Planar Pixel Sensors for the ATLAS tracker upgrade at HL-LHC

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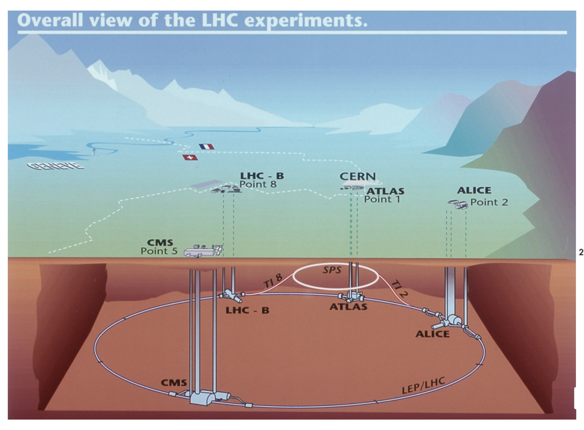
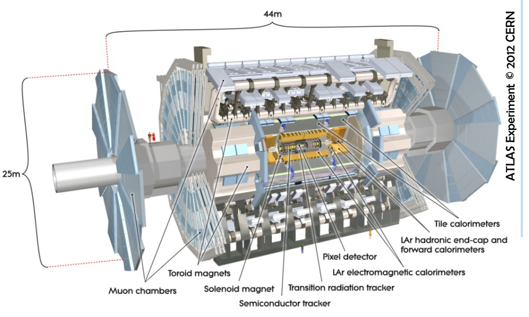
The ATLAS Planar Pixel Sensor (PPS) R&D Project is a collaboration of 17 institutes and more than 80 scientists, started to explore the feasibility of employing planar pixel sensors for the upgraded tracker at the High Luminosity Large Hadron Collider (HL-LHC). Different pixel concepts are investigated for the inner and outer layers for future tracking detectors. The focus for inner layers is on extreme radiation hardness, with the use of very thin pixel sensors (with an active thickness in the range of 75μm to 150μm), and the achievement of slim and active edges to provide low geometrical inefficiency. In the case of the outer layers, different approaches are being investigated to face the challenge of instrumenting an increased surface with respect to the present pixel system: production on 6" instead of 4" wafers; more cost-efficient and industrialized interconnection techniques; establishing the n-in-p technology which as a single-sided process requires less production steps.

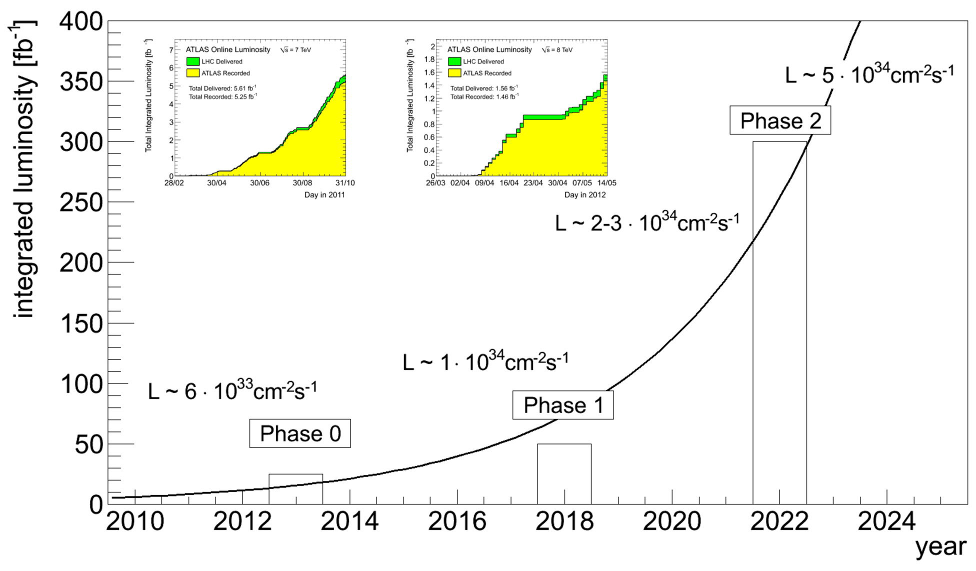
Analysis of measurements with radioactive sources and tracking efficiencies of different planar technologies extracted from beam tests with pions at CERN SPS and positrons at DESY have been carried out with FE-I3 and FE-I4 pixel modules. Up to now tracking efficiencies of 97% after a fluence of $2\cdot10^{16} n_{eq}cm^{-2}$ have been demonstrated with n-in-n FE-I3 modules as well as efficiencies of 98-99% at a fluence of $5\cdot10^{15} n_{eq}cm^{-2}$ for n-in-p modules.

