SCIPP 95/45
November 1995

Monitoring the Performance of Silicon Detectors with Binary Readout in the ATLAS Beam Test

H. F.-W. Sadrozinski*, J. DeWitt, D. E. Dorfan, T. Dubbs, A. A. Grillo, S. Kashigin, W. Kroeger, J. Rahn, W. A. Rowe, A. Seiden, E. Spencer, A. Webster, R. Wichmann, M. Wilder, D. Williams
SCIPP, Univ. of California, Santa Cruz, CA, USA

J. Dane, A. Lankford, S. Pier, B. Schmid
Univ. of California, Irvine, CA, USA

R. Bonino, C. Couyoumtzelis, P. Demierre
Univ. of Geneva, Geneva, Switzerland

Y. Iwata, T. Ohsugi
Hiroshima Univ., Hiroshima, Japan

H. Iwasaki, T. Kondo, S. Terada, Y. Unno
KEK, Tsukuba, Japan

W. Dabrowski, M. Idzik
IPNT, Krakow, Poland

J. Godlewski
INP, Krakow, Poland

R. Takashima
Kyoto Univ. of Education, Kyoto, Japan

A. Ciocio, T. Collins, C. Haber , I. Kipnis, M. Shapiro, J. Siegrist, H. Spieler
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

N. Tamura
Okayama Univ. , Okayama, Japan

* Corresponding author. Tel +1 408 459 4670, e-mail hfws2@slac.stanford.edu

A. Grewal, R. Nickerson, R. Wastie
Oxford Univ. , Oxford, UK

Y. Gao, R. Gonzalez, A M. Walsh, Z. Feng
Univ. of Wisconsin,, Madison, WI, USA

ABSTRACT

The monitoring of the performance of silicon strip systems with binary read-out is discussed. Due to the fact that neither pulse height nor noise level are recorded, the system is monitored with the efficiency and noise occupancy. As an example, on-line monitoring of the binary silicon strip system at the ATLAS H8 beam test at CERN is described.

INTRODUCTION

The large detector systems for the next generation hadron collider LHC, ATLAS [1] and CMS [2], rely on large-scale silicon detector systems as inner tracker. Simplicity of design and robustness of performance in the high radiation environment are of primary importance. Both silicon detectors and front-end electronics (FEE) are susceptible to radiation damage, and consequently, monitoring of the performance is crucial. The historic way of monitoring the performance of silicon strip detectors is the determination of the signal-to-noise ratio (S/N), which is possible if the analog pulse height information of signal and noise are recorded simultaneously. For the large LHC detectors, S/N = 15-20 is required.

We are proposing to simplify the readout of silicon detectors by using a binary readout [3], which records only the addresses of strips with pulse height exceeding a fixed threshold value. Thus the pulse height will not be available directly during data taking. We have shown that the pulse height information can be recovered by varying the threshold and measuring the count rate, which is the integral of the pulse height spectrum. Likewise, the noise can be determined from threshold scans without beams. During data taking, this method of determining the signal and noise is not usable, because the threshold will be kept constant. Thus the question arises how the performance will be monitored in a binary system.

It is important to note that the primary parameters of interest for a tracking device are not the signal and noise, but the single channel efficiency and the noise occupancy, and we propose to monitor both directly on-line during data taking.

In the following, we report on our experience with on-line monitoring at the ATLAS beam test in summer 1995 and outline a monitoring system of the performance of the silicon tracker with binary read-out.

ATLAS BEAM TEST IN H8 AT CERN IN SUMMER 1995:

During the ATLAS beam test in the CERN H8 beam line in 1995 [4], on-line monitoring of the efficiency was only one of many objectives for the binary system. Table 1 lists the various detector modules used in the beam test. All modules are so-called "r-f" modules, where the detector strips are directly bonded to the FEE. Consequently, the hybrid, which carries the FEE and the data and control signals, is mounted across the detector strips in the approximate center of the 12cm silicon detector module.

