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## Test results on silicon micro-strip detectors for ATLAS

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### Abstract

We report results from beam tests on silicon microstrip detectors using a binary readout system for ATLAS. The data were collected during the H8 beam test at CERN in August/September 1995 and the KEK test in February 1996. The binary modules tested had been assembled from silicon microstrip detectors of different layout and from front-end electronics chips of different architecture. The efficiency, noise occupancy and position resolution were determined as a function of the threshold setting for various bias voltages and angles of incidence for both irradiated and non-irradiated detectors. In particular, the high spatial resolution of the beam telescope allowed the evaluation of the performance as a function of the track location in between detector strips.

### 1. Introduction

A simplified readout of silicon detectors has been developed (now named Binary Readout) which records only the addresses of strips with pulse height exceeding a fixed threshold value [1–4]. Work on silicon microstrip detectors for use in high intensity colliders has been an ongoing development effort for HERA, SSC and now LHC programs. This readout is now employed in the Leading

Proton Spectrometer at ZEUS [5] and the NA50 experiment at CERN and is the baseline design for the ATLAS Semiconductor Tracking Detector (SCT) [6–8]. All the data presented here were taken with this readout. A block diagram of the readout architecture is shown in Fig. 1.

We have shown that the distribution of pulse heights can be recovered by varying the threshold and measuring the counting rate, which is the integral of the pulse height spectrum [9,10]. Likewise, the noise can be determined from threshold scans without beams. Figs. 2 and 3 show the result of threshold scans taken with a p-strip detector with beam on and beam off. Fig. 4 shows the pulse height

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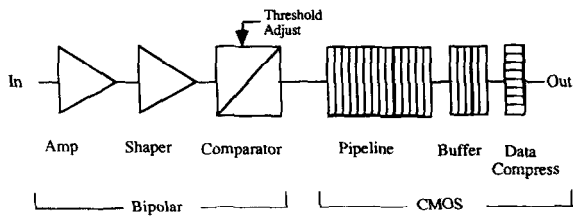


Fig. 1. Block diagram of binary readout.

distribution of beam particles derived by differentiating the right most threshold scan. Results are now available from beam tests conducted at CERN (H8) in Summer and Fall of '95 and at KEK in Winter '96.

## 2. Beam setup

The setup at H8 was as shown in Fig. 5. Three silicon microstrip detector modules were tested with an outer beam telescope to accurately define the track position [11,12]. The center detector module could rotate about an axis parallel to the silicon strip direction to test the effects of inclined tracks. The setup at KEK was similar but another two binary readout silicon micro-strip detectors replaced the beam telescope as “anchor planes” and all 5 detector planes rotated together instead of just the center plane. Table 1 lists the module which were tested at either the Summer H8 test or the Winter KEK test. The detectors had been fabricated by both Hamamatsu and LBL [11,12].

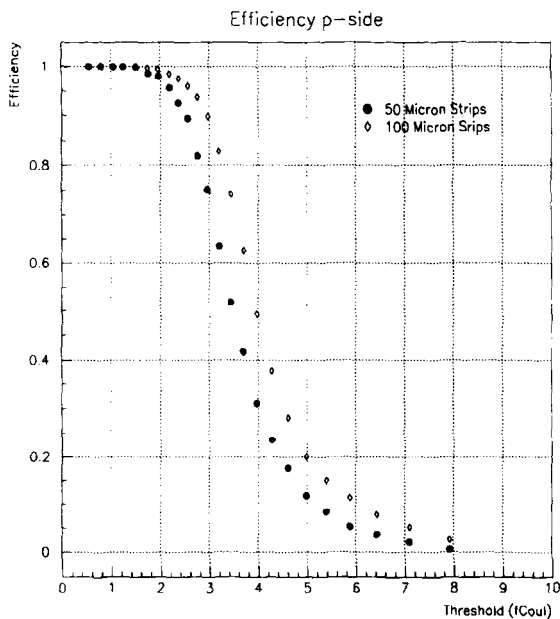


Fig. 2. Efficiency vs. threshold.

