PROCEEDINGS OF SCIENCE

Using the CMS Tracker for BRIL Operations in the HL-LHC

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For the High Luminosity LHC, the Beam Radiation Instrumentation and Luminosity (BRIL) project will employ CMS tracker modules for precision luminosity measurement with an ambitious target offline luminosity precision of 1%. Inner tracker endcap (TEPX) luminosity will be based on the online clustering algorithm. An FPGA-based clustering algorithm has been developed to count hit clusters detected by RD53B readout chips. Simulations and beam tests have been conducted to validate the algorithm under realistic conditions. Disk 4 Ring 1 (D4R1) of the TEPX will be fully dedicated to luminosity, while the rest of TEPX will allocate 10% of the trigger rate for luminosity. The Outer Tracker (OT) system will be utilized for high-statistics online luminosity measurements by providing high-rate physics objects known as Level-1 (L1) track stubs. Stubs are formed by detecting two-hit coincidences on closely spaced silicon sensors using front-end ASICs and are transmitted at a frequency of 40 MHz to the L1 track reconstruction system. For luminosity measurement, stubs will be aggregated in the histogramming firmware block. Currently, common mode noise within OT modules is being studied to evaluate its impact on the luminosity measurement using comparisons between a toy strip-strip (2S) module simulation and noise data from real 2S production modules.

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Contents

1. Phase-2 CMS Tracker Diagram

Various parts of the Phase-2 upgrade of the CMS Tracker, as well as labels for those specifically used for luminosity measurements, are highlighted in Figure 1.

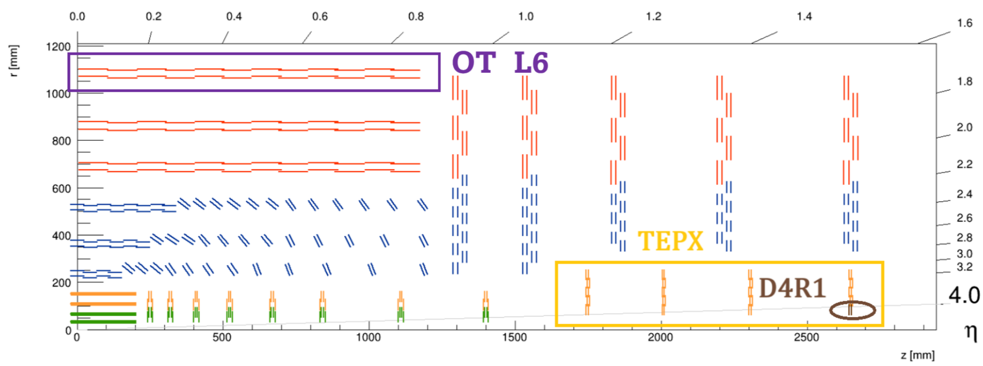

Figure 1: The Phase-2 CMS Tracker, with parts used for luminosity measurement highlighted [1].

2. Phase-2 Tracker Endcap Pixel Detector (TEPX)

Currently, 10% of the TEPX trigger bandwidth is dedicated for luminosity, while 90% is dedicated for physics (tracking). Because of its position (large η), TEPX D4R1 not useful for tracking, so 100% of the D4R1 trigger bandwidth will be dedicated to luminosity. As shown in Figure 2, the TEPX D4R1 cluster counting simulation shows excellent linearity up to a pileup (PU) of 200; the linear fit is performed at low PU, similar to beam conditions used for luminosity calibration (van der Meer scan). The fit is then extrapolated to high PU, where residuals are used to check deviation from linearity in percent, also shown in Figure 2. Next, noise sampled from test-beam data will be injected into the algorithm to quantify the impact of noise on linearity in these plots. Preliminary simulations based on the two-pixel minimum cluster size show that noise injection results in the addition of vertical pedestal without significantly altering linearity, but studies are still ongoing.

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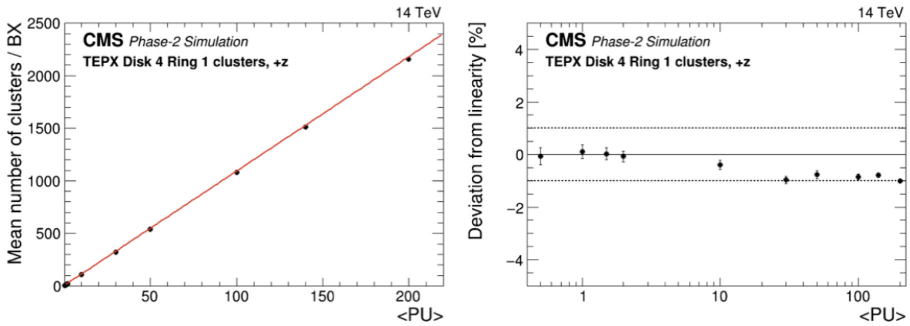

Figure 2: Mean number of clusters as a function of PU in D4R1, where the linear fit is performed for PU between 0 and 2 and then extrapolated up to a maximum pileup of 200 (left). On the right, the residuals are plotted to check the deviation from linearity [1].

3. Phase-2 OT Layer 6 (L6)

The Phase-2 OT provides high-statistics "stubs", two-layer coincidences in closely-spaced silicon sensors, for luminosity measurement. The OT L6 is composed of several ladders of two silicon-strip (2S) sensors. This outermost layer, L6, is validated in GEANT4 detector simulation to give the best linearity performance in stub multiplicity as a function of PU among all OT layers. Moreover, the OT is the most statistically powerful luminometer in Phase-2. An example of a single ladder of 2S modules, as well as an example of a stub reconstruction diagram, is provided in Figure 3.

