Test beam results of the CMS 2S P_T-module prototypes using the CBC2 read-out chip.

Ali Harb, on Behalf of the CMS Tracker Collaboration

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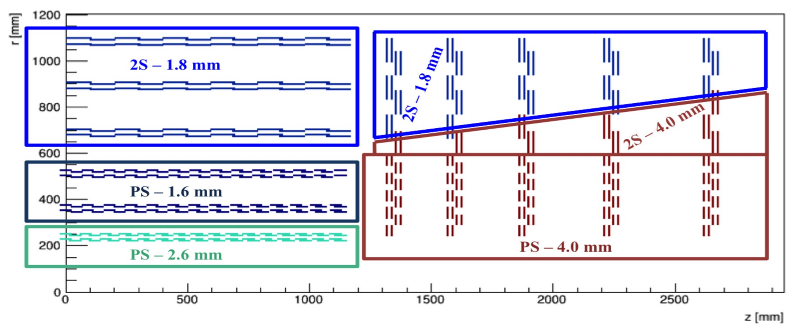
CMS Phase-II Tracker Upgrade for the HL-LHC

Upgrade Motivation

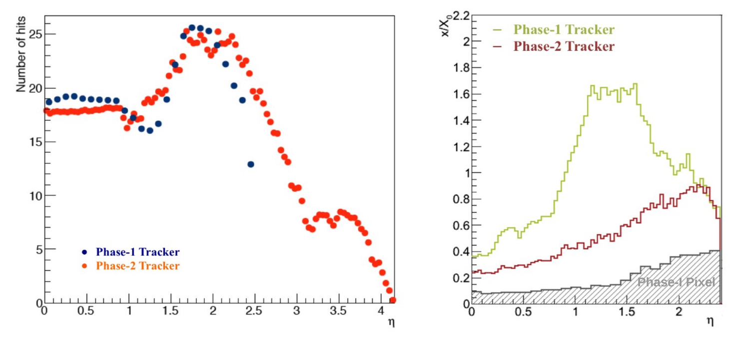
For the High Luminosity LHC (HL-LHC) a major upgrade is planed for the CMS experiment. In its Phase-II, the accelerator will reach luminosities up to 5×10^{34} cm^{-2} s^{-1} . To cope with the increased rates and occupancies, CMS will replace the current tracker with an entirely new system, which must be able to withstand the increased radiation corresponding to 3000 fb^{-1} integrated luminosity and resolve up to 140 collisions per bunch crossing while being able to provide information to the first level trigger (L1) and maintain the excellent tracking performance.



Map of the sensor spacing adopted in the Tracker. The sensor spacing is optimized at the same time as the acceptance window using tkLayout, to obtain a P_T threshold of 2 GeV for the stub selection in all module locations. The optimal acceptance window is then recalculated and fine-tuned using the Monte Carlo simulation [1].

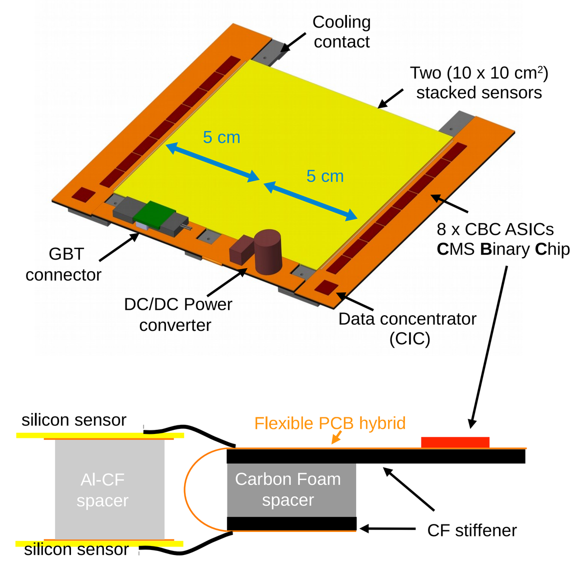
The Phase-II Outer Tracker Detector

The outer tracker consists of two types of P_T-modules, which are capable of rejecting signals from particles below a certain P_T threshold. The PS (7084) modules composed of closely-spaced silicon pixel and strip sensors, and the 2S (8424) modules with two closely-spaced strip sensors. The stacked sensors in each module are read out with a common chip which correlates signals, for the L1 trigger, that pass the P_T threshold, which are called stubs.



