Real Time Tracker Based Upon Local Hit Correlation Circuit for Silicon Strip Sensors

Niklaus Lehmann^{a,*}, Lorenzo Pirrami^b, Andrew Blue^c, Sergio Diez^{a,d},
Nandor Dressnandt^e, Silvan Duner^b, Maurice Garcia-Sciveres^a, Carl
Haber^a, Amogh Halgeri^e, Paul Keener^e, John Keller^d, Mitchell Newcomer^e,
Jacob Pasner^f, Richard Peschke^d, Amar Risbud^g, Eric Ropraz^b, Jonas
Stalder^b, Haichen Wang^a

^a*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720, USA*

^b*University of Applied Sciences Western Switzerland, Boulevard de Pérolles 80 - CP 32,
CH-1705 Fribourg, Switzerland*

^c*SUPA School of Physics and Astronomy, University of Glasgow, G12 8QQ, United
Kingdom*

^d*Deutsches Elektronen-Synchrotron, Notkestraße 85, 22607 Hamburg, Germany*

^e*University of Pennsylvania, Philadelphia, PA 19104, USA*

^f*University of California Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA*

^g*University of California Berkeley, Berkeley, CA 94720, USA*

Abstract

For the planned high luminosity upgrade of the Large Hadron Collider (LHC), a significant performance improvement of the detectors is required, including new tracker and trigger systems that makes use of charged track information early on. In this note we explore the principle of real time track reconstruction integrated in the readout electronics. A prototype was built using the silicon strip sensor for the ATLAS phase-II upgrade. The real time tracker is not the baseline for ATLAS but is nevertheless of interest, as the upgraded trigger design has not yet been finalized. For this, a new readout scheme in parallel with conventional readout, called the Fast Cluster Finder (FCF), was included in the latest prototype of the ATLAS strip detector readout chip (ABC130). The FCF is capable of finding hits within 6 ns and transmitting the found hit information synchronously every 25 ns. Using the FCF together with external correlation logic makes it possible to look for pairs of hits consistent with tracks from the interaction point above a transverse momentum threshold. A correlator logic finds correlations between two closely spaced parallel sensors, a “doublet”, and can generate information used as input to a lowest level trigger decision. Such a correlator logic was developed as part of a demonstrator and was successfully tested in an electron beam. The results of this test beam experiment proved the concept of the real time track vector processor with FCF.

Keywords: Trigger concepts and systems (hardware and software), HL-LHC, silicon strip tracker, high speed readout

*Corresponding author. Tel. 510-486-7305; Fax. 510-486-4047.
E-mail address: niklaus.lehmann@cern.ch (Niklaus Lehmann).
Preprint submitted to Elsevier

September 27, 2015

1. Introduction

An upgrade of the Large Hadron Collider (LHC), the High Luminosity LHC (HL-LHC) is under way and it is expected to be finished by mid 2020's. This upgrade is performed in multiple phases. The Phase-II upgrade for ATLAS, a general purpose detector, is designed to match the requirements of the increased luminosity in the HL-LHC [1]. The instantaneous luminosity is assumed to increase up to $7 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. This requires a performance improvement in the trigger and data acquisition system (DAQ) to guarantee the same physics performance of the detector during operation.

Currently, ATLAS uses a Level 1 (L1) trigger with 100 kHz maximum rate to read the full data from the entire detector front end electronics. The planned baseline for the Phase-II upgrade is to insert a 1 MHz Level 0 (L0) trigger to retrieve partial tracker information, and then incorporate this information in a L1 decision to read the full experiment, with an average L1 rate of up to 400 kHz.

An alternative to relying on a L0 trigger would be to retrieve reduced information from the tracker at the full 40 MHz bunch crossing rate, as is the case for the calorimeter and muon systems. The correlator scheme described in this note addresses this alternative by reducing the tracker data volume in-situ and in real time. Data reduction is needed because full triggerless readout of all tracker data from every collision is not considered technically feasible with low mass and low power. The correlator approach provides a data reduction factor of 20 to 40 [2], comparable to the baseline of reading data from just 1 out of 40 collisions with an externally supplied 1 MHz L0.

The Compact Muon Solenoid (CMS) experiment proposes to use hit correlations from two closely spaced layers to reduce the tracker information read from each collision [3]. Their proposed correlation hardware is different from that presented here.