Table 1: Binary r-ϕ Modules in the H8 Beam Test

Tested Module	Hybrid	Detector [side,type,AC]			Pitch [micron]	Length [cm]	# of strips	Amp Chip	Pipe Line
UCSC	Kapton	n	n	AC	50	6,12	384	LBIC	CDP128
DDR2	Kapton	p	n	AC	50	6	384	LBIC	DDR2
LBIC1,LBIC2	Ceramic	p	n	DC	75	12	1536	LBIC	CDP128
ATT1,ATT2	Ceramic	p	n	DC	75	12	256,128	CAFE	CDP128
ATT	Ceramic	n	p	DC	75	12	180	CAFE	CDP128

The large number of modules available was mainly a consequence of the availability of both tested SSC-style and newly developed LHC-style detectors and front-end electronics (FEE), respectively. Two bipolar amplifier-comparator chips with peaking time of close to 20ns were used, where the LBIC [5] was developed for AC-coupled SSC detectors, and exhibits strong gain dependence on input current when used with DC-coupled detectors, and the CAFE [6] chip is designed for operation with finite input current for use with ATLAS DC-coupled detectors; unfortunately the production run with AT&T yielded too few chips to instrument the full complement of modules. Two CMOS digital pipelines were used, with the CDP128 [7] a clock-driven binary pipeline and the DDR2 [8] a data-driven binary pipeline with zero suppression and a data transmission protocol similar to the ATLAS protocol. The silicon detectors tested were AC-coupled double-sided detectors with 50μ pitch developed in Japan for the SSC [9] and DC-coupled ATLAS-type 75μ pitch detectors fabricated at LBNL [10]. Both Kapton flex-circuit and ceramic hybrids were successfully used, although the yield of Kapton circuits turned out to be extremely low. Note that among the modules were full-scale 12cm by 6cm modules with read-out on all channels.

Table 2 lists the main objectives of the beam test, which centered on gaining experience with the 12cm modules, the new front-end electronics and a new fast data acquisition system based on 40MHz DSP's, allowing high speed data acquisition and flexibility to accommodate the many different modules.

Table 2: Objectives of the Binary H8 Beam Test

Test of ATLAS style front-end chips & detectors
Determination of signal/noise for 6cm and 12cm strip length
Determination of signal/noise for inclined tracks in 75m pitch detectors
On-chip data sparsification (ATLAS style data transmission protocol)
Test of clock pick-up for hybrids mounted across detectors
Module fabrication techniques
High speed DAQ (40MHz) based on DSP modules
On-line monitoring

MONITORING THE FRONT-END ELECTRONICS: CALIBRATIONS

The role of the calibration in a binary system differs from that in an analog read-out system: it simply has to monitor the performance of the FEE, but has no function in the data correction/analysis. Thus the requirements on the accuracy and frequency of calibration runs are very relaxed. Known charges are injected at the FEE input and the response (gain) and the noise sigma determined[11,12]. This is usually done during beam-off time and can be as exhaustive as one wishes, because there will be dedicated time to calibrate the other detector components (calorimeter, muon system, straws...). One important result of the calibration is the list of "bad" channels, which have bad gain or noise and have to be masked during operations and data analysis. In addition, the calibrations might possibly show that an adjustment of the threshold voltage for part of the silicon tracker is required.

We gained experience with a binary system in the LPS [13] of ZEUS [14] at HERA, consisting of about 35k channels: every few month, a calibration is done, ascertaining that the system is stable. We did not find it necessary to adjust the threshold and in over a year of operation at HERA, the common threshold was held fixed at 0.78 fC. The architecture, chip design and fabrication technology of the ZEUS FEE system [15] resembles closely the proposed binary system for the silicon tracker of ATLAS. During H8, we took a total of four calibrations, one before and one after each of the running periods in August and September 1995.

MONITORING OPERATIONAL CONDITIONS: OCCUPANCY PLOTS

Both during beam-on and beam-off operations, occupancy plots ("channel maps") are an important diagnostic tool. Again, hot or dead channels are flagged, and abnormal conditions of the beams or the operations are recognized.

Due to the low occupancy of the system, we were able to align the detectors in H8 relative to the beam by just looking at the profile of the beams in channel maps of all recorded events.

In Ref. [15], it was shown that the strip occupancy taken during normal operations at HERA, where the silicon detectors were operated as close as 2mm from the center of the 820GeV proton line, is of the order $< 10^{-3}$ at a threshold of 0.78fC; this includes both electronics noise and beam related contributions. The event multiplicity is low with no long tails, indicating that common noise is no problem. Both the channel occupancy and the event multiplicity are useful to identify noisy beam conditions on-line. From the occupancy, the charged particle dose is calculated directly.