Large Hadron Collider and the ATLAS Experiment





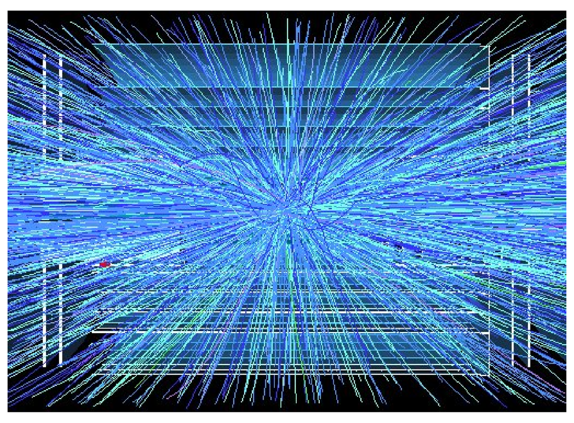
Up to the end of 2011 the Large Hadron Collider (LHC) delivered a total integrated luminosity of $5.61fb^{-1}$ of proton-proton collisions at a center of mass energy of 7TeV. Since the beginning of 2012 more then $1.46fb^{-1}$ at a increased center of mass energy of 8TeV have been recorded by the ATLAS Experiment. In the addition increased number of bunches in the beam resulted in a peak luminosity of $5.54\cdot10^{33}cm^{-2}s^{-1}$.



Challenges at High Luminosity

The LHC upgrade project is planning to extend the physics reach with increased peak luminosity in order to increase the sensitivity for physics beyond the standard model like the Higgs, SUSY, extra dimensions and heavy bosons.

For this aim the detectors have to cope with increased occupancy and high event rate. An event rate of the order of 100 events per bunch crossing will cause increased event pile up which represents a challenging task for the reconstruction.



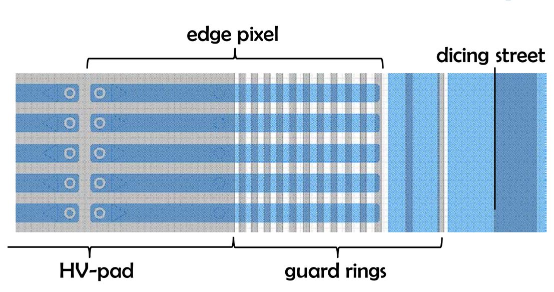
An additional challenge is the increasing radiation damage in the sensor which results in reduced charge collection. Future detectors will have to withstand a fluences of more than $10^{16}n_{eq}cm^{-2}$ in the innermost layer which can only be accomplished with radiation hard material, thinner bulk material and improved sensor layout.

ATLAS Planar Pixel Project

The goal of the ATLAS Planar Pixel Sensor Project is to evaluate and improve the sensor efficiency and the charge collection performance at HL-LHC fluences and beyond which results in increased radiation hardness.

The research efforts concentrate on two points which is the optimization of the sensor geometry and a reduction in cost.

Different layout possibilities are currently under investigation in order to optimize the sensor design. This includes the pixel size, the pixel implant and the bias grid which affect the pixel performance. Different sensor edge solutions as the slim and active edge and dicing pitches are also under investigation to reduce the inactive sensor area.



A possibility to reduce the production cost is to move from a double sided process to a single sided process which reduces the number of mask steps and with it the handling time and costs. Other possibilities would be to work with bigger wafers than the currently used 4" wafer which would reduce the number of wafers to process. Increased sensor area would also reduce the cost for bump-bonding as this is related to the number of sensors and not the size.

