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Test beam results of the first CMS double-sided strip module prototypes using the CBC2 read-out chip

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Abstract

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Abstract

The CMS Binary Chip (CBC) is a prototype version of the front-end read-out ASIC to be used in the silicon strip modules of the CMS outer tracking detector during the high luminosity phase of the LHC. The CBC is produced in 130 nm CMOS technology and bump-bonded to the hybrid of a double layer silicon strip module, the so-called 2S-p_T module. It has 254 input channels and is designed to provide on-board trigger information to the first level trigger system of CMS, with the capability of cluster-width discrimination and high-p_T track identification. In November 2013 the first 2S-p_T module prototypes equipped with the CBC chips were put to test at the DESY-II test beam facility. Data were collected exploiting a beam of positrons with an energy ranging from 2 to 4 GeV. In this paper the test setup and the results are presented.

Keywords: CMS upgrade, Binary read-out, 2S-p_T module, Test beam

1. Introduction

For the High Luminosity LHC (HL-LHC), a major upgrade is planed for the CMS experiment [1]. The accelerator will deliver luminosities of up to $5 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$. To cope with the increased rates and occupancies, CMS will replace the current tracking detector with an entirely new system which must be able to withstand the increased radiation corresponding to $3000\,\text{fb}^{-1}$ integrated luminosity and resolve more than 140 collisions per bunch crossing. The upgraded tracking detector is also required to provide information to the first level trigger (L1) and to maintain excellent tracking performance.

It is foreseen that the future detector modules will provide trigger information by means of an on-board p_T discrimination. High-p_T tracks (≥ 2 GeV), called stubs, will be isolated from the low-p_T background by a programmable correlation logic looking at the coincidence between the clusters on two closely separated silicon sensors of the 2S-p_T module [1]. A new chip, the CMS binary chip (CBC) [2], is being designed for this purpose.

2. Chip design overview

The CBC is the proposed readout chip for the CMS outer tracking detector 2S-p_T modules at the HL-LHC. The binary architecture has been chosen to reduce the amount of data that needs to be processed, and to keep the L1 trigger rate of 100 kHz despite the increase in occupancy and the high pile-up environment. The CBC is manufactured in 130 nm CMOS technology.With 254 channels the CBC2 [3], an evolved version from the first CBC design, can correlate 127 strips on the upper sensor with 127 strips on the lower sensor of the modules, as illustrated in Figure 1. The chip is foreseen to provide data to the L1 trigger, and once a L1 decision is received, it will send all hit data to the data acquisition system for further event reconstruction.

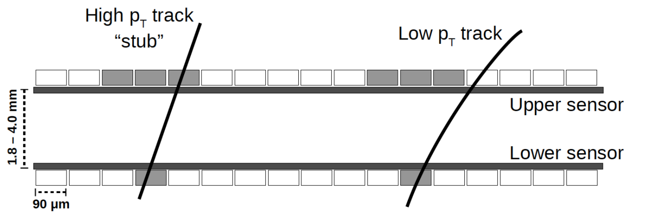

Figure 1: Concept of p_T discrimination on the 2S-p_T module using a search window size of ±1 strip on the upper sensor, seeded by a signal on the lower sensor.

Data follow two independent paths. In one path, data are stored in a 256-deep RAM memory buffer, together with bunch crossing information. Once the L1 trigger is received, they are loaded to a 32-deep buffer to be read out at 40 Mbps. The second data path passes through a logic block responsible for stub finding and read-out [3].

The logic block - shown in Figure 2 - consists of successive stages featuring the hit detection logic, the cluster width discrimination (CWD), and the offset correction and correlation logic. The hit detection logic synchronizes the comparator signal with the bunch crossing clock and passes it to the pipeline RAM and, in parallel, to the next combinatorial logic stages. It also allows the masking of individual channels. The CWD logic receives the synchronized signal, and can be programmed to reject wide clusters with more than 3 strips, typically associated with low-p_T tracks.