Number of hits (left) and radiation length (right) versus η for the Phase-II Tracker and the Phase-I Tracker. The radiation length distribution is shown for the tracking acceptance of the Phase-I Tracker, and reflects only the material inside the tracking volume; the expected contribution of the Phase-I pixel detector (hashed histogram) is provisionally used also for the Phase-II Tracker [1].

The 2S Module Design



Module Design

> Two sensors, with parallel strips, wire bonded to the same flexible-hybrid

> 5 cooling contacts, 4 at the end of the spacers + 1 close to power components

> CBC ASICs bump-bonded on the flexible hybrid

> Single service hybrid carries low power GBT data link, and DC/DC power converter

Sensors

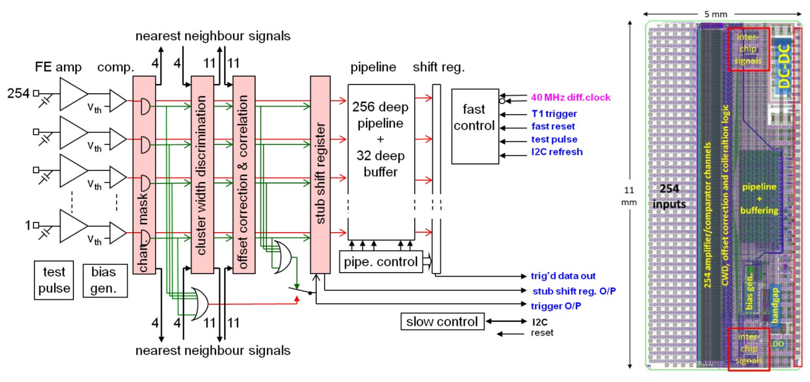
> n-in-p Silicon bulk

> 2 columns of 5 cm long strips with 90 µm pitch

> ~ 10 x 10 cm^2 active area

The CMS Binary Chip

The CBC2[2] is a 130 nm CMOS readout chip. It has 254 input channels (127 per sensor) and is designed to provide an on-board L1 trigger using stub-finding logic for high-P_T track identification.



CBC2 block diagram and layout [2].

Chip logic block

> Cluster width discrimination (CWD), max. 3 adjacent strips.

> Offset correction (±3 strips) & correlation logic (±8 strips).

Read-out:

> Neighboring CBCs exchange data to identify boundary clusters.

> The data flow separates L1 readout (DAQ) from Trigger (TRIG).

> Unsparsified binary readout data up to a 1MHz L1 rate per CBC.

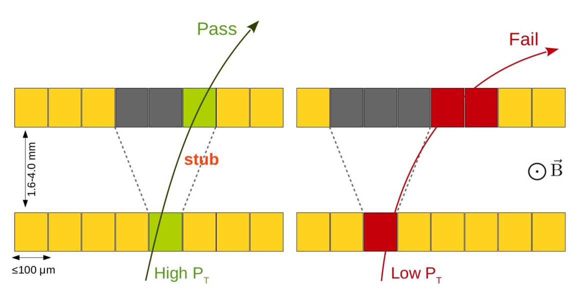
The "stub" Concept

The first stage of stub finding starts with the analysis of adjacent strips, and wide cluster rejection on both sensors. For every valid cluster on the lower sensor the correlation logic will search for a valid cluster in the coincidence window on the upper sensor. Finding any indicates that a valid stub is present.

> Stub data are sent out to the L1 trigger at each bunch crossing (40 MHz).

> 5 to 10% (~125 stubs per bunch crossing) belong to primary tracks with P_T > 2 GeV [1].

> Tracks are reconstructed by the L1 Track Finding system based on pattern recognition.



The concept of the two layers P_T-module of discrimination between high and low-momentum tracks identified as "pass" and "fail" stubs respectively.