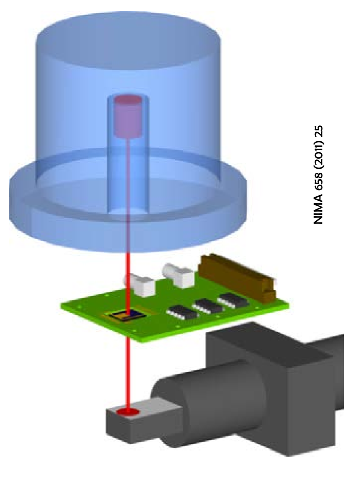
Currently different sensor designs are produced by several vendors which use the two ATLAS pixel front-end chips FE-I3 and FE-I4.

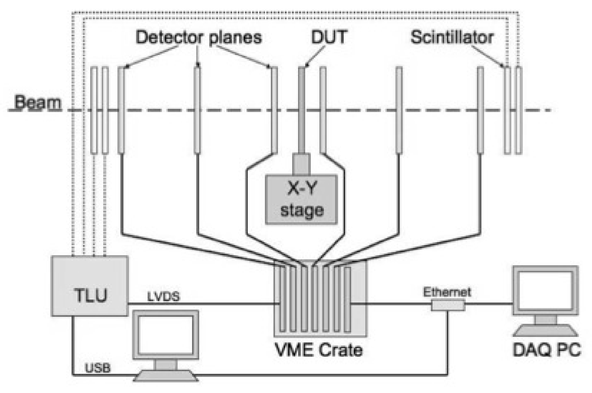
In order to evaluate the sensor performance four irradiation facilities which provide neutron and proton irradiation with different energies and to fluences in the order of $2\cdot10^{16}n_{eq}cm^{-2}$ performed several irradiation campanes.

TCAD simulations combined with measurements of the dopant profiles are favored methods to understand and to optimize the sensor behavior.

Sensor measurements

Measurements with radioactive sources as Sr-90 and analysis with a 120GeV pion beam at CERN and a 4GeV positron beam at DESY are used to characterize the behavior of the samples before and after irradiation. The results shed light on the performance of different parts of the pixel as well as the efficiency and the charge collection of the sensor.



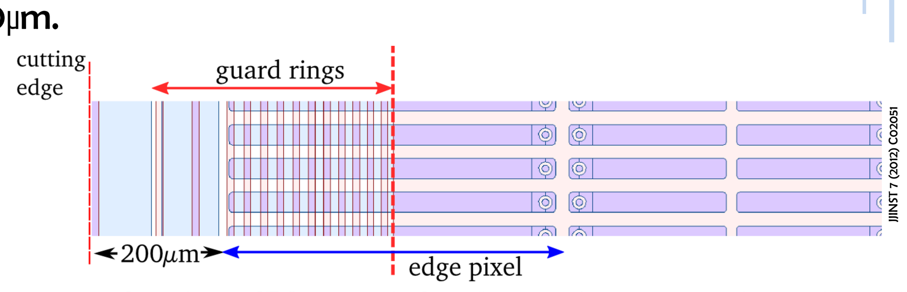


Source measurements with sensors bonded to FE-I3 and FE-I4 read-out chips are typically used to test the proper functioning as well as to confirm the charge calibration and the energy deposition of the detector module.

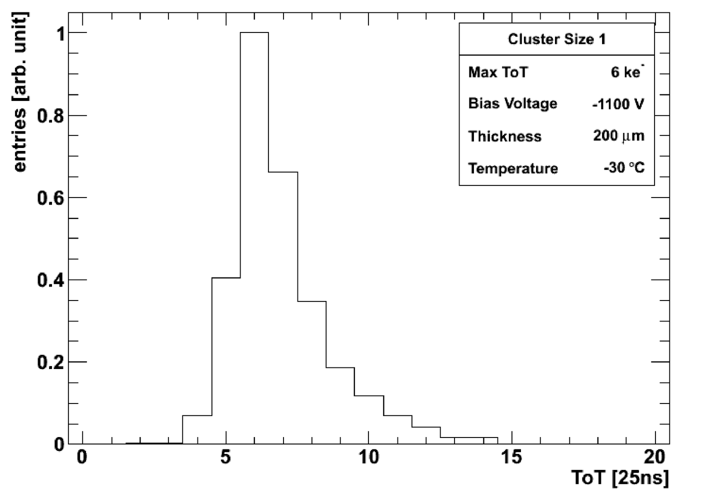
The EUDET beam telescope enables tracking measurements in test beams which make it possible to evaluate the module performance including the efficiency and the spatial resolution.