Following the CWD, the correlation logic uses the informa-

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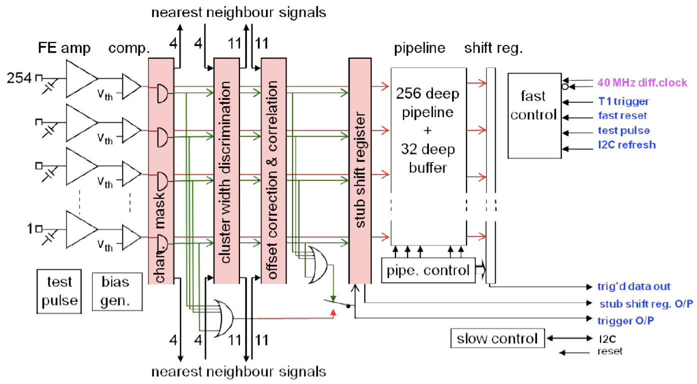

Figure 2: Block diagram of the CBC2 showing the principle components of the correlation logic and the read-out sequence.

tion of valid clusters on the lower sensor in a search for a correlated cluster on the upper one within an acceptance window. A stub will be considered valid once a cluster is found within the window. The width of the window is configurable up to a maximum of ± 8 strips. Geometrical offset along the module can be corrected by shifting the window by ± 3 strips using a programmable setting. To maintain a uniform p_T threshold of 2 GeV across the tracking detector, various sensor spacings (1.8 and 4.0 mm) and coincidence window sizes must be implemented in different regions of the tracking detector.

3. The prototype modules

Two mini-2S prototype modules were operated in the test beam simultaneously. Table 1 summarizes the main characteristics of the sensors used in the modules. The module with CNM sensors was chosen as device under test (DUT), while the module with Infineon sensors - shown in Figure 3 - served as a reference (REF). The sensors were wire-bonded to a prototype hybrid and read out with a pair of CBC2 ASICs, which were bump-bonded to the hybrid. The sensors on each module were separated by $d = 2.72$ mm. The modules were mounted into identical units which provide mechanical support and temperature control.

Module	bulk	pitch [μm]	thickness [μm]	strip length [mm]	strips [#]
Infineon	n-type	80	300	50	256
CNM	p-type	90	270	54	254

Table 1: Parameters of the prototype module sensors.

4. Test beam setup

The setup - shown in Figure 4 - has been installed in area TB21 of the DESY-II test beam facility in November 2013. The DUT unit was mounted on a rotation stage which in turn was mounted on xy-stages. The REF unit was fixed downstream. For both modules, the strips were oriented along the

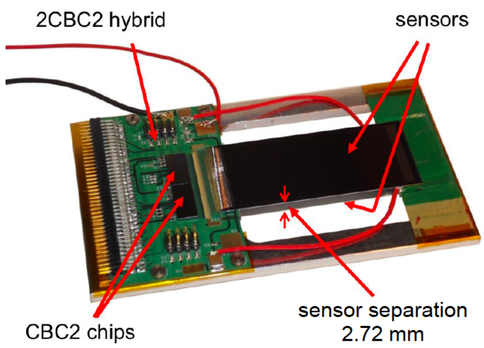

Figure 3: Prototype of the mini-2S module with the Infineon sensors operated in the test beam.

z-axis, which was also the rotation axis of the DUT. The distance between the units was about $L = 23$ cm. Two scintillators, located downstream, provided the trigger to the modules. Tests have been performed using positron beams with an energy range from 2 to 4 GeV.