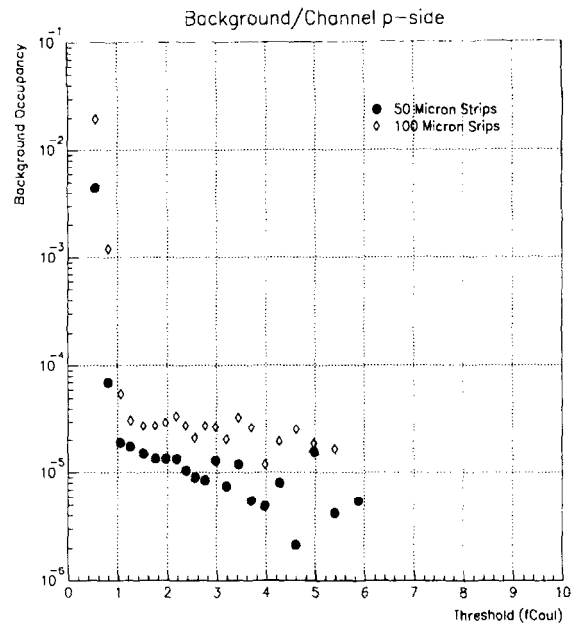


Fig. 3. Background occupancy vs. threshold.

## 3. Noise occupancy

The noise occupancy was measured as a function of the threshold voltage to determine the rms noise. This was done before and after the run using the full DAQ. Channels which were obviously noisy were removed from the data. Fig. 6 shows the occupancy per channel as a function of threshold squared during the H8 test.

The occupancies are approximate Gaussian functions of

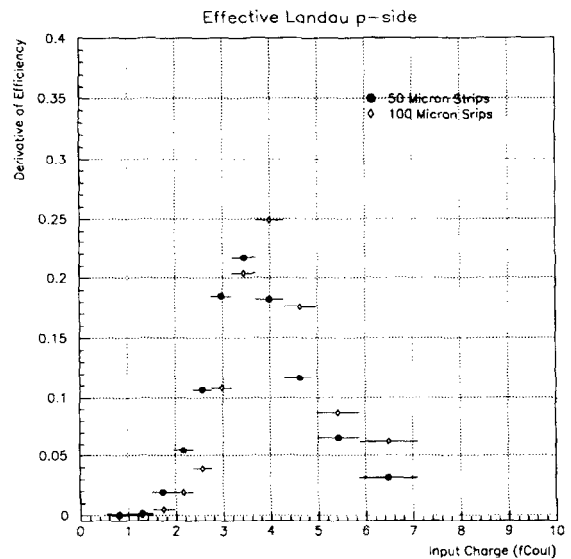


Fig. 4. Pulse height spectrum.

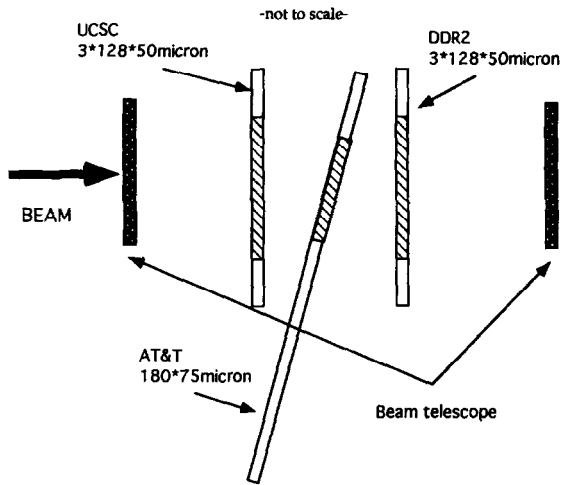


Fig. 5. Binary H8 beam test setup – CERN 1995.

the threshold voltage [13,14]. We observe the expected dependence of the noise on the strip length (12 cm vs. 6 cm). Extrapolating the noise occupancies to a threshold setting of 1 fC gives a noise occupancy of  $0.8 \times 10^{-4}$  for the AT&T3 module and  $1.5 \times 10^{-4}$  for the UCSC1 module with the slightly noisier LBIC front-end IC.

After the Summer '95 H8 run, it was discovered that the bias current on the input transistor of the CAFE chip was not set at the optimum value. This was adjusted for the KEK test in Winter '96 with the improvement shown in Fig. 7. A nominal threshold setting of 1 fC now results in a noise occupancy  $< 1.0 \times 10^{-5}$ .

