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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

# Performance of the ATLAS silicon strip detector modules

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**Abstract**

The performance of the silicon strip detector prototypes developed for use in ATLAS at the LHC is reported. Baseline detector assemblies ("modules") of 12 cm length were read out with binary electronics at 40 MHz clock speed. For both irradiated and unirradiated modules, the tracking efficiency, noise occupancy, and position resolution were measured as a function of bias voltage, binary hit threshold, and detector rotation angle in a 1.56 T magnetic field. Measurements were also performed at a particle flux comparable to the one expected at the LHC. 

## 1. Introduction

ATLAS is a large general purpose magnetic spectrometer planned for use at the CERN Large Hadron Collider (LHC) [1]. The Semiconductor Tracker (SCT) [2] will be placed between radii of 30 and 54 cm from the LHC interaction point. The basic specifications for this tracker include a response time of 25 ns to match the LHC collision frequency of 40 MHz, operation after a fluence of $2\times10^{14}/\text{cm}^2$ MIP equivalent irradiation, and a point resolution of about 20 μm. The solution adopted by ATLAS is to use single-sided strip detectors glued back-to-back to form an effective double-sided detector with small angle stereo readout. These so-called modules have a strip length of 12 cm. Readout will be AC-coupled from n-type implant strips in n-bulk crystals. After radiation induced type inversion of the bulk and increased depletion voltage [3], the junctions will be at the n-strips allowing the possibility of operation under partial depletion of the silicon. The readout electronics [4] employs a 1 bit binary scheme whereby only hits above a single threshold are recorded. In such a scheme the required resolution is achieved with 75 μm pitch detectors. Noise occupancy must be well below $10^{-3}$ not to exceed the bandwidth of the data transmission system. A key performance requirement of such a system is to maintain high tracking efficiency at low noise occupancy.

The present work builds on a series of previous beam tests and experience with binary readout electronics [5–10]. In this paper a report is given of measurements made during the Summer of 1996 in the CERN H8 beam line. In this data set, detectors and electronics designed to meet the ATLAS specifications described above were used. Both irradiated and unirradiated detectors and electronics were employed. These components were operated at $-10°$C in a 1.56 T magnetic field. Measurements were made at various silicon bias voltages and at rotation angles between $+27°$ and $-12°$ with respect to the beam line, in excess of the crossing angles expected at ATLAS [11].

## 2. Experimental setup

Fig. 1 shows the overall layout of the experimental setup. The devices under test (DUT) were denoted ATT7 (irradiated) and ATT8 (unirradiated) and were placed with their strips vertical in a combined shielding and cooling box which could be rotated about the direction of the vertical magnetic field of the dipole magnet "Mopurgo". Beam particles were tracked by two independent systems. One was a beam telescope (T1–T4), consisting of silicon strip detectors with 50 μm pitch and slow analog electronics, capable of locating track positions in the DUTs to 2 μm [12]. The other was a pair of two-sided binary readout planes (LBIC2, LBIC1) with 75 μm pitch, These were mounted in the shielding box and used as anchor planes to allow independent, albeit coarser, resolution tracking. Both systems were used off-line for various phases of the analysis.

The DUTs were geometrically and mechanically identical and were constructed as follows. Each module was single-sided and consisted of a pair of 6 cm × 6 cm, n-strip in n-bulk, AC-coupled detectors with 75 μm pitch readout. The strips were

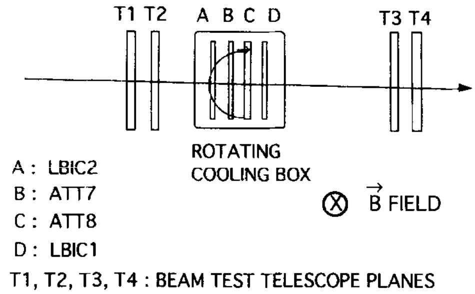


Fig. 1. Top view of the experimental setup in the 1.56 T magnet.