MONITORING SIGNAL-TO-NOISE: THRESHOLD SCANS

By recording the counting rate as a function of varying threshold, the pulse height spectrum can be extracted. The so-called threshold scan yields the efficiency, which is the integral spectrum of all hits with pulse height exceeding the threshold setting. Its derivative is the pulse height spectrum. Data from a previous beam test at KEK (Ref [16]) are shown in Fig. 1, with the threshold curve in Fig 1a and the pulse height spectrum in Fig. 1b. An operating threshold of 1fC was established for the binary system.

Performing these threshold scans interferes with data taking, and the question arises how often and how long data acquisition has to be interrupted for threshold scans. With the anticipated high rate of charged particles at the LHC, scans will take only a few minutes. Bearing in mind that the overall degradation of the system due to radiation is a slow process, we expect that only occasional detailed threshold scans with beams are needed to measure the median pulse height, maybe as often as once a week. Threshold scans will be needed after major intervention into the system, like after warming it up for repairs, in order to determine the operating conditions, i.e. threshold and bias voltage.

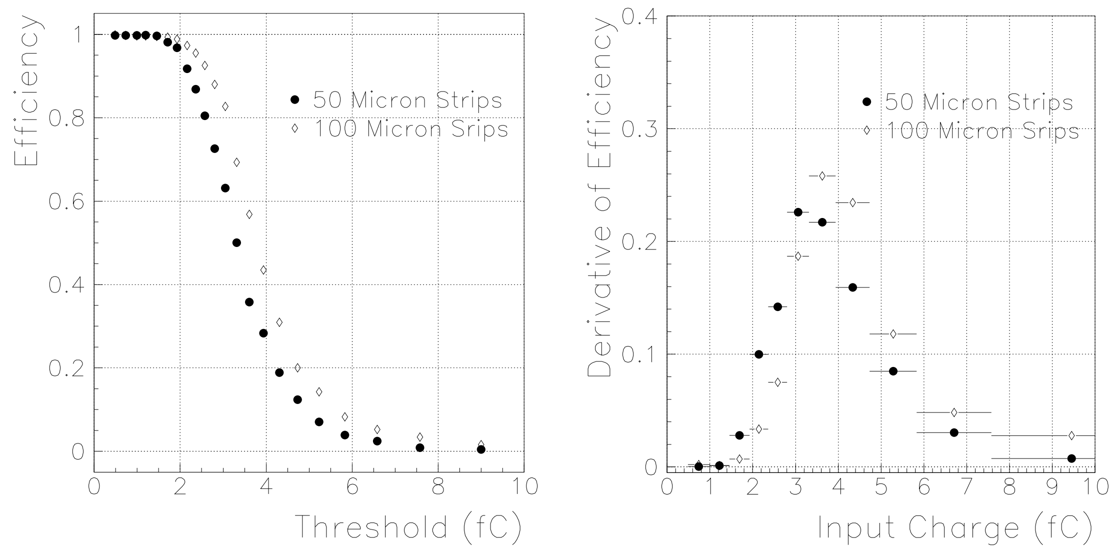

Fig 1: a. Efficiency as a function of threshold, b. Pulse height. (Ref. [16])

In a similar procedure, the noise sigma can be extracted, from a threshold scan without beams, a task which can be completed in a few minutes. Fig. 2 shows the noise occupancy of the ATT module taken on-line in H8.