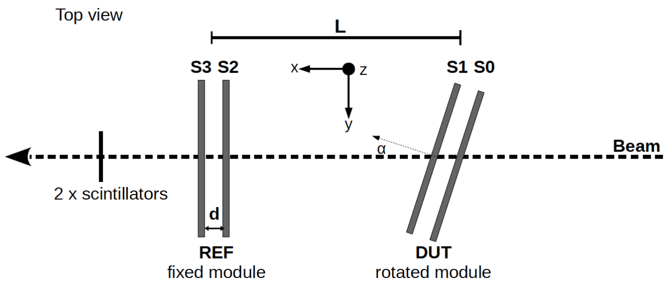

Figure 4: Schematic drawing of the test beam setup, showing the upper (S0) and lower (S1) sensors of the DUT, and the upper (S2) and lower (S3) sensors of the REF. The beam direction is from the right to left, traversing the two mini-modules and two scintillators located downstream.

5. Results

Threshold and angular scans have been performed to study the behavior of the cluster parameters, cluster efficiencies, and the efficiency of the stub trigger logic. The global comparator threshold (V_{CTH}) and the rotation angle α of the DUT were varied, scanning both in suitable steps. Each of the two parameters was varied independently while the other parameter was fixed at an optimized value of $V_{CTH} = 120$ ($\sim 6.5\,\mathrm{ke}^-$) or $\alpha = 2°$, respectively. An addition of 2° to the normal incidence was necessary to correct for the angular misalignment in the setup.

5.1. Cluster width

As the CBC2 provides binary signals, clusters are defined as a group of adjacent strips that register a hit signal. The cluster width w is the number of strips forming a cluster, and the cluster position is defined as the average between the first and the last strips of a cluster.

The mean value of the cluster width for the two sensors of the DUT is shown in Figure 5 as a function of the beam incidence

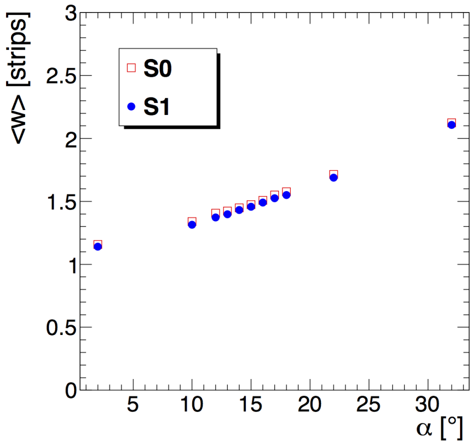

Figure 5: Mean cluster width as a function of the beam incidence angle for DUT sensors, S0 and S1.

angle. The expected increase of the cluster width at higher angles is similarly visible in both sensors.

The fraction of clusters as a function of incidence angle is shown in Figure 6 for various cluster sizes. At $\alpha = 2°$ single-strip clusters constitute almost 90% of all clusters, while two-strip clusters account for about 10%, with negligible contribution from multi-strip clusters. At higher angles, around $\alpha = 16°$, single-strip and two-strip clusters have a similar fraction of around 50% each. At $\alpha = 32°$ the two strip clusters dominate, reaching about 75% of all clusters. Three-strip clusters exceed single-strip clusters at very high angles. Multi-strip clusters with more than three strips did not show a strong dependence on the incidence angle, making the choice of maximum 3 strips for the CWD reasonable for all angles, as it covers more than 99% of all clusters.

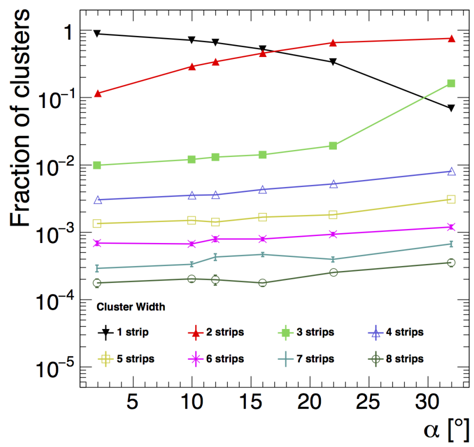

Figure 6: Fraction of clusters with different strip multiplicities shown as a function of incidence angle for one of the sensors of the DUT.

