The ATLAS Pixel Detector

Fabian Hügging

***Abstract*— The ATLAS Pixel Detector is the innermost layer of the ATLAS tracking system and will contribute significantly to the ATLAS track and vertex reconstruction. The detector consists of identical modules, arranged in three barrels concentric with the beam line and centered on the interaction point and three disks on either side for the forward region.**

The position of the Pixel Detector near the interaction point requires excellent radiation hardness, mechanical and thermal robustness and good long-term stability, all combined with a low material budget. The detector layout, results from production modules and the status of assembly are presented.

***Index Terms*— silicon detector, pixels, LHC**

I. Introduction

THE ATLAS Inner Detector [1] is designed for precision tracking of charged particles with 40 MHz bunch crossing identification. It combines tracking straw tubes in the outer transition-radiation tracker (TRT), the microstrip detectors of the semiconductor tracker (SCT) at intermediate radii with the Pixel Detector, the crucial part for vertex reconstruction, as the innermost component.

The Pixel Detector [2] is subdivided into three barrel layers and three disks on either side for the forward direction. The innermost barrel layer is close to the beam pipe at radius $r = 50.5$ mm, the other two layers are at $r = 88.5$ mm and $r = 122.5$ mm. With a total length of approx. 1.3 m this layout results in a three-hit system for particles with $|\eta| < 2.5$.

The main components are approx. 1700 identical modules, corresponding to a total of $8 \cdot 10^7$ pixels. The modules consist of a package composed of sensors and readout-chips mounted on a hybrid. They have to be radiation hard to an ATLAS life time dose of 50 MRad or 10^{15} neutron-equivalent.

II. Module Layout

A pixel module consists of an oxygenated single n-on-n silicon sensor, approx. $2{\times}6$ cm^2 in size [3]. The sensor is subdivided into 47,268 pixels which are connected individually to 16 front-end (FE) chips using fine pitch "bump bonding" either done with Pb/Sn by IZM[1] or with Indium by AMS[2]. These chips are connected to a module-control chip (MCC) [4] mounted on a kapton-flex-hybrid glued onto the back-side of the sensor. The MCC communicates with the off-detector electronics via opto-links, and power is fed into the chips via cables connected to the flex-hybrid. A cross-section of an ATLAS pixel module is shown in figure 1.

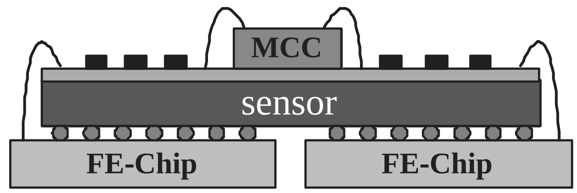

Fig. 1

Cross-section of an ATLAS pixel module.

To provide a high space-point resolution of approx. 12 μm in azimuth ($r\phi$), and approx. 110 μm parallel to the LHC beam (z), the sensor is subdivided into 41,984 "standard" pixels of 50 μm in $r\phi$ by 400 μm in z, and 5284 "long" pixels of 50×600 μm^2. The long pixels are necessary to cover the gaps between adjacent front-end chips. The module has 46,080 read-out channels, which is smaller than the number of pixels because there is a 200 μm gap in between FE chips on opposite sides of the module, and to get full coverage the last eight pixels at the gap must be connected to only four channels ("ganged" and "inter-ganged" pixels). Thus on 5% of the surface the information has a two-fold ambiguity that will be resolved off-line.

The FE chips [5] built in the IBM $0.25\,\mu$m technology contain 2880 individual charge sensitive analogue circuits with a digital read-out that operates at 40 MHz. The analogue part consists of a high-gain, fast preamplifier followed by a DC-coupled second stage and a differential discriminator. The threshold of the discriminator ranges up to 1 fC, its nominal value being 0.5 fC. When a hit is detected by the discriminator the pixel address is provided together with the time over threshold (ToT) information which allows reconstruction of the charge seen by the preamplifier.