Planar IBL sensors

The IBL is going to be equipped with planar n⁺-in-n double chip modules which are bump-bonded to FE-I4 readout-chips. The 200μm thick pixel modules consist of 53760 pixel with a pixel size of $250\cdot50\mu m^2$. Several steps have been taken to enlarge the active sensor area. This included a shorter distance between the high-voltage pad and the cutting edge of about 450μm as well as an extension of the edge pixel which lead to an inactive edge of about 200μm.

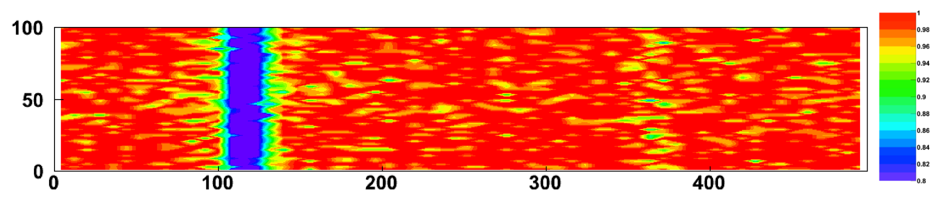


Several planar single chip IBL modules have been irradiated with protons and neutrons up to the IBL specification of $5\cdot10^{15}n_{eq}cm^{-2}$ to assure the proper functioning in the experiment.



Source measurements with Sr-90 of planar IBL modules have shown a charge collection of more than 10ke⁻ after an neutron irradiation of $5\cdot10^{15}n_{eq}cm^{-2}$. This result which is about six times higher than the threshold of 1600e- shows that IBL modules still meet the limits of the IBL specifications.

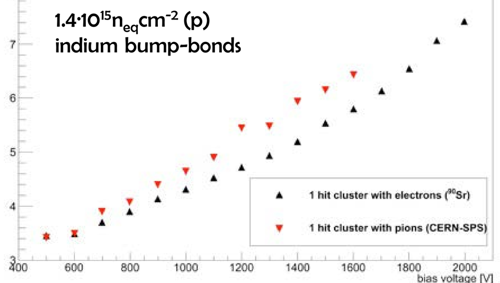
Test beam measurements at a $6\cdot10^{15}n_{eq}cm^{-2}$ proton irradiated sample showed an efficiency higher than 80% within the pixel cell at which the bias grid had the strongest influence on the efficiency.

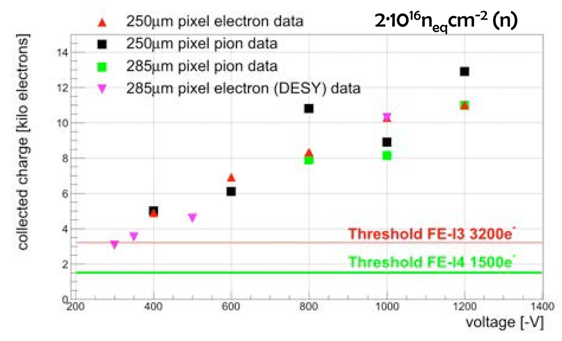


n+-in-n sensors

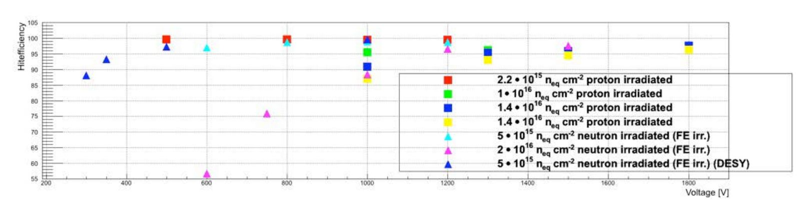
Planar n⁺-in-n pixel sensors are currently under investigation to test the radiation hardness for future applications up to fluences of $2\cdot10^{16}n_{eq}cm^{-2}$.