The idea of the real time tracker is to use the information from two adjacent detector layers. Hit information of detected particles is directly analyzed in real time in-situ every 25 ns, corresponding to the time between two collisions. This is done with a dedicated correlation logic, called “correlator”, implemented on the module. A module is an assembly of silicon sensors and readout electronics. The correlator reconstructs track vectors across two layers and filters them by the transverse incident angle, using the cluster size and azimuthal offset between the clusters on the two layers. The incident angle is correlated with the transverse momentum for particles coming from the interaction point¹. Secondary particles from interactions in the detector material can have any angle-momentum correlation and constitute a background. A sketch

¹ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector, and the z-axis along the beam line. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam line. Observables labelled “transverse” are projected into the x - y plane.

of the real time tracker concept is shown in figure 1. See also reference [4]².

Figure 1: On the left is a sketch of the inner tracker strips barrel. Each barrel is built out of staves, which are actively cooled support structures. Strip sensors are mounted on both sides of the stave. The curvature of particle tracks depends on the transverse momentum due to the applied magnetic field in the inner tracker. In the middle is a sketch of a stave cross-section with sensors on both sides. On the right is a sketch representing hits from particles with some possible reconstructed tracks. The figures are not to scale and only represent the principle of the correlator.

The newest version of the front end application specific integrated circuit (ASIC) for reading the strip sensor is the ATLAS Binary Chip 130 (ABC130). This chip includes a logic block called the Fast Cluster Finder (FCF), to find clusters within 6 ns and read out their digital positions once every 25 ns clock period. A cluster is defined here as one or two adjacent hit strips. Larger clusters with 3 or more hit strips are ignored, as these are inconsistent with the small transverse incidence angles of interest, as was shown in previous studies [5]. An exception are clusters that are broadened by delta rays, which we therefore will reject, incurring a $\sim 2\%$ efficiency penalty.

The cluster information is serially transmitted at a maximal rate of 640 Mbps per line. Two lines are used per chip, so each chip can transmit the clusters at up to 1.28 Gbps. This fast readout provides the complete cluster information every 25 ns. An external correlator ASIC processes the cluster information to find correlations. The correlator filters the correlations depending on the incident angle. Only hits passing the filter are sent off-detector for use by the trigger system, without any level 0 trigger stage. Reference [6] discusses the FCF design while reference [7] describes the electronics for the ATLAS Phase-II upgrade.

The strip sensors for the upgrade will be either for the barrel part or the endcap. There are different geometries for the two parts. The modules used here are intended for the barrels. They have a pitch of $74.5 \mu\text{m}$ and are $310 \mu\text{m}$ thick. There are two kind of sensors: short strip sensors with a strip length of 2.5 cm and four rows, and two row sensors with 5 cm long strips. Each row has 1280 strips [8]. The strip sensors will be placed on different barrels with radii between 0.4 m and 1 m [1]. Each barrel is designed to be built with staves. A stave is a carbon fiber composite structure with active cooling. Silicon strip

²The term “self-seeded trigger” is used in the references instead of real time tracker.

modules are mounted on both sides and are separated by ~ 5 mm [2]. With these radii, strip pitch and an ~ 5 mm spacing within the doublet, the targeted P_T range is from a few GeV/c to about 20 GeV/c.

In this work a proof of principle prototype correlator was developed with an FPGA [9] using two rows of a short strip sensor prototype. The system contains four different printed circuit boards (PCBs): 1. FPGA board, 2. interface board (IB), 3. support board and 4. hybrid board, which are described in section 4. The correlator can read the FCF lines from two hybrid boards with 10 ABC130's and find correlations between two rows of 1280 strips each. A doublet with two sensor modules was constructed to demonstrate the principle. The development of the demonstrator for the real time tracker was presented in reference [10], and reference [11] describes the final design used in the test beam experiment.

2. ABC130 with Fast Cluster Finder

The ABC130 is the newest generation of the ATLAS Binary Chip. It implements the front end electronics (FEE) chain for the ATLAS silicon strip tracker in the Phase-II upgrade. The ABC130 can read 256 channels, which are arranged in two rows and implemented as two separate 128-channel blocks, one for each row. Each channel has an individual FEE chain with a one bit analog to digital converter (ADC). The threshold of the ADC can be set globally for the chip. It is further possible to adjust the threshold of each channel to compensate small differences between the channels. An additional mask register allows masking bad channels right after the ADCs.

There are two FCF logic blocks integrated in the ABC130, each working on one row of 128 channels and independent of the conventional readout. The FCF finds clusters of one or two hits as explained in section 1. The FCF starts searching for clusters from both ends of the row, i.e. channel 0 and 127. Scanning from the ends towards the center, the FCF selects the first cluster smaller than three strips. Each FCF finds at most two clusters. In case there are more than two clusters, those in the middle are lost. Figure 2 gives an example how the cluster finder works.