III. Module Performance

During prototyping several prototype modules have been built with two generations of radiation-hard chips in $0.25\,\mu$m-technology before the production started with the final chip generation in early 2004. Up to now roughly 200 modules have been built; in order to assure full functionality of the modules in the experiment, each module will be extensively tested after assembly including measurements at the production sites before and after thermal cycling. Moreover, several modules from different production sites have been tested in a test beam and

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after irradiation with charged hadrons, the later includes lab tests as well as test beam studies with irradiated modules.

A. Laboratory measurements

An important test that allows a large range of in-laboratory measurements is the threshold scan. Signals are created with on-chip charge injection for each pixel individually. Scanning the number of hits versus the so injected charge yields the physical value of the threshold of the discriminator and the equivalent noise charge as seen by the preamplifier. A set of such scans is used to reduce the threshold dispersion by adjusting a 7-bit DAC-parameter individually for each channel, a procedure that takes about 1 hour. The resulting threshold and noise after threshold tuning is shown in figures 2 and 3. Typically approx. 60 e$^-$ threshold dispersion across a module and a noise value of below 200 e$^-$ for standard pixels is achieved, as is needed for good performance.

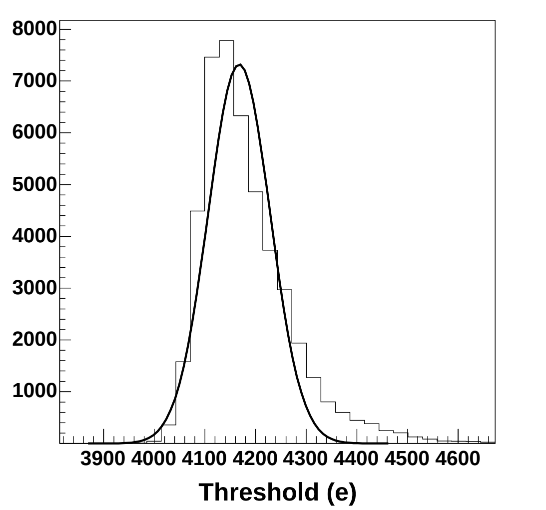

Fig. 2

THRESHOLD DISTRIBUTION OF A MODULE AFTER THE TUNING PROCEDURE, THE MEAN THRESHOLD IS 4,170 E$^-$ WITH A DISPERSION OF 61 E$^-$.

Note that there is not a single pixel with threshold lower than $3,900\ e^-$. This shows the high tuning capability of this chip allowing to reach small thresholds on the whole module without any pixel having its threshold too close to the noise, a fact of particular importance after irradiation. We also measured the cross-talk to a few per cent for standard $50 \times 400\ \mu$m^2 pixels.

A measurement of the timewalk, i.e. the variation in the time when the discriminator input goes above threshold, is an issue since hits with a low deposited charge have an arrival time later than those with high charges, in particular for ganged pixels because of their higher input capacity. The difference in threshold for a signal arrival time of less than 20 ns and the nominal discriminator threshold is for standard pixels approx. 1,500 e$^-$, for ganged pixels approx. 2,300 e$^-$ and for long pixels approx. 2,000 e$^-$, see figure 4. Because