isolated by a continuous p-frame. The detectors were manufactured by Hamamatsu Photonics. The two detectors were butt-joined end-to-end and wire bonded to form a 12 cm active strip. The backsides were biased negative and the n-type implants were held at ground. The front-end electronics (FEE) was mounted on a ceramic hybrid which was glued directly upon the silicon, close to the butt joint. Wire bonds were made from the hybrid to pads near the middle of the 12 cm active strip. The FEE consisted of a two chip set. The first chip, CAFE [13], was a bipolar preamp, shaper, and discriminator. The second chip, CDP128 [14], was a 1 bit binary pipeline clocked at 40 MHz, which stored the hit bit from the CAFE at a time corresponding to a beam trigger recorded by the experiment. The CAFE output showed a hit if the pulse height in the detector exceeded the externally controllable analog threshold applied to the CAFE discriminator. This threshold is kept fixed during normal data taking, but in these measurements threshold scans were performed at each of the operating conditions (bias and detector angle) in order to investigate the performance of the detectors. A typical threshold region for high efficiency was around 1.0–1.4 fC equivalent input charge, for a most likely deposited signal charge of 4 fC.

The ATT8 module was unirradiated and had a depletion voltage of 70 V. The ATT7 module was uniformly irradiated to a fluence in excess of $10^{14}$ equivalent high energy protons/cm$^2$. The irradiation was performed at the 88″ Cyclotron at Lawrence Berkeley National Laboratory with 55 MeV protons. The hybrid with powered FEE and the detectors were irradiated separately and then assembled into a module. The irradiated detectors underwent type inversion [3]. Given the temperature dependence of the annealing effects [15,16] the detectors were stored near $-20°C$ except for short periods. A capacitance versus bias voltage ($C$–$V$) measurement performed 10 weeks after the end of the beam test determined the depletion voltage to be $290 \pm 10$ V. This depletion voltage matches closely the one expected at the end of the SCT lifetime at the LHC.

## 3. Data analysis

The analysis identified tracks in the beam telescope or the anchor planes, predicted their locations in the DUTs, and correlated found hits with tracks. Events with more than one track found were eliminated. The efficiency was defined as the ratio of tracks with a match in the DUT to all tracks. Depending on the track definition, different cuts were employed: for tracks found in the telescope (anchors), a match was found if the predicted position of the track agreed with a hit within $\pm$ 3 strips. The noise performance of the detectors was characterized by the "off-track occupancy", which was the number of hits outside of 500 μm of a track, divided by the total number of strips. In addition, the occupancy associated with noisy channels was determined with beam-off data.

## 4. Results

### *4.1. Bias dependence of the response*

In order to determine the operating conditions of the detectors, bias voltage scans were performed with no applied magnetic field and at zero rotation angle. By varying the threshold to the CAFE chip, both the efficiency and median pulse height of the single strip signal could be measured. The latter corresponds to the threshold which results in a 50% hit finding efficiency. Fig. 2 shows the efficiency for the unirradiated module, ATT8, for thresholds of 1.0 and 1.2 fC. We find, as in previous

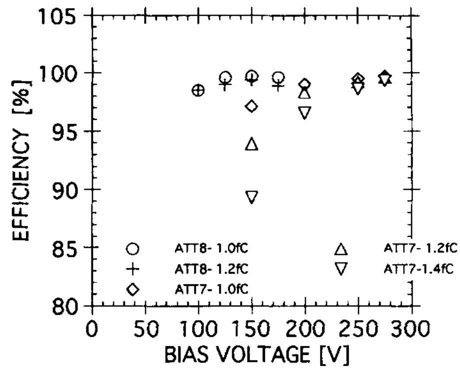


Fig. 2. Efficiency of ATT8 (unirradiated) and ATT7 (irradiated) as a function of bias voltage, for $V_{th}$ = 1.0, 1.2, 1.4 fC.