A typical tracker with binary readout is meant to operate with an occupancy of less than 1% in the worst pile-up conditions (200 events). The FCF was designed as a simple method to implement a fast and synchronous readout, which was practical at the present time. For this prototype we have not gone further than this. The specific inefficiency for this implementation would have to be calculated in a chosen scenario and can also be physics signature dependent.

The found clusters are transmitted serially on dedicated differential outputs. A dedicated fast clock (FCLK) is provided for the FCF readout. The two clusters found by each FCF are encoded with 16 bits, therefore an FCLK 16 times faster than beam crossing (BC) clock is required. The ABC130 was designed to work with an FCLK of up to 640 MHz for a 40 MHz BC.

References [6, 7, 12] give a more detailed description of the FCF and the ABC130 in general.

Figure 2: Sketch of the FCF search procedure for one bank, where each ABC130 has two of these blocks. Each square represents a strip and all the filled squares indicate a detected hit. The number in the squares is the strip address used by the ABC130. Strips 1 to 3 form a 3-hit cluster, which is ignored. A 1-hit cluster at address 6 and a 2-hit cluster is observed at address 124 to 125. These hits are valid and detected by the FCF. The hit at address 120 is also a valid 1-hit cluster but is ignored, because already two other clusters were found. The arrows indicate the direction of the cluster search.

3. Correlation logic

The correlator would need to be realized in a dedicated radiation hard ASIC in an actual use case. In this work the correlator was implemented in a Virtex 6 FPGA to demonstrate the principle. The implemented correlator can read a double sided module (doublet) with 10 ABC130's on each side. This allows it to match the data from two rows of 1280 strips each. Each ABC130 has a differential line for each row, which are read in parallel. Tracks can therefore be matched between the same row on both layers, or across the two rows. More details about the doublet are given in the next section.

The correlator is designed with multiple stages as shown in Figure 3. The first stage finds correlations on the same row of both sensors. The second stage looks for correlations across the different rows of strips on the two sensors, using the result from the first stage. The third stage implements the logic to transmit the found correlations to a readout system. A detailed description of the correlator design and realization are given in references [9] and [11] respectively. A particular DAQ and test system on a computer was used to acquire the found correlations for the studies shown here. See reference [11] for more details about the DAQ used.

Figure 3: Block diagram of the correlator logic.

The correlation logic is a purely combinatorial block that calculates the

distance between all clusters found on the bottom and top layer of the doublet. The correlator considers only correlations within a given range of offsets. A maximal distance of ± 3 strips is used for the measurements presented here. With the limited window size only a cluster from each chip pair plus the adjacent chips have to be compared. To simplify the system a fixed window size was used for this demonstrator. It would be nevertheless possible to implement a flexible window size with the same approach. A flexible windows size would be required for a use in ATLAS to take into account the different locations of the modules in the detector.

To illustrate the correlation matching, some examples of possible correlation patterns are given in Figures 4 and 5.

Figure 4: Examples of the correlation search for one row. Each chips returns a lower and a higher cluster, corresponding to the two clusters found from each end of the chip, which are represented by the rectangles in these graphics. The numbers in the rectangles are the found cluster addresses, a dash represents that no cluster was found. The numbered arrows indicate all the verified combination of bottom and top clusters in the correlation logic. In (a) one valid correlation is found in test number 2. The others are rejected due to missing clusters either on the top or the bottom layer. The example shown in (b) has a valid correlation in test number 6, which is across two chips. Number 2 and 4 are rejected, because the offset from the top to bottom address is too large. The others are rejected due to missing clusters on the top layer.

Figure 5: Example of a cross row correlation. The rectangles represent clusters returned by the FCF as in Figure 4. The arrow indicates the valid checked combination of top and bottom cluster. The invalid checks are not shown.

178 4. Demonstrator setup

179 A physical demonstrator was built to test the real time tracker with FCF
 180 and correlator. The concept of the demonstrator is described in reference [10].
 181 The electronics for the demonstrator are assembled on four PCBs:

- 182 • an FPGA board, which implements the correlation logic,
- 183 • an interface board (IB), which provides drivers for the differential lines,
- 184 • a support board to hold the sensor and to make the connectivity to the
 185 hybrid board,
- 186 • a hybrid board, which supports the ABC130's together with the connec-
 187 tion lines to the support board.