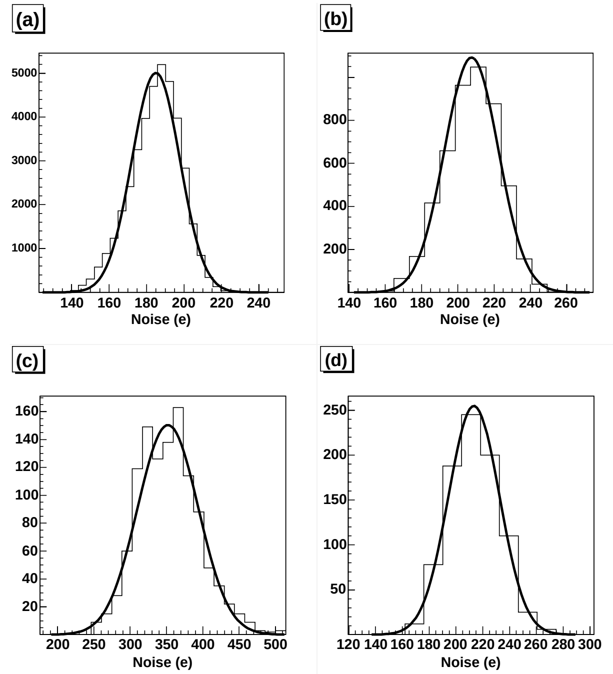

Fig. 3

NOISE DISTRIBUTIONS FOR THE DIFFERENT PIXEL TYPES OF A MODULE AFTER THE TUNING PROCEDURE, (A) FOR STANDARD PIXEL WITH A MEAN NOISE OF 185 E$^-$ AND $\sigma = 13$ E$^-$, (B) LONG PIXEL WITH A MEAN NOISE OF 208 E$^-$ AND $\sigma = 15$ E$^-$, (C) GANGED PIXEL WITH A MEAN NOISE OF 352 E$^-$ AND $\sigma = 42$ E$^-$ AND (D) INTER-GANGED PIXEL WITH A MEAN NOISE OF 213 E$^-$ AND $\sigma = 19$ E$^-$.

the discriminator threshold can easily be tuned to values below 3,000 e$^-$ the achieved timewalk is sufficient to meet the ATLAS requirement of 6,000 e$^-$ for all pixels.

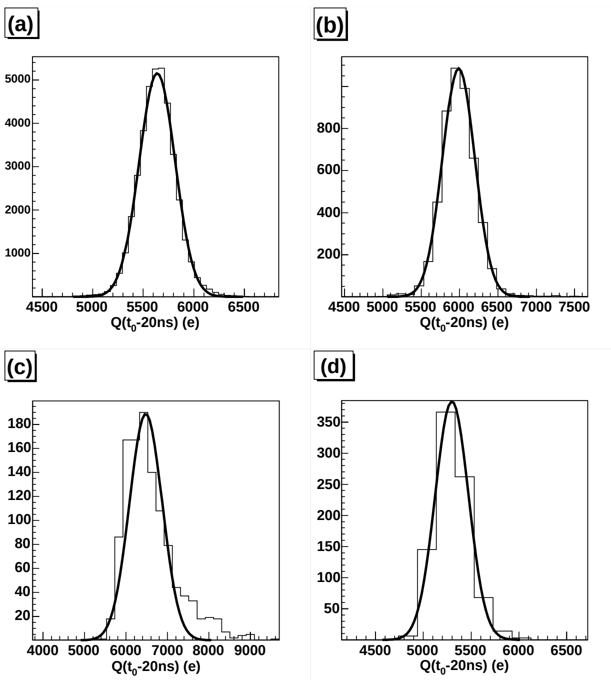

Fig. 4

IN-TIME-THRESHOLD DISTRIBUTIONS FOR THE DIFFERENT PIXEL TYPES OF A MODULE TUNED TO AN AVERAGE THRESHOLD OF 4,200 e^-, (A) FOR STANDARD PIXEL WITH A MEAN OF 5,640 E$^-$ AND $\sigma = 180$ E$^-$, (B) LONG PIXEL WITH A MEAN OF 5,990 E$^-$ AND $\sigma = 210$ E$^-$, (C) GANGED PIXEL WITH A MEAN OF 6,680 E$^-$ AND $\sigma = 400$ E$^-$ AND (D) INTER-GANGED PIXEL WITH A MEAN OF 5,300 E$^-$ AND $\sigma = 170$ E$^-$.

Data taken when illuminating the sensor with a radioactive source allows in-laboratory detection of defective channels. Such a measurement obtained with an Am^{241}-source can be seen in figure 5. $1,400,000$ events per FE-chips have been accumulated for this measurement to ensure enough hits per channel for a subsequent analysis. The integrated source-spectrum for all pixels reconstructed from the ToT-readings is in agreement with expectations (see figure 5, (a)); the main 60 keV γ peak can clearly be distinguished from the background which is dominated by events with charge sharing between neighbouring pixels. Furthermore the individual pixel spectrum (see figure 5, (b)) can be used for an absolute charge calibration per readout channel, because here also the 60 keV γ line can be identified.