Source and test beam measurements on irradiated samples bump-bonded to FE-I3 read-out chips have shown a considerable charge collection at HL-LHC fluences. Using a front-end chip like the FE-I4 which can be operated at lower threshold values it might be possible to even improve these results.



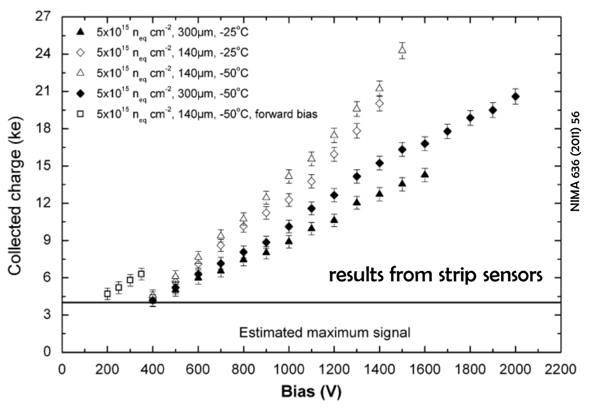


Measurements regarding the hit-efficiency after irradiation have shown that an increase in the bias voltage makes it possible to recover the full hit efficiency of the sensors.



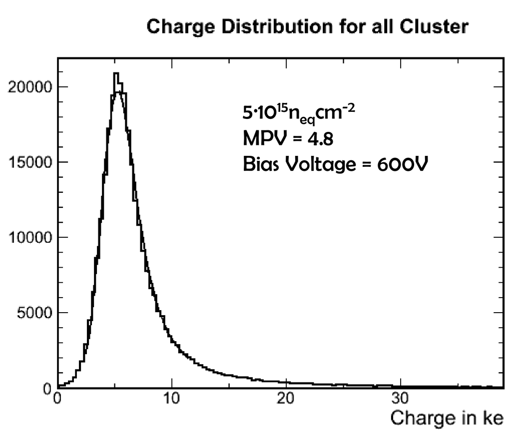
n-in-p sensors

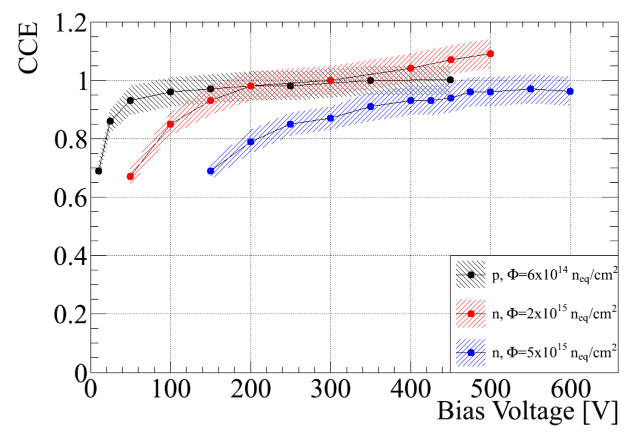
Ongoing investigation concerning the charge multiplication in planar detectors have shown an unexpected high charge in irradiated sensors. Sensors with a thickness of 300μm to 140μm have been investigated and shown that the effect becomes more significant in thin sensors.

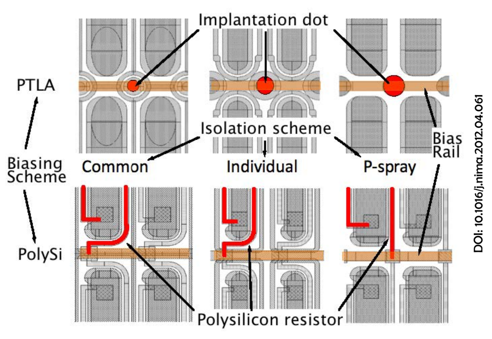


Sr90 source measurements on $1\cdot10^{16}n_{eq}cm^{-2}$ irradiated planar n-in-p sensors bump-bonded to the FE-I3 readout chips showed a collected charge which more than doubles the front-end threshold of 3200e⁻. Pion beam measurements on $2\cdot10^{16}n_{eq}cm^{-2}$ neutron irradiated samples revealed a overall efficiency of 98.8% at a operation voltage of 600V. For more detailed information refer to "Silicon n-in-p Pixel Sensors for future ATLAS Upgrades" by A. La Rosa.