188 4.1. Electronic system

189 The ML605 development board [13] with a Xilinx Virtex 6 FPGA was used
 190 to implement the correlator. Several additional PCBs were developed to pro-
 191 vide the connectivity and signal integrity from the FPGA to the ABC130's. A
 192 simplified block schematic is shown in Figure 6. The two support boards were
 193 mounted back to back to form the doublet. Each support board (top or bottom)
 194 contains a set of differential lines. The lines to the bottom board pass through
 195 the top board.

Figure 6: Simplified block schematic of the complete demonstrator. The control lines are BC, the readout clock (RCLK) and the command and trigger lines.

196 The communication between the FPGA and the ABC130 goes through dif-
 197 ferential lines. On the FPGA side the signals have the levels of the low voltage
 198 differential signaling (LVDS) standard. Because the ABC130 operates at a lower
 199 voltage, it uses an adjusted version of the LVDS with a smaller common voltage
 200 levels, called sub-LVDS.

201 The IB serves to adjust the levels on the differential lines from LVDS to
 202 sub-LVDS and is described in reference [14]. A transceiver ASIC designed by
 203 the Bonn ATLAS group was used to convert the LVDS signals from the FPGA
 204 [15]. This driver operates only up to a frequency of 320MHz. Therefore it was

not possible to run the test at the goal design speed. Instead all the frequencies were divided by two, resulting in a 20MHz BC and 320MHz FCLK.

A support board provides the connectivity from the IB to the hybrid and serves also together with an aluminum plate as mechanical support for the sensor. The support board holds one sub-LVDS transceiver for the FCLK and provides the connectivity for the ABC130 power and sensor high voltage bias (HV) supplies. The FCLK is the most critical high speed signal going into the board and the corresponding transceiver was placed close to the hybrid to provide a better signal.

The ABC130's are mounted on a hybrid board, which is a PCB holding bare die and surface mount components. The hybrid includes the command and clock lines to the ABC130's together with the FCF output lines. A more detailed description is given in reference [16]. The hybrid used implements a "star topology" with the FCF readout. This means that every chip is connected directly to a central node, which is here the correlator. As mentioned, the ABC130 has two FCF lines, each serving 128 of the 256 channels. All 10 chips per hybrid can be read in parallel with 20 differential lines. The layout of the hybrid with the FCF readout is shown in Figure 7. The central point for the connection to the correlator is on the left side of the board.

Figure 7: Layout of the hybrid with top and internal layer. The FCF lines are embedded in planes (not shown) to create a well shielded controlled impedance structure. The control lines are the clock, command and trigger lines for the ABC130's.

The boards are shown in Figure 8. There is a second module, consisting of support board, sensor and hybrid not visible in the picture, because it is mounted back to back to the first module. The sensor used is an ATLAS07 silicon strip sensor [8]. This sensor has four rows of strips, each 2.5cm long. There are two axial and two stereo rows. For the correlator only the axial rows are used.

4.2. Doublet

The doublet was built to provide a test setup for the correlator. An aluminum frame provides the mechanical support. The support board is mounted on an insulated anodized aluminum plate and the area for the silicon sensor is cut out from the support board. A conductive HV frame held on the anodized plate holds the silicon sensor and creates the contact from the backplane to the HV contact on the support board. A close up of the unfinished doublet is shown

Figure 8: Picture of the complete demonstrator setup. On the left is the ML605 Virtex 6 development board. The middle PCB is the interface board. On the right is the doublet with one side visible. The sensor with the mounted hybrid is in the middle of the support board.

237 in Figure 9. The sensor was glued with conductive epoxy to the HV frame. A
 238 screw makes electrical contact to the support board.

Figure 9: Close up picture of the HV frame as a support and contact for the sensor bias voltage.

239 Figure 10 shows a schematic view of the doublet. To simulate a magnetic
 240 field in the test beam, one side of the doublet can be moved horizontally with a
 241 micrometer. The micrometer pushes the mobile side and two springs are used
 242 to create a counter force that pulls the mobile side back, in case of releasing the
 243 micrometer. This allowed the manual setting of an offset between the two sides.
 244 The springs and micrometer are shown in Figure 11.

245 5. Test beam experiment

246 A test beam experiment was performed at the Stanford Linear Accelerator
 247 Center (SLAC). The correlator demonstrator was tested in a electron test beam
 248 located at end station A (ESA). The beam used at ESA is generated by redi-
 249 recting a fraction of the electron bunches for the Linac Coherent Light Source
 250 (LCLS) [17]. The electron energy of the beam was in the range of 9-10 GeV with
 251 about 20 electrons per bunch. The beam frequency was 5Hz. Some variations

Figure 10: Sketch of the demonstrator doublet. View is a cut in the middle of the sensor.