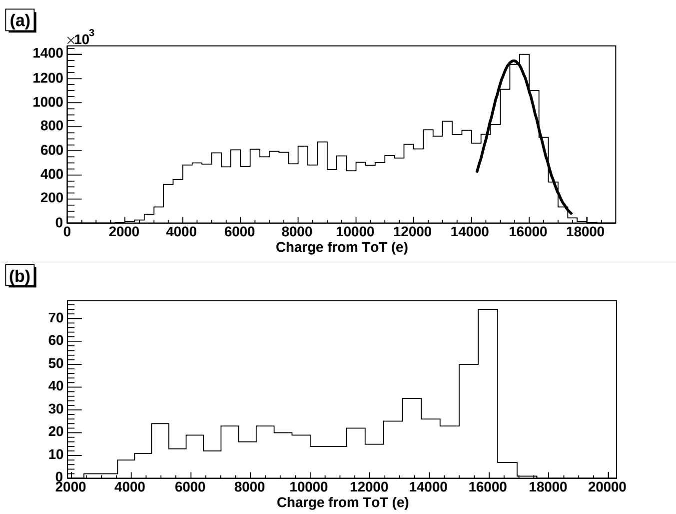

Fig. 5

Am^{241}-Spectrum measured with an ATLAS pixel module using the self-trigger capabilities and the ToT charge information. Each channel of the module has been individually calibrated. The spectrum (a) is a sum over all pixel without any clustering. The peak has been fitted to 15,460 e^-. The spectrum (b) is for a specific channel, i.e. chip 3, column 14, row 33 given as an example.

Up to now roughly 150 modules have been produced and completely characterized; every module undergoes an extensive test procedure to ensure good performance inside the ATLAS detector. This includes tests at room temperature as well as tests at the operation temperature of $-10°$C. A thermal cycling of at least 48 hours with rapids cycles between $-30°$C and $+30°$C to stress the modules is also part of the procedure. Finally each module will be tuned and calibrated for a source test to evaluate the number of non-responsive pixels. The resulting distribution for the first 150 modules produced is shown in figure 6. Typically the number of defective channels per modules is far less than 50 or 0.1% of all 46,080 pixels showing the excellent hybridization yield of the fine pitch bump bonding.

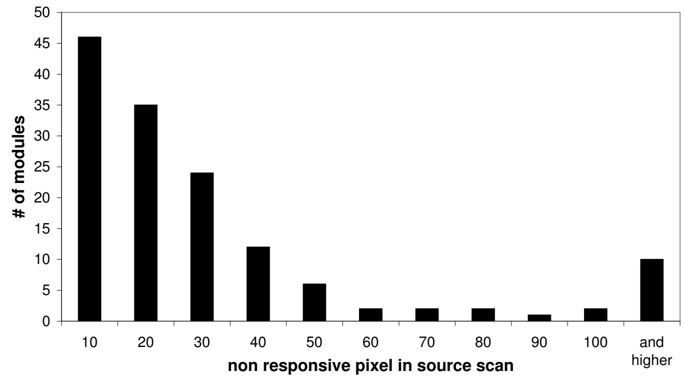

Fig. 6

Distribution of the non responsive pixels for the first 150 modules produced for the ATLAS pixel detector.

B. *Test beam measurements*

Tests have been performed in the beam line of the SPS at CERN using 180 GeV/c hadrons. The setup consists of a beam telescope for the position measurement [6], trigger scintillators for timing measurement to 36 ps, and up to four pixel modules. The number of defective channels is observed to be less than 10^{-3}. For standard 50×400 μm^2, non defective pixels the efficiency for normal incidence particles is 99.90$\pm$0.15% which can be seen in figure 7. Because the shown efficiency measurements contain also information about the arrival time of the charge at the discriminator w.r.t. system clock the measurements allow also a determination of the timewalk. The measured timewalk is in agreement with those measurements from lab tests (see section III-A) giving a timing window of 15 ns with high efficiency.

Furthermore the efficiency of the ATLAS pixel modules can be improved to perfect values of 100.00$-$0.03% (see figure 8) by using a digital hit duplication of the front end chip. Here the discriminator of each pixel duplicates all hits below an adjustable ToT threshold to the previous bunch crossing to recover the hit information for small charges. Of course the drawback of this method is an increase of the data volume inside the chip.