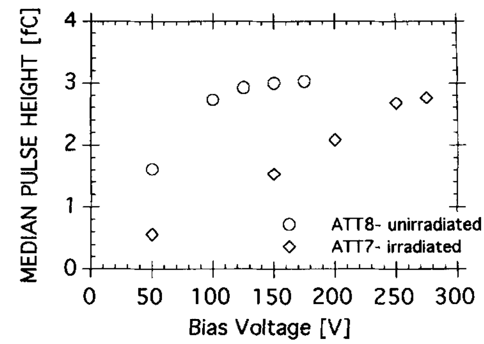


Fig. 3. Median pulse height of ATT7 and ATT8 as a function of bias voltage.

tests [9], that the unirradiated n-strip in n-bulk detectors require an over-bias to achieve high efficiency. In later measurements, ATT8 was operated at 125 V which is still not fully efficient at 1.2 fC. Previous studies [17] indicated an optimum bias in excess of 150 V to minimize inter strip capacitance and noise.

At the time of the beam test, the depletion voltage of the irradiated module, ATT7, had not yet been determined by the *C–V* characteristic. The depletion voltage was underestimated. Bias voltage scans, shown in Fig. 2, were done up to 275 V, still short of the 290 V depletion point. At 275 V bias the efficiency approaches 100%. In later measurements, this module was operated at 250 V bias where inefficiencies would be expected for 1.4 fC and above. Fig. 2 also confirms an effect seen in earlier work [8,9,18], that if biased at half the depletion voltage (150 V), the efficiency of the inverted detector is still above 95%.

The binary readout does not yield the pulse height directly. As mentioned above, one measures instead the median of the single strip pulse height, i.e. the threshold giving 50% efficiency as extracted from threshold curves. In Fig. 3, the median pulse height is shown for both unirradiated and irradiated modules as a function of the bias voltage.

The absolute pulse height scale is known for both modules to about 10%. The unirradiated module shows a plateau in the pulse height above 150 V. For the irradiated module, the pulse height is still rising at 275 V, a confirmation of the subsequent *C–V* measurement mentioned in Section 2. At 150 V the median pulse height is 50% of the unirradiated value. In the following, ATT8 was biased at 125 V which results in a small signal loss and ATT7 was biased at 250 V, at about 80% of the full depletion voltage.

### 4.2. *Efficiency and noise occupancy*

The parameters which have direct application in tracking algorithms are position resolution, efficiency and noise occupancy. They have been determined in threshold scans for the different modules. Fig. 4 shows both the efficiency and noise occupancy as a function of the applied threshold voltage in mV for ATT8 for 12° rotation in the magnetic field; 90 mV corresponds to 1 fC. The efficiency and noise occupancy for the irradiated module ATT7 for the same conditions is shown in Fig. 5. Here the 1 fC point is at 80 mV. The difference in the threshold scale of the two modules is due to the CAFE chips used which come from different fabrication runs, respectively. The efficiency and noise occupancy curves, Figs. 4 and 5, suggest that operation with a threshold between 0.8 and 1.2 fC is possible with large enough noise suppression and efficiency. Noise occupancies taken without beam are about a factor 10 lower at 1 fC. Correlation of hit locations in the different modules indicates that part of the occupancy at larger thresholds is associated with an additional track, missed in the original track finding step. In order to compare the

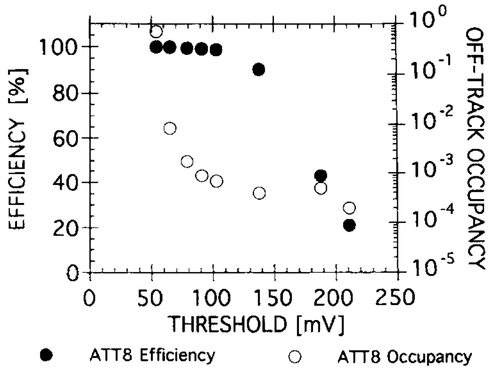


Fig. 4. Efficiency and noise occupancy vs. threshold for ATT8.

