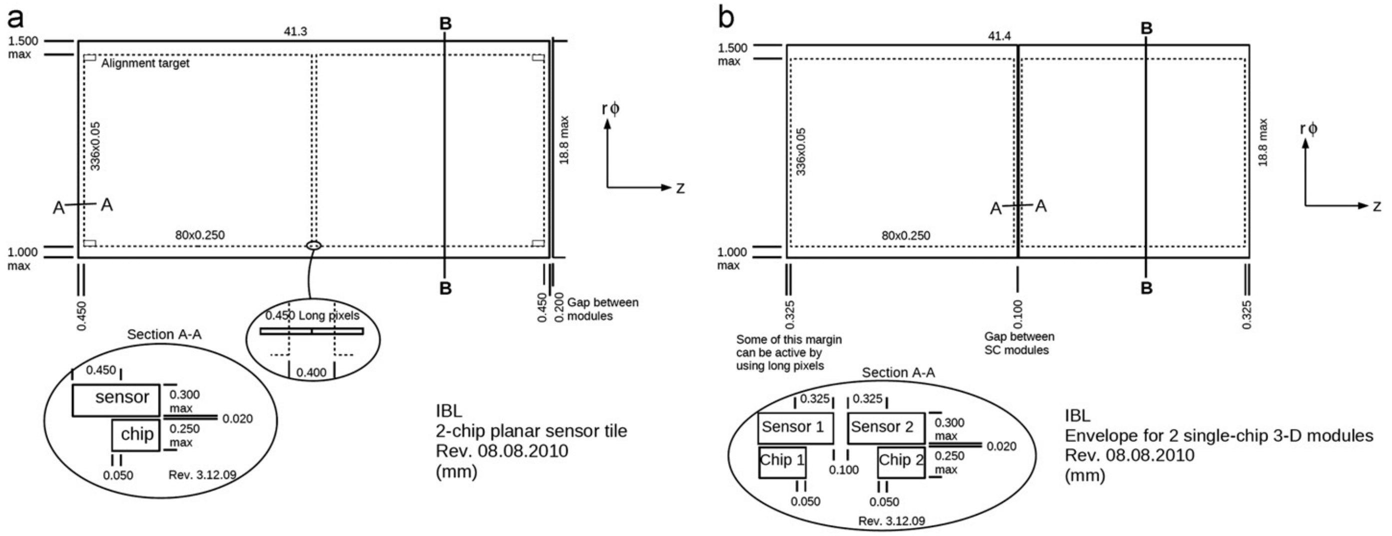

Fig. 1. The (a) PPS- and (b) 3D-module design. (a) The PPS modules are being assembled with two chips on a module with an additional spacing between the sensor-chip assemblies - 400 μm, to account for safe sensor operation at high bias voltage. (b) The 3D modules contain only one sensor-chip assembly. The distance between the sensor edges being reduced to 100 μm. Figures from [3].