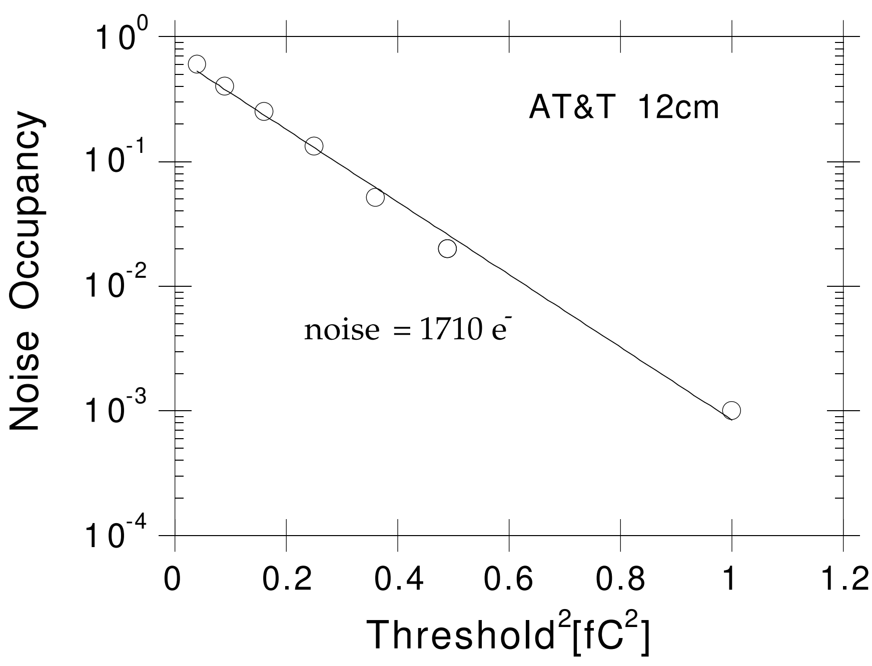

Fig. 2 On-line noise occupancy of the 12cm p-bulk n-side ATT module

The extracted noise sigma of 1700 electrons is somewhat higher than desired because the detector was not optimized for low interstrip capacitance due to the relatively narrow p-isolation strips between the n strips in the p-bulk detector.

The noise improves with wider p-isolations is shown in Fig 3, where the noise occupancy of n-bulk Hamamatsu detectors of the "UCSC" module of H8 with 12cm and 6cm long n-side strips are shown as function of threshold for different bias voltages.

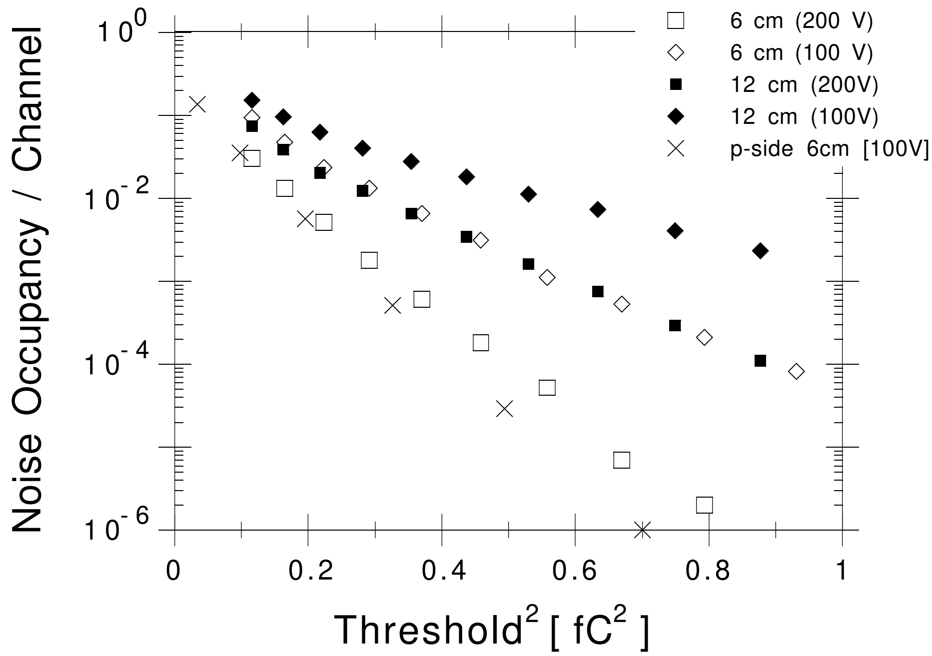

Fig. 3 Noise occupancy per channel for the n-side detector as a function of the threshold, for different bias voltages. For comparison, noise occupancy of a 6cm p-side detector is included (Ref [11]).

An error function fit [12] to the occupancy curves of Fig. 3 gives the noise sigma's in Table 3. The data in Fig. 3 and Table 3 indicate that 12cm long n-side detectors with binary readout can be operated with noise occupancy of close to 10^{-4} (corresponding to noise sigma's of 1500 electrons) if the bias voltage is kept high. The bias voltage dependence of the noise reflects the bias voltage dependence of the interstrip capacitance for the n-side detectors [17]. This applies only to n-side detectors before inversion; after inversion which occurs at a fluence of about 10^{13} particles/cm^2, the n-side capacitance is reduced to below the pre-radiation level and is independent of the bias voltage [11].