The effect of the V_{CTH} on the cluster width is shown in Figure 7. The mean cluster width at $V_{CTH} = 120$ ($\sim 6.5\,\mathrm{ke}^-$) is about 1.2 strips, with a long tail to higher values. For higher threshold at $V_{CTH} = 70$ ($\sim 25\,\mathrm{ke}^-$), cluster sizes larger than one

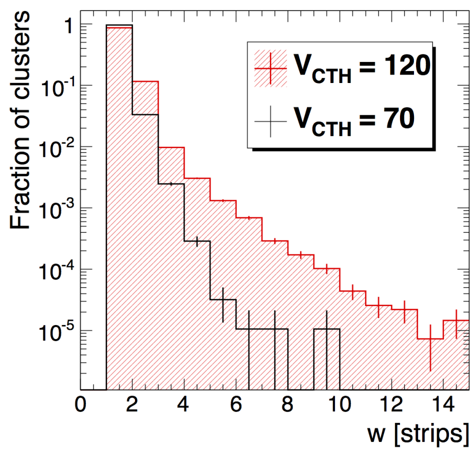

Figure 7: Cluster width distribution for two different values of V_{CTH} for one of the DUT sensors. The long tail at low threshold ($V_{CTH} = 120$) is related to delta-rays in the silicon bulk.

are strongly suppressed. This behavior is expected, as ionization through the whole bulk thickness is needed in order to measure signals equal or higher than this threshold.

5.2. *Cluster efficiency*

In order to define a cluster efficiency and to reject background events, tracks are reconstructed using information from three sensors and extrapolated into the fourth sensor. Inefficiencies due to edge effects are excluded. The efficiency is mainly studied for the DUT, while the REF was only operated for the track prediction. The total number of events defining the denominator of the efficiency comes from stringent selection criteria on both REF sensors and on the sensor not under study of the DUT. The numerator is defined by the number of events on the sensor under study, where a cluster has to be within a certain window, compared to the other DUT sensor. The efficiency has been studied as a function of the threshold by varying the V_{CTH} of both CBC2 chips of the DUT simultaneously in steps of 5 in a range from 30 ($\sim 45\,\mathrm{ke}^-$) to 120 ($\sim 6.5\,\mathrm{ke}^-$). Cluster efficiency as function of V_{CTH} is shown in Figure 8. It can be seen that both sensors of the DUT behave similarly with efficiencies close to 100% at $V_{CTH} = 120$.

5.3. *Stub trigger efficiency*

Rotating the DUT provides the possibility to test the correlation logic of the CBC2, as it emulates the bending of the tracks in the magnetic field of CMS. The beam with incidence angle α emulates particles with a certain bending radius in the transverse plane, r_T, on modules at a radial position R in the tracking detector following the equation $\sin(\alpha) = R/2r_T$. This bending radius corresponds to a particle with charge q and transverse momentum p_T, for a homogeneous magnetic field of given strength B, via the relation $r_T = p_T/qB$. The relation between the incidence angle of the particle and its transverse momentum can thus be described as:

$$p_T[GeV] \approx \frac{0.57 \cdot R[m]}{\sin(\alpha)} \quad (1)$$

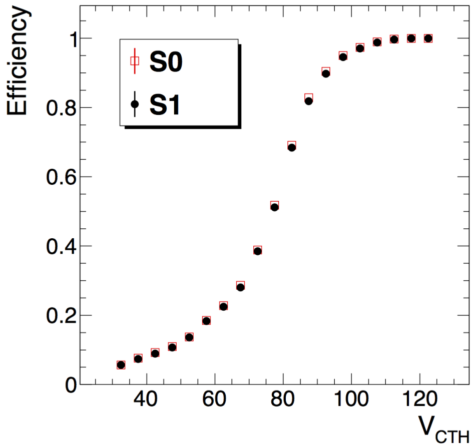

Figure 8: Cluster efficiency as a function of V_{CTH} for DUT sensors, S0 and S1.

under the assumption of $q = \pm e$ and the magnetic field strength of CMS $B = 3.8\,\mathrm{T}$.