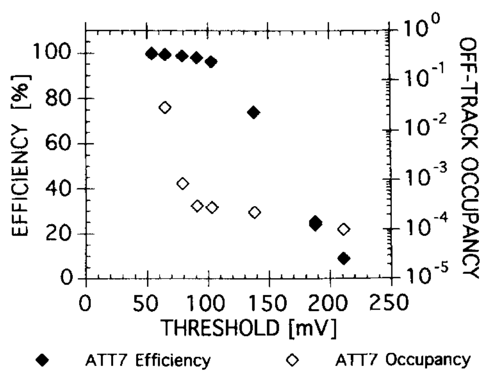


Fig. 5. Efficiency and noise occupancy vs. threshold for ATT7.

occupancy with the ATLAS requirements, the occupancy numbers should be normalized to the width in clock cycles of the comparator output pulse, which for the CAFE chip corresponds to dividing by 2.5. This correction has not been applied to the data.

### *4.3. Rotation in the magnetic field*

The ATLAS silicon tracker will be operated in an axial magnetic field of 2 T, corresponding to a Lorentz angle of about 15° for electrons. If the detectors are rotated by the Lorentz angle out of the tangential direction, the charge collection should be optimized. But the bending of charged particles and the finite width of the detectors cause particles of momentum 1 GeV to cross the tangential plane of a cylinder at 30 cm radius by a maximum angle of ± 13° [11]. Thus the Lorentz angle has to be determined and the response of the detector for particles crossing with angles up to ± 13° relative to that direction has to be measured. At crossing angles greater than 15°, tracks always cross two or more strips. Based on the measurements of Refs. [5–7] in a 1 T field, a Lorentz angle of + 12° was expected in this experiment. The detectors were rotated in several steps from − 12° to + 27°.

We have shown previously [8] that the cause of inefficiencies at high thresholds or finite rotation angles can be investigated by determining the position of the track between the strip centers, using the high resolution telescope. The so-called inter-strip position $\eta$ is the distance from the track location to the center of the next lowest strip, divided by the pitch, and thus varies from 0 to 1. The efficiency decreases first in the region where the generated charge is shared between strips, i.e., at the edge of the strips (the "crack", $\eta \approx 0.5$). This is shown in Fig. 6, where the efficiency of ATT8 and ATT7 are shown as a function of $\eta$ for 2 fC threshold for three rotation angles in the magnetic field: for 12°, close to the Lorentz angle, where the charge sharing is minimal, and − 3° and + 27°, where it is maximal. The loss in efficiency is visible in the region of the crack ($\eta = 0.5$). While this area is fairly narrow for 12° rotation, it is much wider for rotations away from the Lorentz angle.

Fig. 7 shows the efficiency averaged over $\eta$, for thresholds of 1.0 fC for all rotation angles in the magnetic field. The efficiency is very high and uniform as a function of the rotation angle, and the only apparent reduction in efficiency is at − 12° rotation. This angle is close to the rotation angle of 27° relative to the Lorentz angle, where all tracks cross three or more strips. The fact that the irradiated module ATT7 has a 1% lower efficiency is an indication that the bias was not sufficient to deplete the detector and to guarantee full charge collection.

### *4.4. Position resolution*

The position resolution shown in Fig. 8 is extracted from the residuals of found hits relative to track positions extrapolated from the high precision