Figure 11: Springs mounted on support board and frame. The micrometer to set the position can be seen in the middle of the picture.

252 were observed in intensity and energy during the experiment. This was because
 253 of changes in the required beam for an experiment using the LCLS at the same
 254 time.

255 The EUDET telescope was used as a reference measurement [18]. The
 256 demonstrator is located in the middle of the telescope as can be seen in the
 257 setup shown in Figure 12.

258 The EUDET telescope includes also a trigger logic unit (TLU) which gener-
 259 ates a trigger signal together with an identifier for each event. The TLU makes
 260 its trigger decision based on two scintillators at the front of the setup and a
 261 signal coming from the accelerator. Each trigger is sent with the identifier to all
 262 devices under test. Using this identifier it is possible to match offline the tracks
 263 from the telescope with the correlations found.

264 The doublet has a mobile side which can be moved with a micrometer as
 265 described in section 4.2. Several runs were performed at different positions of
 266 the micrometer. Each run consisted of 3000 events, where one event corresponds
 267 to a trigger from the TLU. The mobile side was moved in total over a distance
 268 of 640 μ m corresponding to more than 8 strips. The complete region of the
 269 correlator acceptance window was covered with this movement.

(a)

(b)

Figure 12: (a) shows a sketch of the setup used for the test beam. There are two scintillator used by the trigger logic unit (TLU) to generate the trigger signal. The EUDET telescope consists of 6 layers and surrounds the demonstrator. The dashed arrow indicates the beam line. A picture of the test beam setup at ESA is shown in (b). The numbers indicate the layers of the EUDET telescope where layer 2 is hidden behind the demonstrator. The scintillators are hidden by the telescope layer 0.

6. Results

6.1. Beam profile

As a consistency check the distribution of the found correlations was plotted as a function of the correlation address to verify the beam profile. Figure 13 shows this result. It can be observed, that the beam was centered in the middle of the sensor. In row 2 we observed a higher number of hits. Variations in the number of correlations are observed in the center part. The FCF sees only the two hits closest to the edge of a chip. Therefore the hits on the edge are favored. This results in peaks observed in the address plots. This shows well the limitations of the system. It is not a problem for analyzing the data, because it is well understood.

At the beginning of the test beam experiment, the setup was moved to have the edge of the beam spot visible on the EUDET telescope. For the measurements with the correlator it was moved again to the center of the beam spot. Because the correlator wasn't ready at that point, no data is available

for both systems observing the edge of the beam spot. Assuming that the character of the beam didn't change over the test beam experiment, figure 13 compares the profile from the two detectors but with different runs. The tail of the beam spot is similar in both experiments. A flat middle part of the beam spot was observed with the telescope while the correlator data shows the peaks as mentioned above. The peaks are located around multiples of 128 strips, what corresponds to the edges of the chips. More comparison of the telescope and correlator data is done in section 6.3.

Figure 13: Beam profile observed with the two detectors. The telescope beam profile was from a preliminary run and shows only one edge because the spot size was larger than the active telescope sensor area. The whole experiment was moved perpendicular to the beam to capture the edge. The setup was again centered for the later measurements. The values of hits plotted are normalized with the total number of hits from each experiment.

6.2. Offset distribution

The beam passes through two collimators before arriving at the experiment setup. This limits the angular distribution of the beam to a fraction of the angular resolution of the doublet. Therefore it is expected that the found correlations should have all the same offset. The offset from the correlations is plotted for two micrometer positions in Figure 14. A peak for a certain offset is observed together with background of correlations over all allowed offsets. The location of the peak depends on how the two sides are aligned, i.e. the micrometer position. Moving the mobile side with the micrometer results in a displacement of the peak. A second offset value next to the peak observes also more correlations than the background and can be explained with an imperfect alignment of the two sides. A certain background is expected to come from secondary particles. Spurious correlations with a random offset could come from wrong track reconstruction of hits from the electron beam and secondary hits close together. The difference of 1 strip between the two rows comes from the wirebonding of the sensor as described in reference [11].

6.3. Alignment and filter with telescope data

A common trigger ID was assigned to each event for both the telescope and the correlator data. This allows to match the two datasets together. The

Figure 14: Offset distribution plots for both rows. The total number of events is indicated for each row, next to the label of the row. Comparing the two plots one can observe that the peaks move by 2 strips from (a) to (b), which corresponds to the movement of $165 \mu\text{m}$ which covers two times the pitch size of $74.5 \mu\text{m}$. The peak of the correlations distance is at 2 for row 1, respectively at 1 for row 2 in (a). And at 0 for row 1, respectively at -1 for row 2 in (b).

reconstructed telescope tracks were used to filter the found correlations with the purpose to remove spurious correlations.