Table 3 : Noise Sigma's derived from Occupancy Plots
for Low Capacitance Hamamatsu Detectors

Side: n/p	Length [cm]	Bias [V]	σ_n [e^-]
n	6	100	1370
n	6	200	1180
n	12	100	1860
n	12	200	1550
p	6	100	1060

MONITORING EFFICIENCY & NOISE OCCUPANCY: TRACKING

As mentioned above, the efficiency and noise occupancy are the performance parameters which are directly usable in tracking programs. The efficiency has to be determined with an on-line tracking program, while the noise occupancy can be extracted from beam crossings out-of-time with the trigger. Owing to the fact that the binary system does not rely on determining the charge sharing between adjacent strips, and therefore achieves a position resolution close to the geometrical one of pitch/√(12), we have found in our beam tests [16,18] that the resolution has automatically the expected value if the efficiency is high and the noise is low. We conclude that we do not need to monitor the position resolution on-line in addition to efficiency and noise occupancy.

The binary data lends itself ideally to the task of on-line monitoring, because no data corrections are needed (and are even possible!). The requirements for the tracking programs are modest due to the low occupancy of the system. Simple ratio's of 2-out-of-3 or 3-out-of-4 hits with modest p_t cut are sufficient. In the following we show two examples how the efficiency determination works

KEK Beam Test

In the KEK beam test [16.18], a tracking program was used to determine the efficiency of each of the planes. This was done off-line after a careful alignment of all the planes relative to each other. The resulting plot (Fig. 1a) shows inefficiencies of less than 0.1% at 1fC threshold for the n-side operating with bias far above depletion. The pulse height spectrum (Fig. 1b) peaks close to the expected value of 4fC.

Fig 4 shows the set-up during a particular run period in September 1995, with two stationary detectors ("anchors") and two devices under test on a rotary stage. In addition to position and rotation scans, two parameters were varied to map out the performance of the detectors: the detector bias voltage and the threshold of the on-chip comparators. The results from the threshold scans are used to determine the pulse height scale and the effect of a finite crossing angle.

Here we will report only on the on-line monitoring during the beam test, while a threshold scan was performed at a fixed bias voltage and a beam crossing angle of 14° relative to the strips. The rotation simulates worse case pulse height during ATLAS operations due to the pulse sharing among adjacent strips.

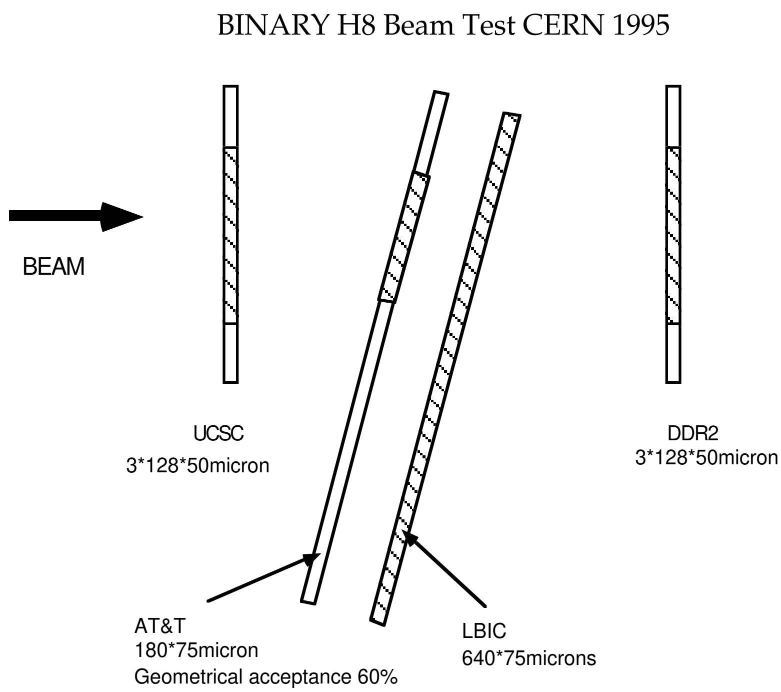

Fig. 4 Set-up of the binary H8 beam test in September 1995. Shaded areas are the extend of read out channels.

Instead of using a tracking program which fits tracks through the detector hits (as in Ref [16]), a simple procedure which relied on correlation plots was used to determine the efficiency. Hits in two anchor planes (UCSC, DDR2) with fixed threshold of 1fC identified beam particles and we then searched for corresponding hits in the third plane (ATT). Fig. 5a is a plot of the channel # of hits in the UCSC detector vs. those in the DDR2 plane. A clear correlation due to beam particles is visible along the diagonal, and very few hits otherwise. The projection onto the line Δ = DDR2-UCS (Fig. 5b) allows to select beam particles with -6 < Δ < 4.