The efficiency of the CBC2 correlation logic and stub trigger generation is defined as the number of stub trigger events of the DUT divided by the total number of selected events. The selected events undergo stringent selection criteria, applied only on the REF, in order to avoid biasing the efficiency, and to provide adequate rejection of background.

The CBC2 of the DUT is configured to generate stub triggers using a coincidence window size of ± 7 strips. The efficiency as function of the beam incidence angle is shown in Figure 9 and is in agreement with the geometrical expectations, given the strip pitch $p = 90\,\mu\mathrm{m}$ and the estimated separation between the sensors $d = 2.72\,\mathrm{mm}$. For $\alpha \leq 12°$ the CBC2 stub-finding logic is able to trigger on positrons with about 99% efficiency. The efficiency for $\alpha \geq 15°$ drops close to zero, as is expected for such high angles, where the clusters on the upper sensor fall outside the coincidence window. Using Equation 1, the efficiency as function of p_T - shown in Figure 10 - is obtained assuming that the module is at a radial position $R = 71.5\,\mathrm{cm}$ in the CMS tracking detector.

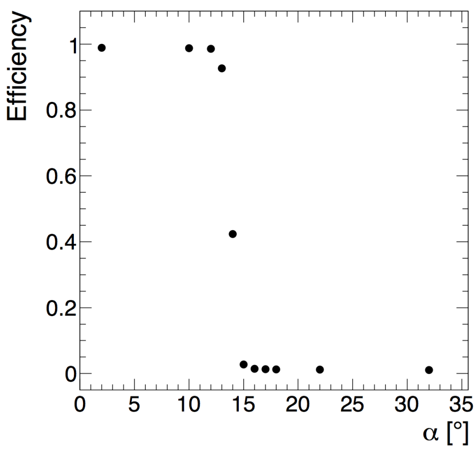

Figure 9: Trigger stub efficiency of the DUT as function of beam incidence angle.

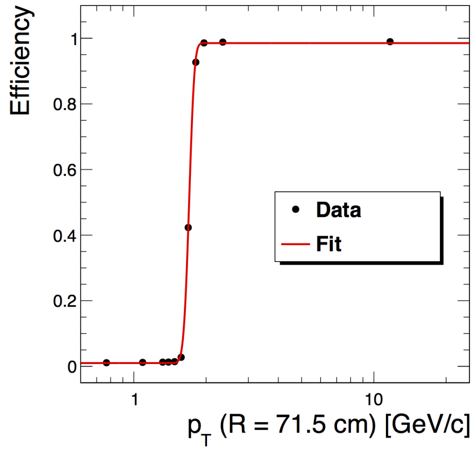

Figure 10: Trigger stub efficiency of the DUT as function of P_T calculated for a radial position of $R = 71.5\,\mathrm{cm}$ in the CMS tracking detector.

Fitting the efficiency curve, with an error function, allows the extraction of the effective p_T selection and resolution. The module would be able to reject hits from particles below $p_T^{trig} \approx 1.70\,\mathrm{GeV/c}$ with a resolution of $\sigma^{trig} \approx 0.07\,\mathrm{GeV/c}$. This would allow the CBC2 to suppress the large low-p_T background present in CMS and only to pass hits from high transverse momentum particles for further processing.

6. Conclusions

Fully functional 2S-p_T modules prototypes using CBC2 chips for read-out have been analyzed for the first time in a test beam. The performance is found to be in agreement with expectations. The cluster width is in good agreement with geometric predictions, and the fraction of very broad clusters is below 1%. The cluster efficiency is uniform across all tested sensors, and can be kept above 99% without introducing significant noise. For the first time, the trigger logic of such modules has been tested, by emulating the p_T dependent track bending in the magnetic field via a rotation of the module. The trigger efficiency shows the desired behavior. The efficiency to identify high-p_T tracks is around 99%. The separation from low-p_T tracks is excellent; with the setup used, particles with momentum below 1.70 GeV/c could be rejected with a resolution of about 0.07 GeV/c.

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