#### 4. Data analysis

Events were filtered by requiring one and only one track reconstructed in each event. For the analysis of a particular module, the projected track was required to be in the fiducial region, defined as:

- the track impact point was not allowed to fall on a dead strip;
- the track impact point was required to be at least 15

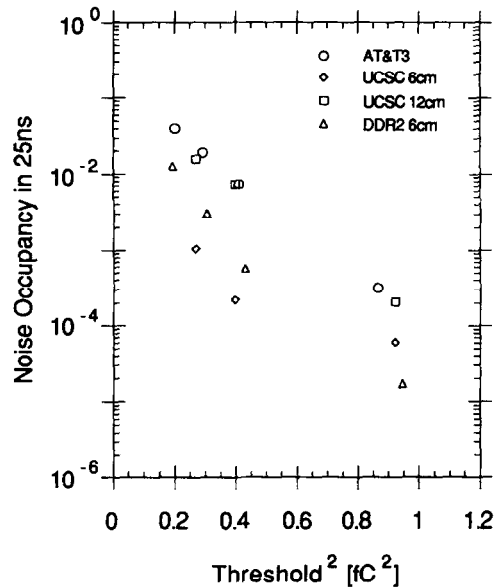


Fig. 6. Noise occupancy of the modules as a function of threshold.

strips away from the edge in the  $x$ -coordinate (the axis perpendicular to the strips);

- the track impact point was required to be approximately 1 mm away from the edge in the  $y$ -coordinate, i.e., along the strips.

In addition, only events with a telescope track  $\chi^2$  value of less than 30 were kept. Clusters were constructed in the following way:

- a cluster seed was started up to  $\pm 2$  strips away from the track impact point;
- searches on the left and right side of the impact point were done independently for hit strips;
- the search stopped when no more hit strips are found;
- all contiguous hits were then clustered.

The cluster position was then taken to be the average strip position for the strips in the cluster. In order to reduce biases in the clustering introduced by noisy or dead channels, events were further rejected if:

Table 1  
Binary  $r$ - $\phi$  modules tested

Module name	Hybrid	Detector fabricator	Detector [side, type, AC]		Pitch [ $\mu\text{m}$ ]	Length [cm]	Irrad.	Amp. chip	
UCSC1	Kapton	Hamamatsu	n	n	AC	50	6, 12	non	LBIC
DDR2	Kapton	Hamamatsu	p	n	AC	50	6	non	LBIC
AT&T3	Ceramic	LBL	n	p	DC	75	12	non	CAFE
AT&T2	Ceramic	LBL	p	n	DC	75	12	non	CAFE
AT&T4	Ceramic	Hamamatsu	n	n	DC	75	12	$1.2 \times 10^{14}$ p	CAFE
UCSC2	Kapton	Hamamatsu	n	n	AC	75	12	non	LBIC
LBIC2	Kapton	LBL	p	n	DC	75	12	non	LBIC

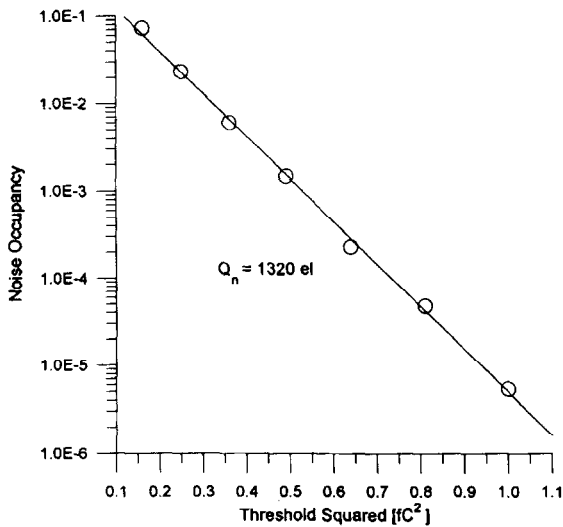


Fig. 7. Noise occupancy of the modules as a function of threshold with optimized input transistor current.

- a found cluster contained a hit on a strip flagged as “noisy”;
- the closest dead strip was less than 2 strips away from the expected hit strip.