The position of the reconstructed telescope tracks is calculated at the location of the correlator. The strip address from the found correlations were converted to the telescope coordinate system with the formula

$$x[\text{mm}] = 74.5\mu\text{m} \cdot x[\text{strips}] - \delta \quad (1)$$

The $74.5\mu\text{m}$ correspond to the strip pitch, $x[\text{strips}]$ is the strip address on the static layer and δ is a conversion factor to match both sensors together. In the y direction a selection was performed on the telescope tracks to choose the matching strip row.

The two data sets were then matched to find tracks and correlations close together. Using one fourth of the correlations found at each micrometer position, a δ of $44.95 \pm 0.03\text{mm}$ for row 1 and $44.88 \pm 0.03\text{mm}$ for row 2 was found.

The found conversion was applied to the rest of the data for a comparison with the EUDET telescope tracks. This allowed the elimination of some of the spurious correlations. Only a fraction of the observed correlation could be associated with telescope tracks, because the beam spot covered a larger area than the sensor area of the EUDET telescope. The telescope consisted of 6 planes of Mimosas26 CMOS Active Pixel Sensors, each sub-divided into 1152 columns of 576 pixels with a pitch of $18.4 \mu\text{m}$. The sensitive area of the sensors is approximately $21 \times 10.6\text{mm}^2$, which is smaller than the active sensor area of $10 \times 5\text{cm}^2$ used by the correlator. Figure 15 shows the address distribution of the correlation matched with a telescope track, compared with all found correlations. Only the correlations between address 510 and 781 were used in the following analysis. This corresponds to the range where the telescope area covers the doublet.

Figure 15: Address distribution of all correlations and filtered correlations found. Filter 1 used here selects all correlations with at least one telescope track closer $80\mu m$. The overlapping area of the telescope and the correlator is between strip address 510 and 781 and is plotted in the selection graph.

Two filters were applied to the matched correlations: Both filters select correlations with a telescope track closer than $80\mu m$, to eliminate correlations from secondary particles. Filter 2 has the additional restriction that only one track can be within $300\mu m$, to select only spatially isolated tracks. From all the correlations observed within the overlapping range defined above, it was possible to match $49 \pm 4.1\%$ of the found correlations for filter 1 and $35 \pm 3.3\%$ for filter 2. These percentages are the average of the correlations observed from all the runs, where the distance was within the window.

Less than half of the correlations could be matched with a telescope track. This can be explained with the telescope sensor area, which did not cover the complete beam spot. The width of the beamspot observed with the correlator is about 3 cm. The telescope has an area of 2 by 1 cm. Assuming a circular beamspot, the telescope would cover only $\sim 30\%$ of the beamspot.

The background in the distance distribution plot could be reduced by applying the filters. The percentage of correlation located in the peak went from $68 \pm 8.7\%$ for all correlations, to $73 \pm 9.1\%$ for filter 1, to $76 \pm 9.1\%$ for filter 2. The offset distribution of the filtered correlations is shown for some micrometer positions in Figure 16.

The further reduction of the background with selecting only correlations with only one nearby track supports the theory that spurious correlations are due to two electrons hitting two strips close together. Not all the spurious correlations forming the background could be removed though. Part of the remaining background could come from two hits close in x distance and separated in y, where only one is detected by the EUDET telescope.

6.4. Tracking performance and efficiency

To test the function of the realised prototype, we moved the mobile side over the complete window range of the correlation logic as mentioned. Correlations were observed independent of the micrometer position, which indicates that there is still a lot of noise. Figure 17 shows the number of correlations observed as a function of the micrometer position. An increase by a factor of more than

Figure 16: The distance distribution from two position with applied filters are shown here. (a) shows position 3745 μm and (b) position 3910 μm . Filter 1 selects all correlations with at least 1 track closer than 80 μm . Filter 2 requires 1 track closer than 80 μm and no other track closer than 300 μm .

367 3 in the number of correlations can be observed when the two sensors are within
 368 the defined range. For row 1 this is approximately between 3630 μm to 4190 μm
 369 and between 3550 μm to 4110 μm for row 2. Note that no measurement were
 370 made outside the upper range of row 2. It is expected that the the number will
 371 be reduced to similar levels as it is the case at the lower range end.