The space resolutions measured for one hit and two hit clusters for different incident particle angles in binary readout mode, i.e. approx. 12 μm in $r\phi$ and 110 μm in z is expected for the pixel size of 50×400 μm^2. An improvement of the resolution for two hit cluster can be achieved by using a center of gravity method.

C. *Irradiation*

Seven production modules have been irradiated at the CERN PS with 24 GeV/c protons to a dose of 50 MRad ($1 \cdot 10^{15}$ n_{eq}cm^{-2}), which is approximately the dose expected after 10 years of ATLAS operation. The radiation damage is monitored reading the leakage current individually for each pixel.

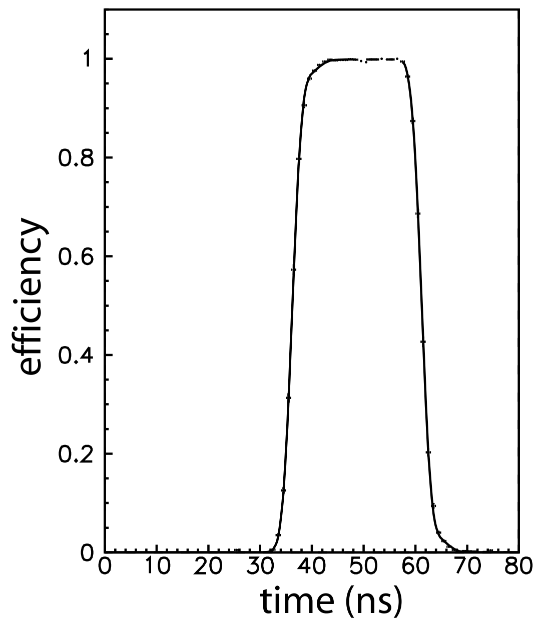

Fig. 7

EFFICIENCY VS. INCIDENT PARTICLE ARRIVAL TIME FOR AN ATLAS PIXEL MODULE AS MEASURED IN THE TEST BEAM. AT THE FLAT TOP AN EFFICIENCY OF 0.9990 IS ACHIEVED.

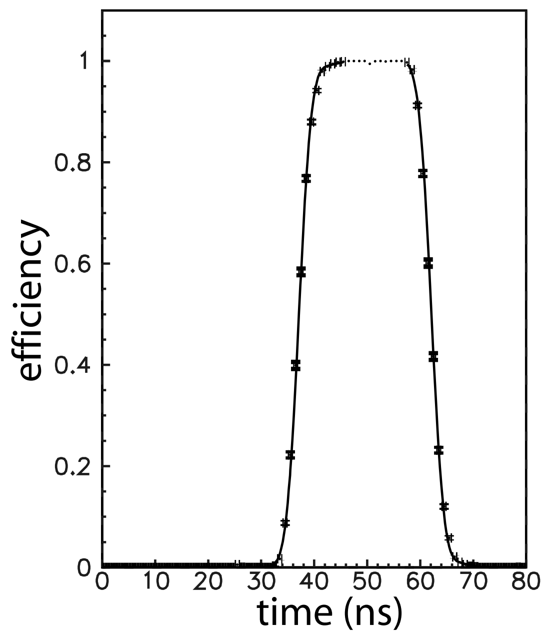

Fig. 8

EFFICIENCY VS. INCIDENT PARTICLE ARRIVAL TIME FOR AN ATLAS PIXEL MODULE IN HIT DUPLICATION MODE AS MEASURED IN THE TEST BEAM. AT THE FLAT TOP AN EFFICIENCY OF 1.0 IS ACHIEVED.

During irradiation the single event upset (SEU) probability for the triple redundant pixel latches was measured by exposing the full configured modules to the beam for several hours and then read back the latches to search for bit flips. The achieved SEU rate is of the order of 10^{-11} SEUs per proton for the 14 pixel latches of each individual pixel cell showing no problems with operation in such a harsch radiation environment.