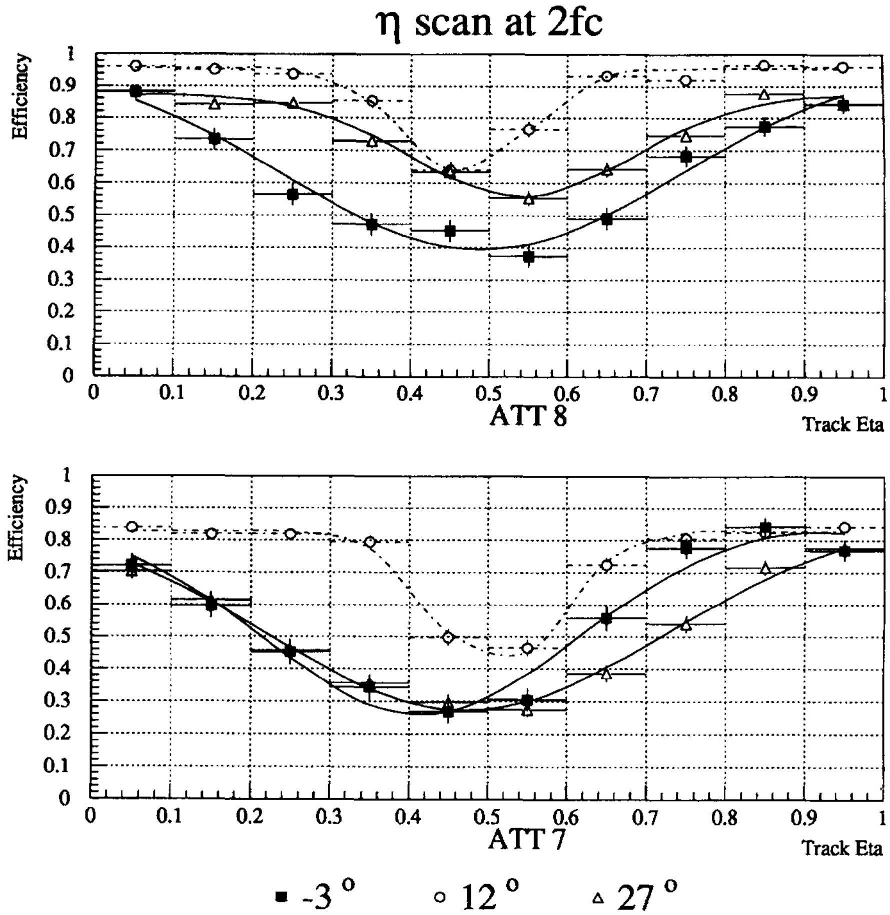


Fig. 6. Efficiency of ATT8 and ATT7 vs. the inter-strip position $\eta$ for 2 fC threshold.

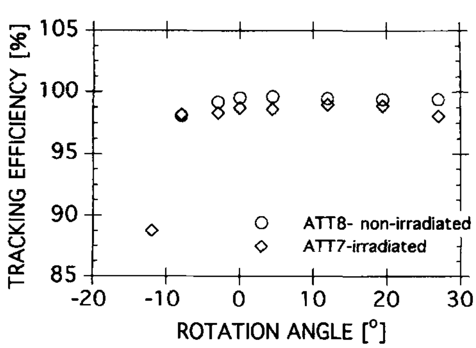


Fig. 7. Efficiency of ATT8 and ATT7 vs. angle for 1 fC threshold.

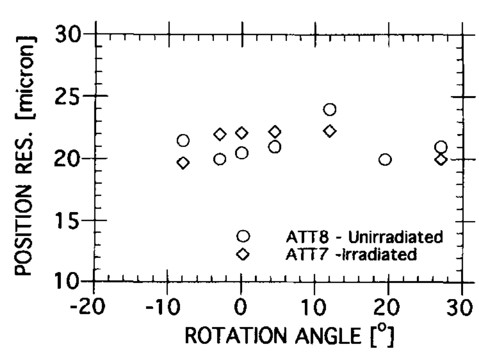


Fig. 8. Position resolution vs. angle at 1 fC threshold

telescope planes. The distributions were fitted with a maximum likelihood function truncated at $\pm$ 60 μm, which cuts out large tails and takes into account the non-gaussian ("square") resolution function of the binary readout. No dependence on the threshold setting is observed for thresholds > 1 fC. In Fig. 8, the resolution for 1.0 fC threshold is independent of the rotation angle and amounts to about 20 μm for the unirradiated module, and about 5–10% worse resolution for the irradiated module, which is within ATLAS specifications.