Clusters and events that passed all the above requirements were then labeled “good” clusters and “good” events and were used in the efficiency and resolution measurements.

### 5. Results

#### 5.1. Efficiency as a function of inter strip position – DDR2 module

The efficiency for the p-side detector readout with the DDR2 chip is shown in Fig. 8. The efficiency is above 99% even at a threshold 40% higher than the nominal 1 fC. It is 50% at close to 3.5 fC, the median of the binary

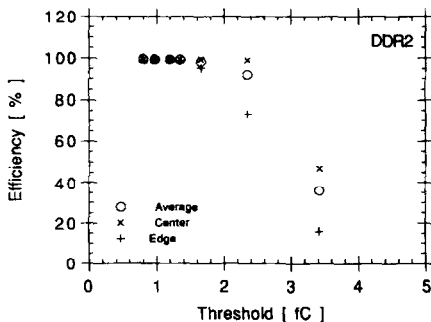


Fig. 8. Efficiency for the DDR2 module as a function of the threshold.

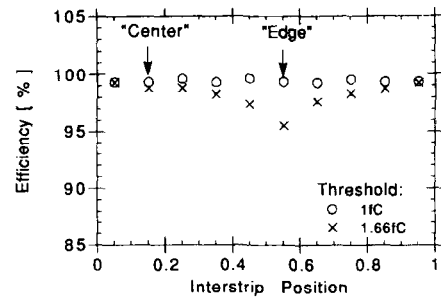


Fig. 9. Efficiency as a function of inter-strip position for 1.0 and 1.66 fC.

Landau distribution. Fig. 9 shows the efficiency as a function of the extrapolated track position between two strips, in fractions of the pitch. The efficiency is shown for two thresholds, 1 fC and 1.66 fC.

As expected, the efficiency starts to degrade in between the strips first, where the charge sharing decreases the effective pulse height detected in a single strip. In the middle between strips, the charge sharing causes higher hit multiplicities. In order to isolate the inter strip effects, we quote, in addition to the efficiencies averaged over all positions, two values for specific inter strip position, “edge”, and “center”. “Edge” refers to the efficiency calculated in a 5 μm wide bin at the edge of a strip, while “center” refers to the efficiency in a 5 μm wide bin at the center of the strip. The values for edge and center were shown in Fig. 8 together with the average efficiency.

Fig. 10 shows the tracking residuals at 1 fC threshold. The distribution is composed of two contributions, one from single hit tracks with a resolution of close to  $\text{pitch}/\sqrt{12} = 14 \mu\text{m}$  and one from multi-hit clusters, with a

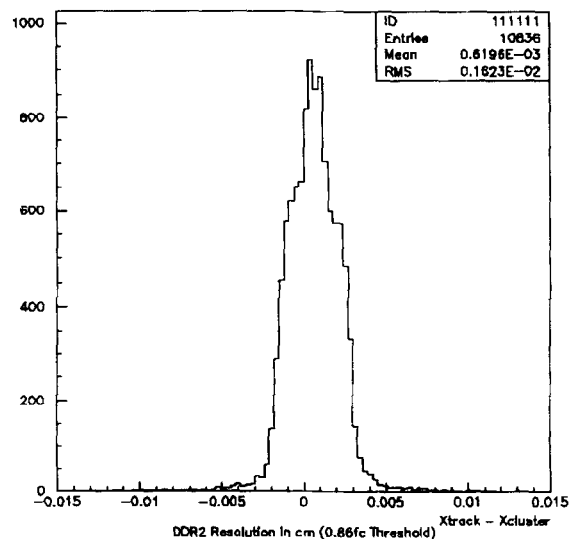


Fig. 10. Residuals between a hit in DDR2 and the projected track position.