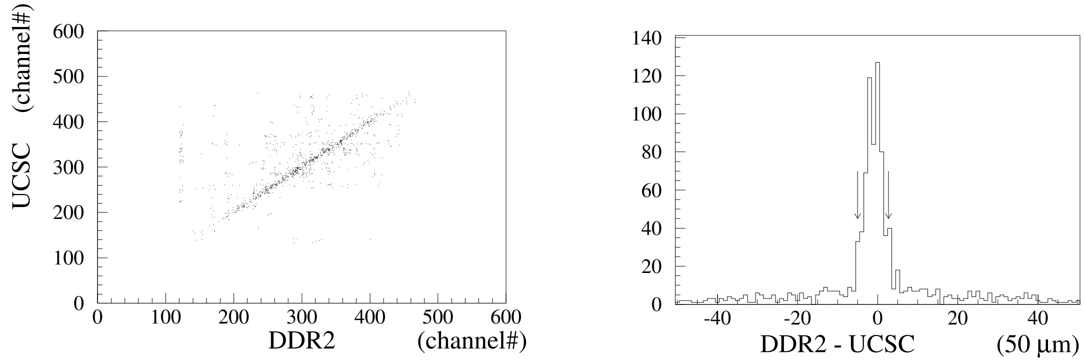

Fig 5: a. Correlation UCSC vs. DDR2 plane (threshold 1fC); b. Projection

Likewise, a beam correlation is evident in the scatter plot between the ATT and the UCSC hits (Fig. 6a). Requiring that the hit in the UCSC plane is associated with a beam particle (i.e. is correlated with a hit in DDR2 with -6 < Δ < 4), gives the correlation of positions in the ATT plane with hits in the UCSC (Fig. 6b), which is essentially background free.

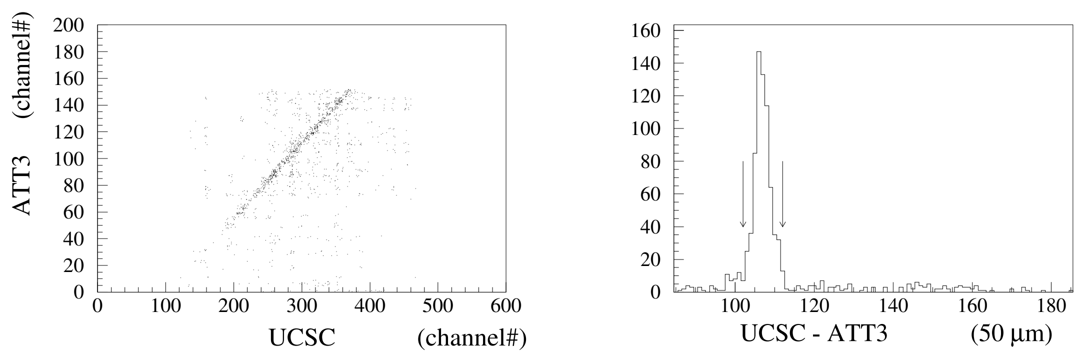

Fig. 6 a. Correlation of hits in the ATT and UCSC planes. b. Projection for hit positions where the UCSC and DDR2 hits have a beam correlation.

The efficiency is the ratio of hits in ATT with a beam correlation (between the arrows in Fig. 6b) to the beam correlated hits in the anchor planes (between the arrows in Fig. 5b). Because the acceptance of the anchor planes were larger than the ATT plane, this simple procedure yielded only relative efficiencies. A cut on the beam position in the anchor planes would have given absolute efficiencies.

During the data taking, we were able to track changing beam conditions. Due to the fact that the beam was not fully contained in the ATT detector, we measured different relative efficiency depending on the beam size, which was determined by the width of the beam in the anchor planes. This is shown in Fig 7, where we plot the efficiency at comparator thresholds of 0.8, 1.0 and 1.2 as a function of the beam size as determined in the UCSC plane. Two different beam conditions were observed, with corresponding different, but stable efficiencies.