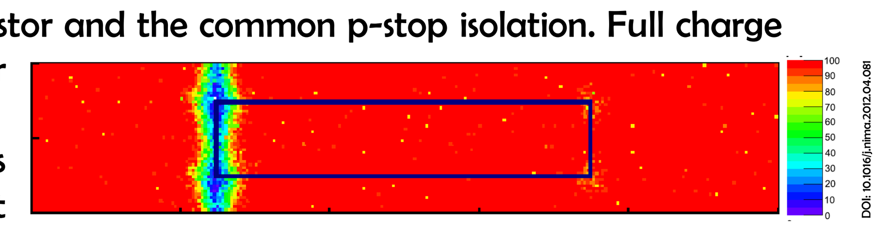
Measurements on 75μm thick proton and neutron irradiated Solid-Liquid Interdiffusion (SLID) modules showed nearly full charge collection efficiency at voltages below 600V.







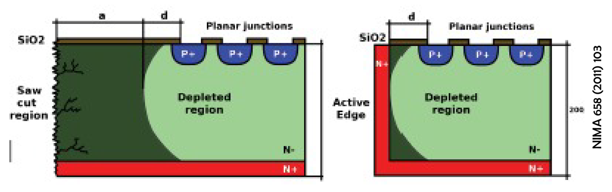
Different bias structures using a punch-through dot or a polysilicon resistor in combination with common and individual p-stop as isolation structure have been tested on 150μm thick n-in-p sensors. Measurements up to a fluence of $2\cdot10^{15}n_{eq}cm^{-2}$ showed an overall efficiency higher than 95% for the sensors using the polysilicon resistor and the common p-stop isolation. Full charge collection for unirradiated samples was observed at about 40V.



Slim edge

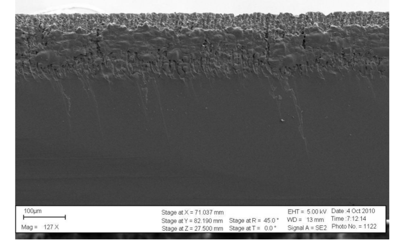
Deep Reactive Ion Etching (DRIE) is currently under investigation to build trenches in silicon wafers with an aspect ratio of 1:20 which can be filled with polysilicon in order to build a slim edge which reduces the inactive area of the sensor.

Promising results have been achieved on test diodes and revealed first improvement possibilities.

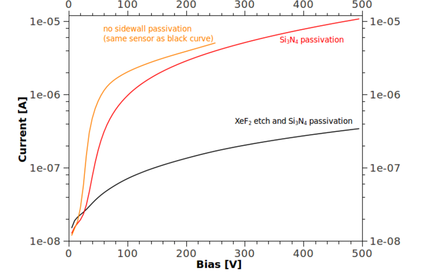


A second possibility is the Scribe-Cleave-Passivate (SCP) technique which consists of three processing steps. The first step is the scribing which was initially done by a laser but can also be performed by an XeF_2 etch step. A surface with a low defect density is revealed after the cleaving step. Which is followed by the surface passivation which leaves a resistive sidewall.

Based on the device type different passivation techniques need to be applied in order to create a possitve and a negative interface charge for n and p-type respectively.



The advantage of this technique is that the passivation step prevents conductive channels in the edges.



IV measurements on cleaved devices show the reduced leakage current after the XeF_2 etch process step. For fully processed devices the etching process revealed an improvement in the leakage current of two orders of magnitude.

Acknowledgment

The author would like to thank A. Dierlamm (KIT), I. Mandic (JSI) and M. Glaser (CERN) for carrying out the device irradiation in Karlsruhe (Germany), Ljubljana (Slovenia) and CERN PS (Switzerland) respectively. The irradiation in Karlsruhe was supported by the Initiative and Networking Fund of the Helmholtz Association, contract HA-101.

We would like to thank all the members of the PPS testbeam crew for their support during the testbeam campaigns of the last years. The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project AIDA, grant agreement no. 262025.