### 4.5. Determination of the optimal tilt angle

It was shown above that the efficiency and position resolution evaluated at 1 fC threshold are nearly independent of the rotation angle. At larger thresholds, the efficiency becomes a function of the angle, and one wants to tilt the detector in the ATLAS SCT such that the inefficiency will be minimized in a 2 T magnetic field. This optimal tilt angle is expected to be close to the Lorentz angle for electrons in a 2 T field, given that the readout is on the n-side. But at larger tilt angle, the track length is increased by the secant of the angle, which increases the deposited ionization charge. At a tilt angle of 27°, the largest rotation angle studied, this amounts to a 12% charge correction. The angular distributions can be corrected for this track length variation by rescaling the threshold considered by the cosine of the angle of incidence. For the median pulse height, the correction factor is simply the cosine of the angle. The corrected median pulse height is shown in Fig. 9. The angles are indicated at which the corrected pulse height is maximized.

For other parameters, like the mean cluster width (MCW), the average number of hit strips in a cluster, and the efficiency, the corrections are more involved. The dependence of the parameters on the threshold are fitted, and the value corresponding to a threshold weighted by the secant of the rotation angle is determined. The corrected distribution is shown for the mean cluster width in Fig. 10 and for the efficiency at 1.2 fC in Fig. 11. We choose the larger threshold to be more sensitive to the angular dependence. The corrected

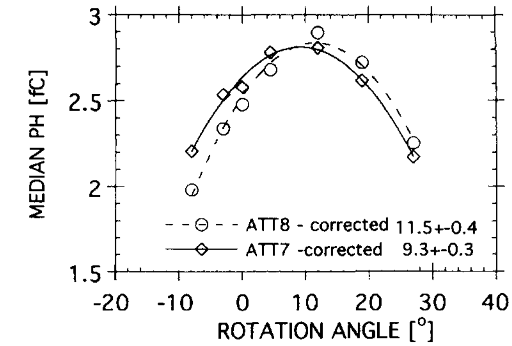


Fig. 9. Median pulse height, corrected for track length, vs. rotation angle in the *B*-field of 1.56 T for ATT8 and ATT7. The angle at which the medians are maximized is indicated.

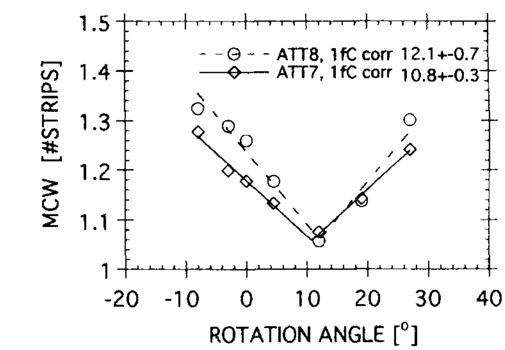


Fig. 10. Mean cluster width MCW at 1.0 fC threshold corrected for track length vs. angle for both ATT8 and ATT7. The angle at which the cluster width is minimized is indicated. A linear fit seems to describe the data well, but has no theoretical justification.

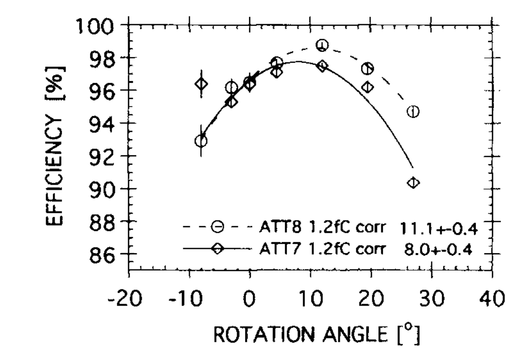


Fig. 11. Efficiency at 1.2 fC threshold corrected for track length vs. angle for both ATT8 and ATT7. The angle is indicated at which the efficiency is maximized.

distributions of the three parameters, Figs. 9–11, are fitted to find the angle which symmetrizes the angular distributions. It turns out that all three distributions yield the same angle for the same detector, but the angle is different for the two detectors. Their average is $(9.4 \pm 0.5)^{\circ}$ for the irradiated detector ATT7 and $(11.6 \pm 0.5)^{\circ}$ for the unirradiated detector ATT8. This difference of the effective Lorentz angle is larger than the estimated uncertainty of the relative rotation. The modules were aligned on one rotation stage, such that the rotation angle of the modules coincided to a fraction of a degree. The extracted value for the effective Lorentz angle is subject to systematics common to the two detectors. For example, the error in the setting of the rotation angle of about 1.5° is common to both. The rotation angle which corresponds to the extremes in the angular distributions is 2° smaller for the irradiated detector than for the unirradiated detector, a fact which might be explained with the reduced mobility in the irradiated detector. The difference is of the order 20%.