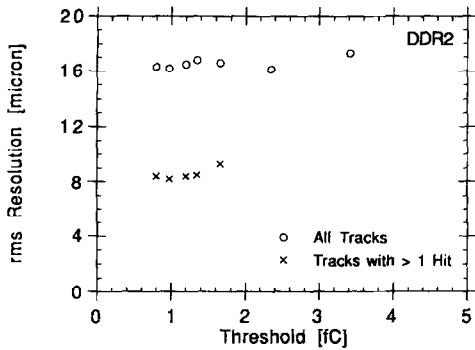


Fig. 11. Rms resolution of all tracks and multi-hit tracks.

resolution of about half of that. Fig. 11 shows the rms resolution for all tracks and for multiple hit tracks only. The fitted resolutions are about 20% lower than the rms values shown. An improvement in the resolution due to charge sharing is evident, but the usefulness of charge sharing in the binary system is limited to the edge of the strips, where the tracking program places the double-hit tracks. This is reflected in the relative population in the two peaks.

Because n-on-n detectors deplete from the backside, the collection of charge might be less efficient at lower bias voltages than at higher ones. The UCSC1 module depletes at about 70 V. We operated the module at 100 V and 200 V bias. Fig. 12 shows the efficiency as a function of the threshold voltage at both bias voltages. The efficiency is close to unity close to the nominal threshold of 1 fC and the median is at 3.5 fC, as found in previous beam tests [9,10].

In order to investigate the effect of the bias voltage on charge sharing, we compared the efficiencies for the two bias voltages at the edge of the strips, where we would expect to be most sensitive to a more efficient charge collection at higher bias. As seen in Fig. 13 we find that the data is virtually identical close to the nominal threshold

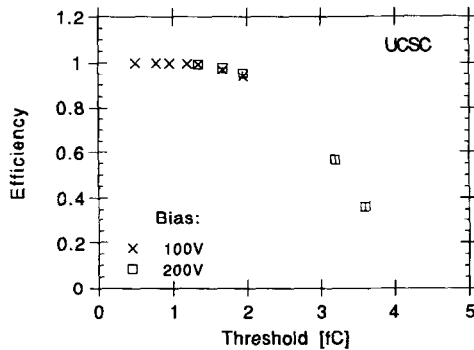


Fig. 12. Efficiency of the UCSC1 module at bias voltages of 100 V and 200 V.

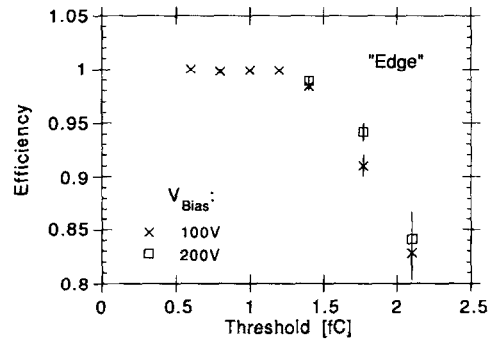


Fig. 13. Efficiency at the edge of the strip vs. threshold for two different bias voltages of the UCSC1 module.

of 1 fC, and only at 1.7 fC, can we observe an increase in efficiency for the larger bias voltage.

For the Winter '96 test at KEK, we were able to irradiate a detector module with  $1.2 \times 10^{14}$  protons/cm<sup>2</sup> (12 GeV). Unfortunately, some of the post-irradiation history of the module included unwanted warm-up periods resulting in a full depletion voltage higher than planned ( $\geq 280$  V). We ran this detector up to 280 V and demonstrated good detector efficiency at partial and near full depletion. We did not run the bias above this point because of concerns about thermal runaway.

The plots in Fig. 14 show noise occupancy vs. efficiency for several threshold settings at 90% and 50% of expected full depletion. At a 250 V bias and ~1 fC threshold, efficiency is >99% and noise occupancy is only slightly above  $1.0 \times 10^{-4}$ . At 50% of full depletion, the efficiency has only dropped to ~96%. This is an extremely interesting result for ATLAS in that it shows the detectors will not become unusable suddenly should our estimates of fluence be wrong, but they can be operated well beyond their expected lifetime in the high radiation environment of LHC with only moderate degradation of performance [17].

The data of the AT&T3 module were taken at constant voltage but varying rotation angle. The n-on-p detector has a depletion voltage of about 150 V, and was operated at about 80 V due to the large bias current, which was reaching the power supply compliance of 2 mA. With the junction on the n-side, this mode of operation corresponds to an inverted n-on-n detector operated at partial depletion, which was shown to be an option for the ATLAS SCT in case of unexpectedly high radiation levels as was mentioned above. The only caveat is that in the module used, the n-implants were somewhat wider and the p-isolation narrower than in the ATLAS direct read-out design.