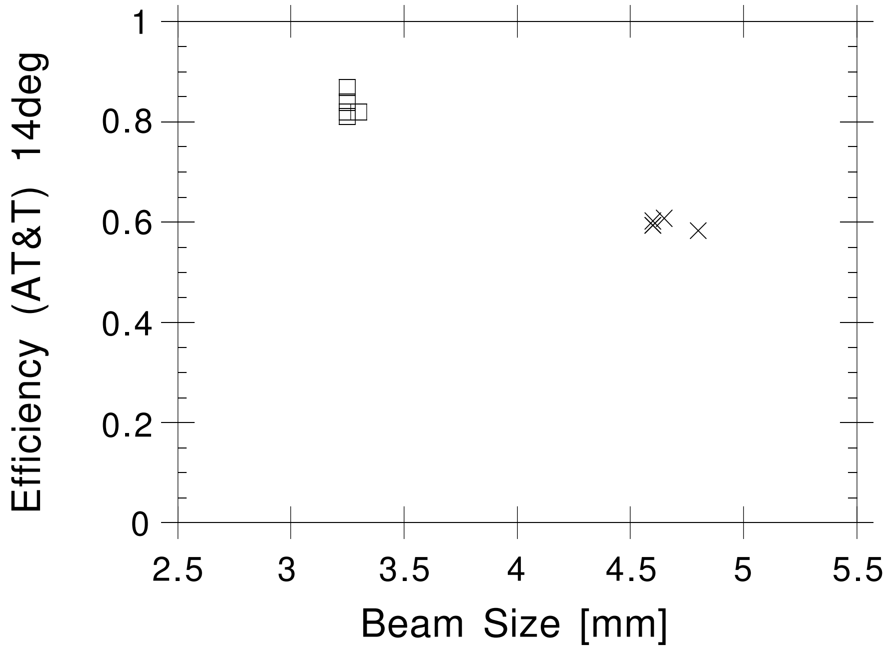

Fig. 7 On-line efficiency at 1fC threshold for different beam sizes.

For the small beam size data, we normalized the efficiencies at low threshold to unity and calculated the efficiency during a threshold scan with the ATT detector rotated by 14^{o}. This threshold curve is shown in Fig 8: it has the same form as the one determined from off-line analysis in previous beam test [16], c.f. Fig 1. The observed median is, as expected, lower than in Fig. 1 because of the finite crossing angle of the beam, yet the efficiency is still very high even at a threshold of 1.4fC.

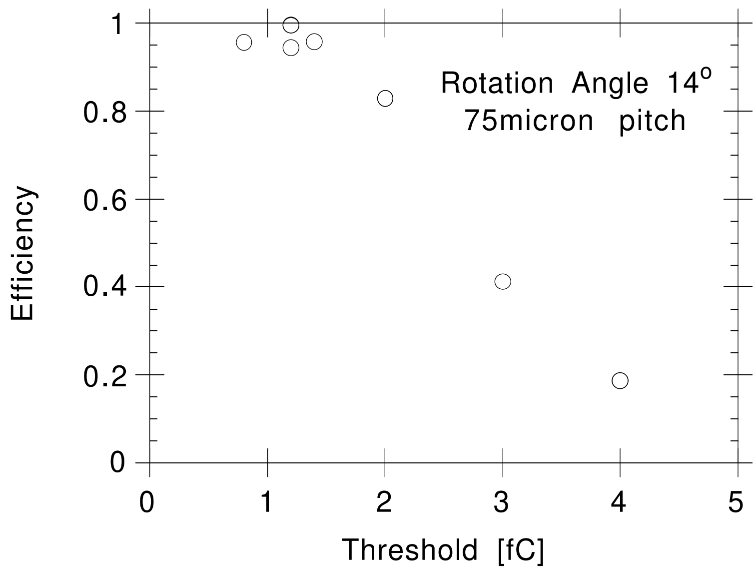

Fig. 8 Relative efficiency as a function of threshold for rotation of 14^{o}.

PROPOSED SILICON SYSTEM MONITORING PROGRAM FOR ATLAS:

We can now outline a monitoring program for the binary silicon detector system:

a) calibration of the FEE	every few days.
b) threshold curves:	every week.
c) occupancy:	continuously, with/without beams
d) efficiency and noise occupancy:	on-line during runs

For the on-line determination of the efficiency, we propose to investigate the usefulness of the LEVEL 2 trigger algorithm. During data taking, the LEVEL 2 trigger performs tracking with cuts on high p_t patterns and stores this information for further trigger decisions [19]. Because the selection is on three hits out of four in closely spaced layers, the output of the trigger program can determine the fraction of misses in three out of four and serve as an inefficiency monitor. It might prove to be sufficient to determine the efficiency per detector module and use the channel maps to monitor the channel to channel variations. Because all LEVEL 1 triggers will participate, as long as there is a track present,- irrespective if they are later accepted as LEVEL 2-, this method affords high statistics.