372 To verify that the observed offset between the two layers is correct, the mean
 373 value of the distance distribution is plotted as a function of the micrometer
 374 position. Figure 18 shows this plot for the two rows. The mean gets close to
 375 zero outside the valid window range. Inside the range, the peak moves linearly
 376 with the micrometer position. The two sides were not perfectly aligned, and the
 377 steps made not at an exact multiple of the strip pitch. This disturbs the mean,
 378 most visibly at a position close to the edge of the window.

Figure 17: Number of observed correlations as function of the micrometer position. The y-axis was normalized with the total number of correlations for better comparison between the two rows. For both rows the number of correlations increases, when the sensors are within the acceptance window.

The efficiency of the system is an indicator of how well the system is working.

Figure 18: The mean value of the distance profile as function of the micrometer position. This shows how the observed peak in the distance profile moves linear with the micrometer position. The error bar on the position (x-axis) spans the from center to center between the measured positions. The error shown on the offset (y-axis) is the RSM of the mean offset from the measurement.

We estimate the efficiency of the real time tracker is defined as follows:

$$\epsilon = \frac{N_c}{N_t} \quad (2)$$

where N_c is the number of correlations captured with the real time tracker and N_t is the number electron tracks from the test beam.

The conditions during the test beam experiment were not ideal, as the instantaneous luminosity was larger than what the ABC130 was designed for. The efficiency of the system is estimated with the telescope as a reference. The following assumptions were made:

1.) The tracks reconstructed by the telescope are assigned a quality expressed as χ^2 . A cut on χ^2 was made to select only good tracks for the evaluation of the efficiency. The tracks from the telescope were converted to strip address and row with the same parameters as found for the alignment and filter.

2.) The applied filter 2 selects only hits, which are separated by at least 0.3 mm from other hits. This filter is also applied to the telescope data together with the restriction on χ^2 to obtain N_t .

3.) The number of correlations detected is N_c^0 . Not all hits are detected because of the threshold set in the ABC130. The electrons deposit charge according to the Landau distribution and with a silicon thickness of 310 μm the most probable charge deposited is 3.6 fC. The ABC130 has a specified gain of 90 mV/fC which results in a most probable value (MPV) of 324 mV. The thresholds V_{th} applied to both sides of the doublet were 308 and 336 mV. This is around the MPV and leads to a low efficiency. Very roughly estimated, the system has a threshold efficiency of $\epsilon_{th1} \approx 0.55 \cdot 0.55 = 0.30$ for 308 mV and $\epsilon_{th1} \approx 0.45 \cdot 0.45 = 0.20$ for 336 mV. This ϵ_{th} is taken into account for the numerator of the efficiency: $N_c = N_c^0 / \epsilon_{th}$.

4.) The instantaneous intensity was larger then what could be handled by the FCF. Additionally, the readout system didn't allow to capture all the cluster

information from the FCF, but only the correlations. This requires additional constraints on how N_t and N_c^0 are determined. We choose to select a region of ± 5 strips around the chip edges to calculate the efficiency. The FCF starts looking from the edge of the chip for clusters and using a small region around the chip edge gives a higher certainty, that the correlation is not obscured by other clusters.

Using the constraints described above, an efficiency of $\sim 80\%$ for a V_{th} of 308 mV, respectively $\sim 75\%$ for a V_{th} of 336 mV was found. The uncertainty of the efficiency is very large and is for both thresholds $\pm 40\%$. More test results are required for a better measurement of the efficiency.

The system is still in an early prototyping stage and not yet efficient enough to be used in an actual detector. Further improvement in the correlation logic and the DAQ system are required and under development.

7. Conclusion

The new Fast Cluster Finder feature in the ABC130 was used for the first time. Together with an FPGA system it was possible to build a correlator, that can detect correlations between the two sides of a stave in real time. The correlator logic and the doublet demonstrator are presented in this paper. The demonstrator can also be seen as a successful example of a star topology readout with fast (320Mbps) transmission lines.

The demonstrator could be successfully operated in an electron test beam at SLAC to demonstrate the principle of a real time tracker. The system still needs improvements to be actually usable in a real detector, nevertheless it is a first working prototype.

The next steps will be to improve further the correlation logic for a better rejection of spurious, wrong correlations. Also improvements in the DAQ system will be made to have a better calibration and a higher output rate. Work is in progress to build multiple doublets with the goal of building a telescope. Each doublet with a correlator would send the found correlations to a higher level “track correlator”. This track correlator searches for correlations between the different doublets to have an even better selection of valid tracks.

Acknowledgments

The authors would like to thank the personnel from SLAC who helped performing the test beam experiment.