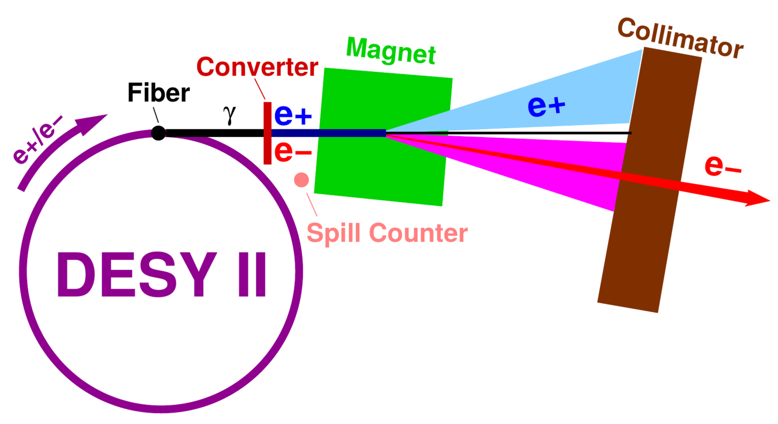
The track P_T discrimination is highly dependent on the position of the module in the tracker volume. To keep a uniform P_T threshold across the tracker (~2 GeV), various sensor spacings (~1.6-4.0 mm) and coincidence window sizes (max. ±8 strips) must be implemented in different regions of the tracker.

DESY-II Test Beam Setup and Measurements

DESY-II electron/positron beam

> DESY operates an electron/positron test beam facility with three test beam lines [3].

> The beam has an energy of 1 GeV to 6 GeV with a spread of ~ 5%, a divergence of ~ 1 mrad, and a rate of O(1) kHz.

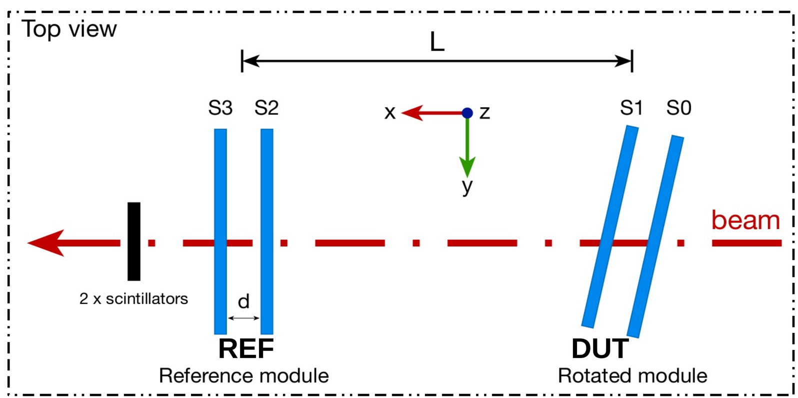


Setup for data taking

> 2 x mini-2S modules, device under test (DUT) and reference (REF), see table and figure

> 2 x upstream and 2 x downstream trigger scintillators

> Trigger Logic Unit (TLU)



Module	Vendor	Bulk	Pitch [µm]	Thickness [µm]	Length [mm]	strips #
DUT	CNM	p-type	90	270	54	254
REF	Infineon	n-type	80	300	50	256

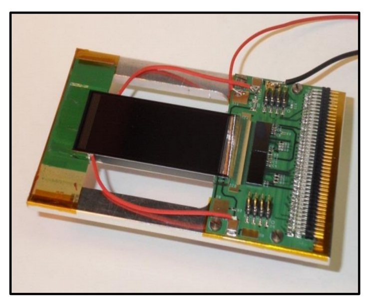
Measurements

> Positron beam, 2-4 GeV energy.

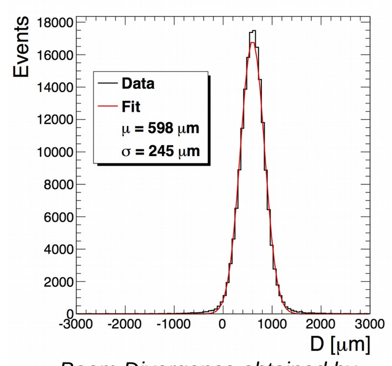
> DUT mounted on xy&Ø stage, with REF fixed downstream.

> Threshold scans (6ke- to 40ke-).

> Angular scans simulating magnetic field effect.



mini-2S module with 2 CBC2 chips wire bonded to 2 sensors (~3 mm spacing) with 254 strips each [1].

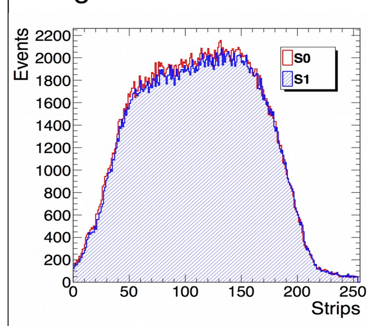


Beam Divergence obtained by the DUT&REF modules ~1mrad.