The noise after irradiation as shown in figure 9 is only modestly increased and still well in agreement with requirements for operation in ATLAS. Also the threshold dispersion of such a highly irradiated module can be tuned to values of 60 e^- as before irradiation.

Irradiated modules have been tested in the beam line again (see section III-B). The bias voltage needed for full depletion has been measured for the highly irradiated modules resulting to be between 400 and 500 V, see figure 10. This has to be compared with the full depletion voltage of typically 50-80 V for modules before irradiation. The deposited charge measured via the ToT readings and the mean charge for irradiated modules is approximately 15,000 e^- for a m.i.p. with an acceptable uniformity w.r.t. unirradiated modules.

Similar efficiency versus incident particle arrival time measurements show for the highly irradiated modules efficiency values of 98.23$\pm$0.15%, well above the end-of-lifetime requirement of 95%, see figure 11. The slope of the efficiency curve is slightly distorted w.r.t. unirradiated modules because of poor charge collection in a small region of the irradiated sensor ("bias-dot" region) which was implemented to allow reasonable testing of the sensor without readout electronics [3], [7].

IV. OFF-DETECTOR ELECTRONICS

The off-detector readout electronics is designed to process data at a rate of up to 100 kHz level-1 triggers. The main data-processing component is the "read-out driver" (ROD), of which final prototypes have been built to pixel specifications and are being evaluated. The first-step event-building and error flagging is done via Field-Programmable-Gate-Arrays (FPGA). The communication to the rest of the data acquisition system is run through a 1.6 Gbit/s opto-link. The communication to modules, online monitoring and calibration runs are performed with Static-Random-Access-Memory(SRAM) and Digital-Signal-Processors (DSP); their programming is ongoing and modules and small systems have already been configured and operated successfully with a ROD.

All components of the off-detector electronics are in production now and the progress and yields are well on track.

V. SYSTEM ASPECTS

A. Support structures

The mechanics of the system has to guarantee good positional stability of the modules during operation while the amount of material has to be kept to a minimum. At the same time it has to provide cooling to remove the heat load from the modules and maintain the sensors at a temperature of -6°C to keep the radiation damage low.

Barrel-modules are glued to "staves", long, flat carbon-structures with embedded cooling pipes. The staves are

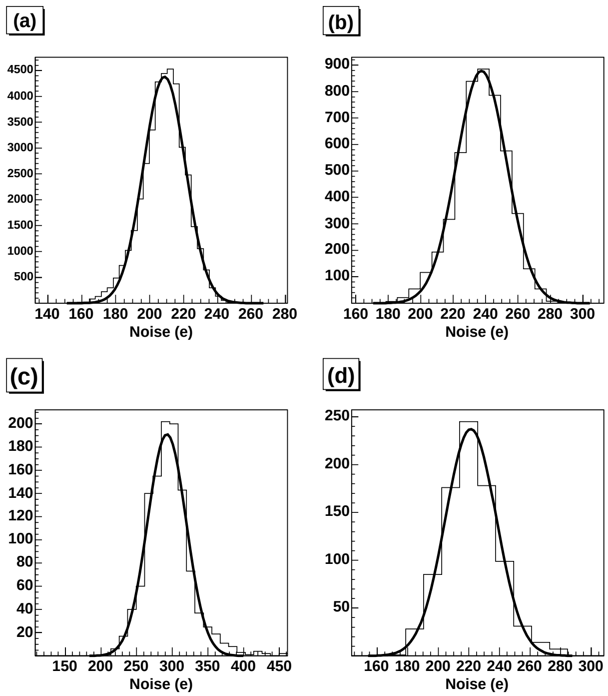

Fig. 9

NOISE DISTRIBUTIONS FOR THE DIFFERENT PIXEL TYPES OF A MODULE IRRADIATED WITH 24 GEV PROTONS TO A FLUENCE OF $1 \cdot 10^{15}$ N_{eq}CM^{-2}, MEASURED AFTER RE-TUNING AT -4°C; (A) FOR STANDARD PIXEL WITH A MEAN NOISE OF 209 E$^-$ AND $\sigma = 12$ E$^-$, (B) LONG PIXEL WITH A MEAN NOISE OF 238 E$^-$ AND $\sigma = 15$ E$^-$, (C) GANGED PIXEL WITH A MEAN NOISE OF 292 E$^-$ AND $\sigma = 27$ E$^-$ AND (D) INTER-GANGED PIXEL WITH A MEAN NOISE OF 221 E$^-$ AND $\sigma = 17$ E$^-$.

mounted inside halfshells, which themselves are assembled into frames to form the barrel system.