CONCLUSIONS

The H8 beam test has shown that binary modules have performance approaching the requirements for the ATLAS silicon tracking detector.

We were able to monitor the performance of the binary system on several levels. Electronics calibration are needed only to monitor the integrity of the system, not for data reduction and analysis. The low noise level in the binary system makes the occupancy plots an important tool to monitor operational conditions. Threshold scans allow to determine the pulse height and noise sigma's, but we advocate to perform them at not too frequent intervals.

Direct determination of efficiency and noise occupancy have been shown to be possible on-line during data taking. For the operation of the ATLAS silicon tracker, we propose to employ the tracking algorithms of the LEVEL 2 trigger to select tracks for the on-line efficiency determination.

ACKNOWLEDGMENTS

We thank our colleagues in H8, especially Steinar Stapnes and Gareth Moorhead, for their help and cooperation. This work was supported by DoE and the US-Japan Scientific cooperation program.

REFERENCES

[1] ATLAS Technical Proposal CERN/LHCC/94-43.

[2] CMS Technical Proposal CERN/LHCC/94-38.

[3] A. Ciocio *et al*, A Binary Readout System for Silicon Strip Detectors at the LHC, Presentation at the LHC Electronics Workshop, Lisbon, Portugal, Sept 12, 1995.

[4] P. Allport: ATLAS Beam Test Results, These proceedings

[5] E. Spencer *et al.*, A Fast Shaping Low-Power Amplifier-Comparator Integrated Circuit for Silicon Strip Detectors, IEEE Trans N.S. **42**, 796(1995)1

[6] I. Kipnis, CAFE, A Complementary Bipolar Analog Front-end Integrated Circuit for the ATLAS SCT, unpublished.

[7] J. DeWitt, A Pipeline and Bus Interface Chip for Silicon Strip Detector Readout,
IEEE N.S. Symp., San Francisco, CA, Nov. 1993, SCIPP 93/37.

[8] K. Shankar *et al*, Digital Read-out Chip for Silicon Strip Detectors at SDC,

IEEE Trans. N.S. Symp. **42**, 792 (1995).
[9] T. Ohsugi *et al*, Double-sided Microstrip Sensors for the Barrel of the SDC Silicon Tracker, Nucl. Instrum. Methods **A342** (1994) 16.
[10] S. Holland, Fabrication of Silicon Strip Detectors using a Step and Repeat Lithographic System, LBL 31595, (1991).
[11] T. Dubbs *et al,* Noise Determination in Silicon Microstrip Detectors 1995 IEEE N.S. Symposium, San Francisco, CA, SCIPP 95/19.
[12] T. Pulliam, Noise Studies in Silicon Micro strip Detectors, UC Santa Cruz Senior Thesis 1995, SCIPP 95/28.
[13] M Derrick *et al.*, First Measurements with the ZEUS Leading Proton Spectrometer, submitted to the International Conference on High Energy Physics, Glasgow, 1994.
K. O'Shaughnessy *et al*., Testing and Installation of ZEUS Leading Proton Spectrometer Planes, Nucl. Instrum. Methods **A342**, 260 (1994).
[14] The ZEUS Detector Status Report, Chapter 13, (February 1993), DESY, Hamburg.
[15] E. Barberis *et al*,, Design, Testing and Performance of the Front-end Electronics for the LPS Silicon Micro strip Detectors, Nucl. Instrum. Methods **A364** (1995) 507.
[16] J. DeWitt *et al*, Signal-to-Noise in Silicon Micro strip Detectors with Binary Readout, IEEE Trans. N.S. Symp. **42**, 445 (1995).
[17] E. Barberis *et al*., Capacitances in Silicon Microstrip Detectors, Nucl. Instrum. Methods **A342** (1994) 90.
[18] Y. Unno *et al,* Characterization of DSSD with fast binary readout electronics using pion beams, 1995 IEEE N.S. Symposium, San Francisco, CA
[19] K. Borer *et al*., A Study of a Second Level Track Trigger for ATLAS, Nucl. Instrum. Methods **A336** (1993) 59.