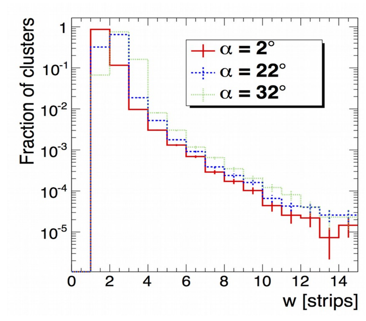
Event Reconstruction

The CBC2 chip provides binary read-out without information about the charge deposition on each strip, therefore, clusters are defined as group of neighboring strips with a signal.

The expected broadening of the clusters for steeper angles is visible in both sensors of the DUT.

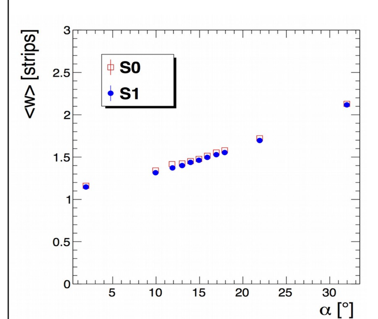


Beam profile distribution on the DUT sensors (S0 and S1) at normal incidence.

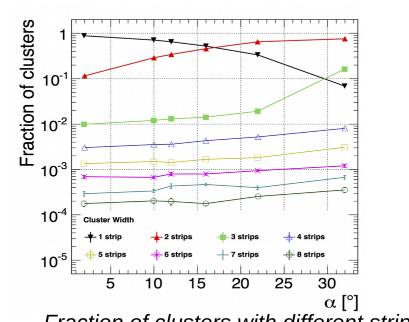


Cluster width distribution as function of beam incident angle on the DUT.

At low rotational angles the cluster width is dominated (~90%) by single strips, while more clusters with 2 and 3 strips arises significantly at 22º and 32º respectively.

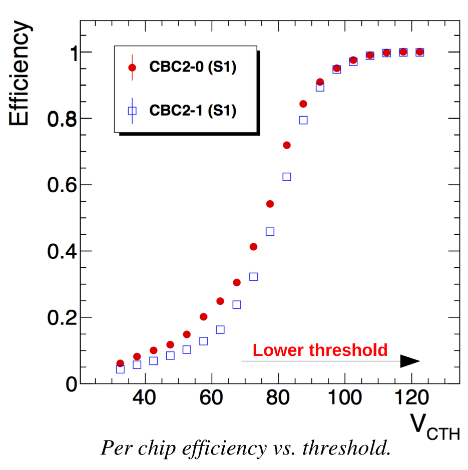


Mean cluster width on DUT sensors (S0 and S1) at different incident angles.

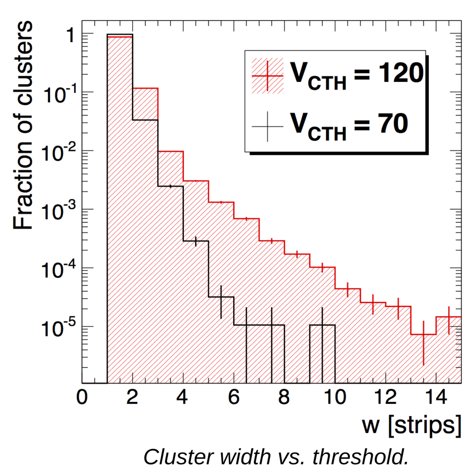


Fraction of clusters with different strip multiplicities as function of beam incident angle on the DUT.

Efficiency Studies vs. Threshold and Rotation Angle



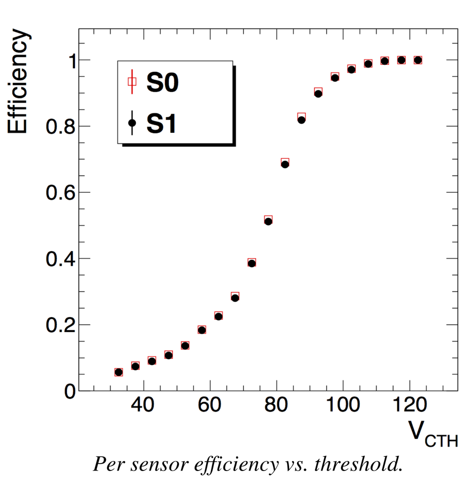
Per chip efficiency vs. threshold.