Fig. 15 shows the efficiency for the three rotation angles 0°, 7° and 14°. Due to increased sharing, the pulse height, i.e., the median of the efficiency curve, decreases going to larger angle. In Fig. 16 we show the average resolution and hit multiplicity as a function of the rotation angle for all events at a threshold of 1 fC. The improvement in res-

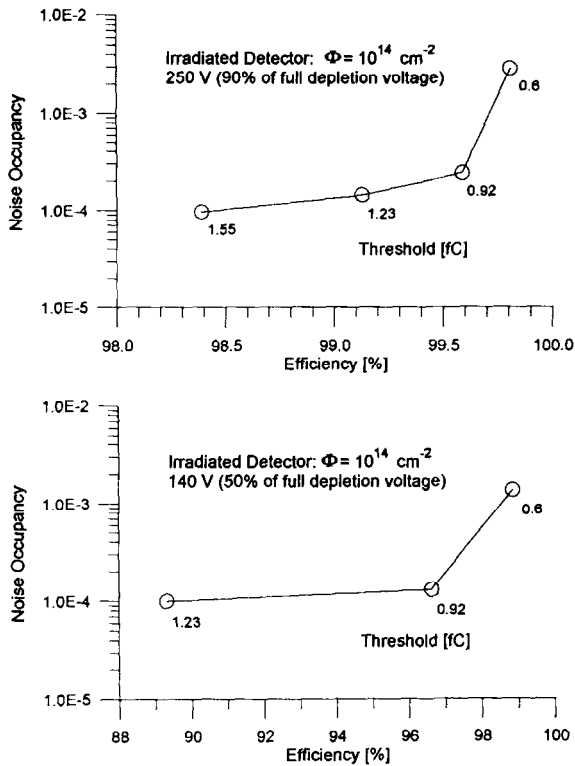


Fig. 14. Noise occupancy vs. efficiency for a 12 cm long module with irradiated detectors operating at two different biases below depletion voltage.

olution with the increased rotation angle is correlated with increased hit multiplicity and thus increased charge sharing between neighboring strips.

### 6. Conclusions

We have performed beam tests with several detector modules using binary readout during the 1995 ATLAS beam test in H8 at CERN and the 1996 beam test at KEK. Previous results showing an extended efficiency plateau

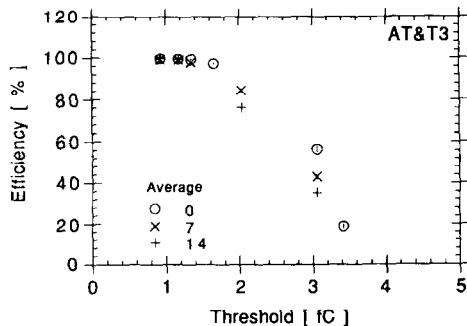


Fig. 15. Efficiency for rotation angles of 0°, 7°, 14°.

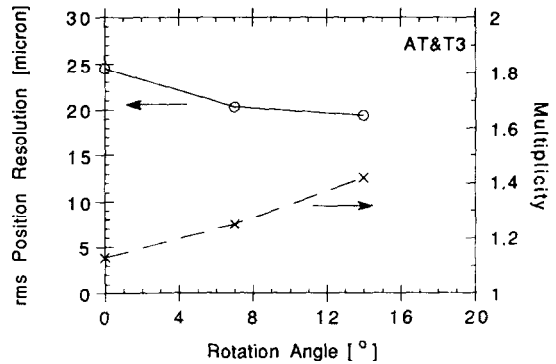


Fig. 16. Position resolution and average multiplicity as a function of angle.

beyond the nominal threshold of 1 fC have been confirmed. With the help of a precision telescope, the efficiency and resolution was mapped out as a function of the track position between strips. We found good efficiency for inclined tracks up to 14 deg. in a 75 micron pitch n-side detector. The efficiency of n-on-n detectors depends only marginally on the bias voltage once the detector is depleted. Furthermore, we have tested an n-on-n detector irradiated to  $1.2 \times 10^{14}$  protons/cm<sup>2</sup> operating just below and well below full depletion with only moderate degradation in performance.

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