The Bachelor and Master theses leading to the results of this paper were made possible thanks to a student exchange between the University of Applied Science Western Switzerland, the École Polytechnique Fédérale de Lausanne and the Lawrence Berkeley National Laboratory.

This work was supported by the Director, Office of Science, Offices of High Energy and Nuclear Physics of the U.S. Department of Energy under the Contracts DE-AC02-05CH11231 and in part by the U.S. Department of Energy under contract number DE-AC02-76SF00515.

References

- [1] ATLAS Collaboration, “Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment,” Tech. Rep. CERN-LHCC-2012-022. LHCC-I-023, CERN, Geneva, Dec 2012.
- [2] M. Garcia-Sciveres, M. Gilchriese, C. Haber, B. Heinemann, and T. Mueller, “System concepts for doublet tracking layers,” *Journal of Instrumentation*, vol. 5, no. 10, p. C10001, 2010.
- [3] J. Jones, G. Hall, C. Foudas, and A. Rose, “A Pixel Detector for Level-1 Triggering at SLHC,” no. physics/0510228, 2005.
- [4] A. Schöning, “A self seeded first level track trigger for ATLAS,” *Journal of Instrumentation*, vol. 7, no. 10, p. C10010, 2012.
- [5] J. Arno, “Data Reduction At Front End Level in a Level-1 Track Trigger,” July 2011. Diploma thesis in Physics for the Department of Physics and Astronomy at the University of Heidelberg.
- [6] N. Dressanandt, A. Halgeri, M. Kamat, V. Koppal, and M. Newcomer, “Prompt trigger primitives for a self-seeded track trigger,” *Journal of Instrumentation*, vol. 7, no. 10, p. C10001, 2012.
- [7] T. Affolder, F. Anghinolfi, A. Clark, W. Dabrowskic, J. Dewitt, S. Diez Cornell, N. Dressdant, V. Fadeyev, P. Farthouat, D. Ferrere, A. Greenall, A. Grillo, J. Kaplon, M. Key-Charriere, D. La Marra, E. Lipeles, D. Lynn, M. Newcomer, F. Pereirab, P. Phillips, E. Spencer, K. Swientekc, M. Warren, and A. Weidberg, “System Electronics for the ATLAS Upgraded Strip Detector,” Tech. Rep. ATL-UPGRADE-PUB-2013-011, CERN, Geneva, February 2013.
- [8] Y. Unno *et al.*, “Development of n-on-p silicon sensors for very high radiation environments,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 636, no. 1, Supplement, pp. S24 – S30, 2011. 7th International “Hiroshima” Symposium on the Development and Application of Semiconductor Tracking Detectors.
- [9] L. Pirrami, “Fast triggering sensor module for the Large Hadron Collider,” January 2014. Master Degree Thesis for University of Applied Sciences and Arts, Western Switzerland.
- [10] S. D. Cornell, S. Duner, M. Garcia-Sciveres, C. Haber, N. Lehmann, L. Pirrami, E. Ropraz, and H. Wang, “Development of a Fast Cluster Finding self-seeded trigger demonstrator,” *Journal of Instrumentation*, vol. 9, no. 12, p. C12022, 2014.

- 483 [11] N. Lehmann, “Tracking with self-seeded Trigger for High Luminosity
484 LHC,” August 2014. Master Degree Thesis for École Polytechnique Fédérale
485 de Lausanne.
- 486 [12] ATLAS Collaboration, “ABC130 specification,” 2013. 4.6Draft.
- 487 [13] XILINX, “ML605 Hardware User Guide UG534,” October 2012. v1.8.
- 488 [14] S. Duner, “Trigger Functions for the High Luminosity LHC,” August 2013.
489 Bachelor Degree Thesis for University of Applied Sciences and Arts, West-
490 ern Switzerland.
- 491 [15] M. Karagounis, “8 Channel LVDS Transceiver,” December 2010. Version
492 1.0.
- 493 [16] E. Ropraz, “Sensor Module for the High Luminosity LHC,” August 2013.
494 Bachelor Degree Thesis for University of Applied Sciences and Arts, West-
495 ern Switzerland.
- 496 [17] H. Fieguth, C. Hast, R. Iverson, J. Jaros, R. Jobe, *et al.*, “ESTB: A New
497 Beam Test Facility at SLAC,” *Conf.Proc.*, vol. C110328, pp. 1373–1375,
498 2011.
- 499 [18] EUDET Collaboration, “Detector Research and Development towards the
500 International Linear Collider - Final Report,” December 2010.