Cluster width vs. threshold.

DUT	Eff. S0
CBC2_0	99.97%
CBC2_1	99.96%

REF	Eff. S3
CBC2_0	99.97%
CBC2_1	99.96%



Per sensor efficiency vs. threshold.

A threshold scan was performed for the DUT during the test beam, which showed similar behavior for both sensors and chips of the module in terms of cluster efficiencies.

The efficiency was studied at different thresholds, where the global comparator threshold (V_{CTH}) of the DUT chips was varied from V_{CTH} = 120 to 30 (~6 ke- to 40 ke-).

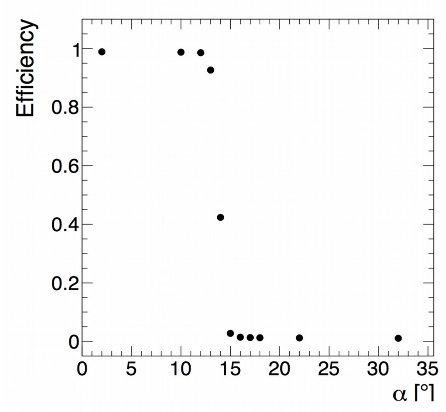
$$\epsilon_{sensor\,(or\,chip)} = \frac{\text{Events selected on sensor (or chip) under study}}{\text{Total number of events}}$$

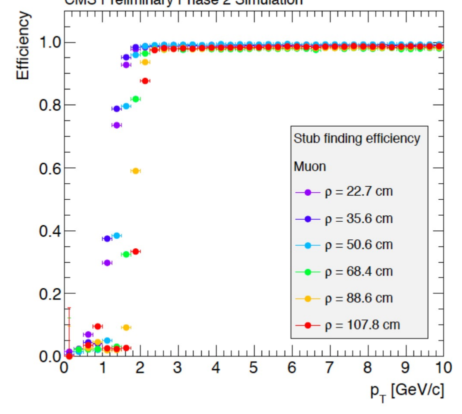
For V_{CTH} > 110 an efficiency higher than ~99% was obtained per sensor (and chip).

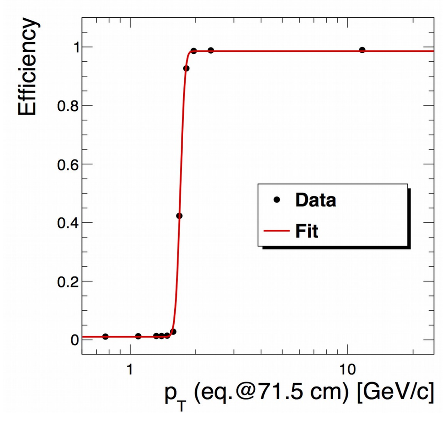
The efficiency was studied at different rotational angles of the DUT simulating the effect of the CMS magnetic field on the transverse momentum of charged particles. The P_T values at distance R from the beam line are obtained using the following equation, where α is the angle of rotation.

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

For a barrel layer with a distance R = 71.5 cm from the interaction point a P_T threshold of 1.7 ± 0.07 GeV is obtained.







Simulation of the stub finding efficiency for muons (left)[1], in all barrel layers of the outer tracker, and stub finding efficiency (right) measured during the test beam; the angle between the beam and the DUT is translated into an equivalent P_T at a radius of 71.5 cm in the barrel region.

Conclusions & Outlook

> A first test beam with mini 2S-module read out by CBC2 chip was performed with a positron beam successfully at DESY.

> The stub concept was proven to be working as expected by performing an angular scan, obtaining a ~99% efficiency for tracks with transverse momentum higher than 1.7 ± 0.07 GeV.

> A threshold scan per sensor and chip showed that at low thresholds (~6 ke-), an efficiency of 99% is achieved.

> A test beam with irradiated mini-2S modules and full 2S module with 8 CBCs took place in 2015. Data is currently being analyzed.

> A third version of the CBC (CBC3) is under development.

References

[1]Technical Proposal for the Phase-II Upgrade of the CMS Detector, CERN-LHCC-2015-010 ; LHCC-P-008

[2]Characterization of the CBC2 readout ASIC for the CMS strip-tracker high-luminosity upgrade - Braga, D. et al. JINST 9 (2014) C03001

[3]http://testbeam.desy.de/

Contact:

ali.harb@desy.de

HELMHOLTZ | GEMEINSCHAFT