The effective Lorentz angle for the 2 T ATLAS field is determined to be 12° for the irradiated and 15° for the unirradiated detector, respectively, by scaling the H8 values up by the ratio of the field strength, $2/1.56 = 1.28$. The corrected efficiency function from Fig. 11 is shifted to center at the new effective Lorentz angle and the track length correction applied by finding the efficiency for the threshold weighted by the track length. This predicted angular dependence of the efficiency (Fig. 12) can

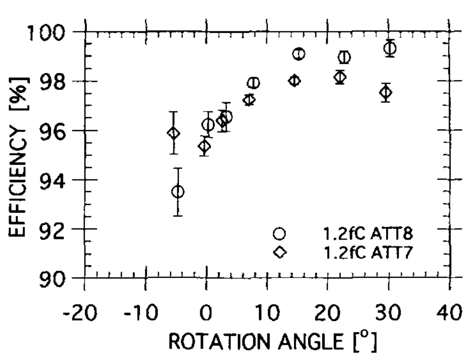


Fig. 12. Efficiency at 1.2 fC threshold vs. rotation angle extrapolated for a $B$-field of 2.0 T for ATT8 (unirradiated) and ATT7 (irradiated to $10^{14}$ p/cm$^2$).

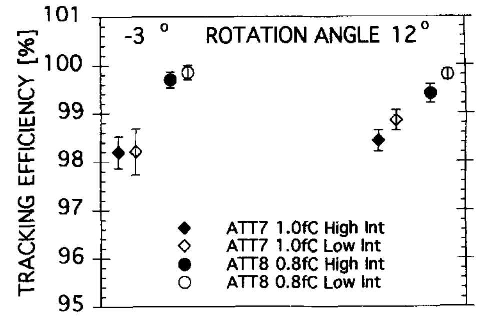


Fig. 13. Efficiency for both irradiated and unirradiated module during high and low intensity running for two rotation angles.

be used to find the optimal tilt angle: the spread of track incidence angles of $\pm 13^{\circ}$ is best accommodated by a tilt angle of about 15° for both unirradiated and irradiated detector.

### 4.6. High intensity operation

During LHC operation, the ATLAS silicon tracker will experience an instantaneous counting rate of the order $10^6$/cm$^2$/s. In order to test the operation of the detectors and electronics under realistic LHC operating conditions, the H8 beam line rate was increased from $3 \times 10^4$/cm$^2$/spill to $2.6 \times 10^6$/cm$^2$/spill. This is close to the instantaneous rate expected at ATLAS and about 20% of the sustained rate. Both the DUTs and the anchor planes used electronics with fast shaping time and performed the tracking without difficulty. The efficiencies at 0.8 and 1 fC threshold for both high and low intensity runs are shown in Fig. 13 for both modules at two rotation angles. Within the statistical errors, the efficiency is the same for high and low operation, for both the unirradiated and the irradiated module, indicating that the efficiency of the detectors does not depend on the rate.

## 5. Conclusions

A beam test of both irradiated and unirradiated silicon micro strip detectors with fast binary readout was performed in a magnetic field of 1.56 T. Good efficiency at low occupancy was found when the detectors were rotated up to 15 degrees relative to the Lorentz angle. The position resolution was about 20 μm for both detectors independent of the angle. The tracking efficiency was determined at beam intensities comparable to those predicted for ATLAS operation and was found to be the same as at low intensity.

## Acknowledgements

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