The disks are assembled from carbon-sectors with embedded cooling covering 1/8 of a wheel. The modules are glued directly to either side of the disk sectors.

The module loading to staves and disk sectors requires high position accuracy and good thermal contact without any risks to damage modules during the process. First disk sectors and barrel staves have been assembled with modules showing unchanged performance of the individual modules after assembly.

The global support structures of the pixel detector are also made of carbon structures and have been recently delivered. Currently these structures are under test at CERN.

B. System tests

First system tests have been performed with six modules on a disk sector and thirteen modules on a barrel-stave. The noise behaviour on the disks or staves shows no significant differences compared to similar measurements with the same unmounted modules. Larger system tests are already in preparation and will include realistic powering and read-out.

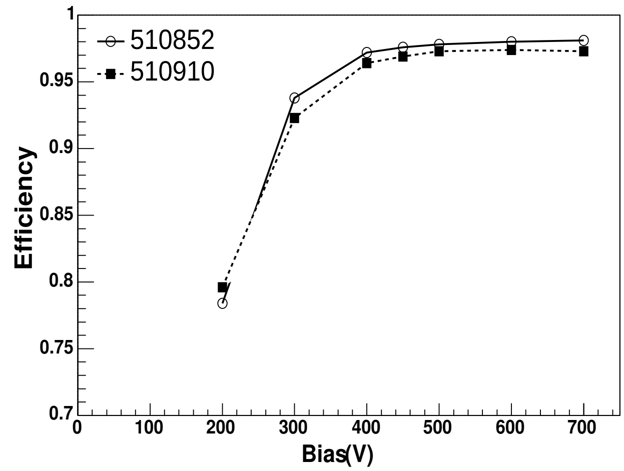

Fig. 10

EFFICIENCY VS. BIAS VOLTAGE OF TWO HIGHLY IRRADIATED PIXEL MODULES AS MEASURED IN THE BEAM LINE.

VI. CONCLUSIONS

Production modules built with the final generation of radiation hard chips show largely satisfying performance in laboratory-tests, in test beam studies and after irradiation. Module production is well in progress with high yield and an acceptable rate to finish the ATLAS pixel detector in time.

Work on the off-detector electronics and the support structures have been going on in parallel and are well on track. First system test results are promising.

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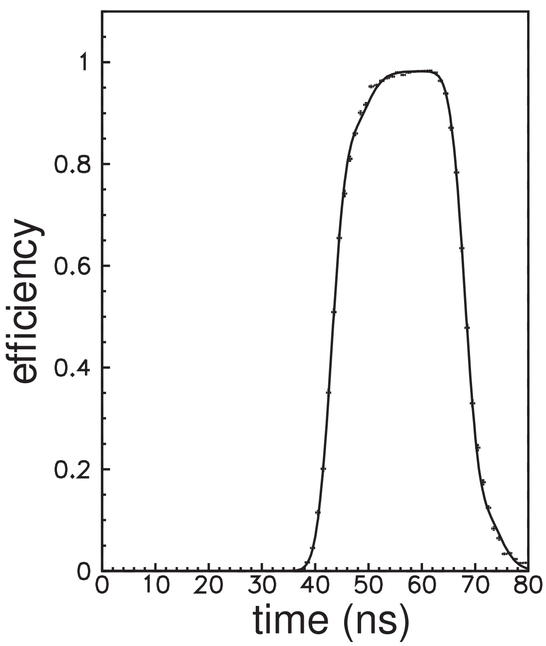

Fig. 11

EFFICIENCY VS. INCIDENT PARTICLE ARRIVAL TIME OF AN IRRADIATED MODULE. AT THE FLAT TOP AN EFFICIENCY OF 0.9823 IS ACHIEVED.