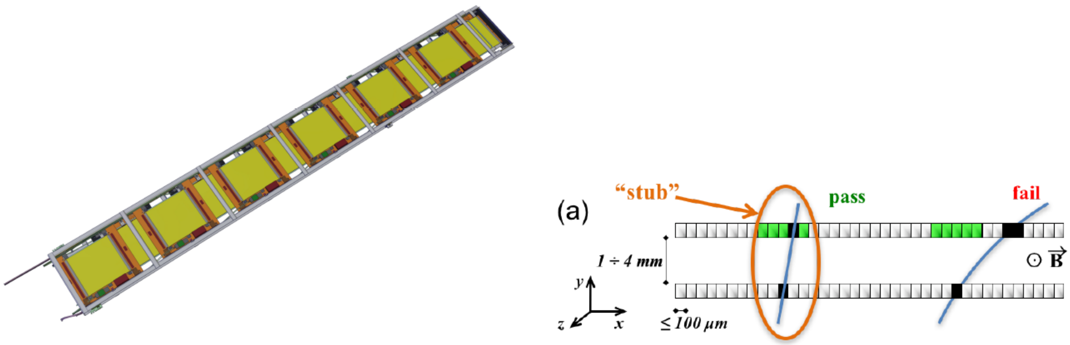

Figure 3: A single 2S module ladder (left), and an example of a stub reconstruction diagram (right) [1].

A linearity study was also conducted in OT L6 as shown in Figure 4, plotting the mean stub count as a function of PU. The maximum deviation from linearity measured in simulation is about 1.5% at a maximum PU of 200, also shown in Figure 4.

4. 2S Toy Model: Noise Simulation and Modeling

A functioning toy model of an OT 2S module was constructed for noise testing, accommodating both hybrids per module, all 8 CMS Binary Chips (CBCs) per hybrid, both layers per CBC (seed and coincidence layer), and all 127 strips per layer. Thus, the toy model is capable of simulating

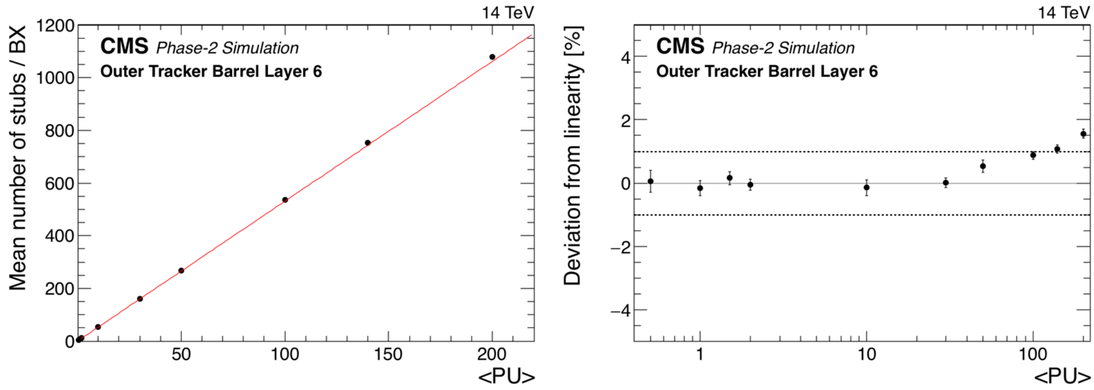

Figure 4: Mean number of stubs as a function of PU in OT L6, where the linear fit is performed for PU between 0 and 2 and then extrapolated up to a maximum PU of 200 (left). On the right, the residuals are plotted to check the deviation from linearity [1].

noise in all 4064 strips per module, per event, as well as reconstructing stubs from strips. Typical OT 2S modules are shown in Figure 5.

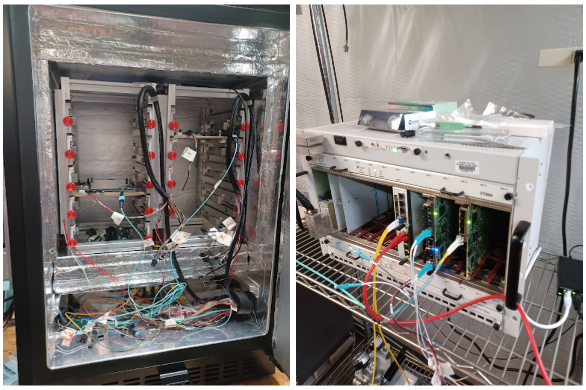

Figure 5: OT 2S Modules used for noise studies at Rutgers University.

For **each event**, and for **each strip** emulated in the module:

- Start from random, uncorrelated, idealized Gaussian noise ($\mu = 0,\ \sigma = 1$).
- Account for common mode noise effects via second added Gaussian with tunable width parameter ($\mu = 0,\ \sigma = c$).
- Find threshold T for a given desired occupancy.
- If total noise exceeds T, record a hit for that strip.

Figure 6 shows the distributions of noise data recorded in real 2S modules in a given CBC, as well as the results of the toy model, both with and without the addition of common mode noise effects. The plots show the improvement in agreement between toy model and real data once common mode noise is accounted for in the toy model.

Further studies are underway using the toy model to gauge the impact of noise (including common mode noise) on stub variables, which will be critical for the luminosity measurement during the implementation of the Phase-2 Tracker Upgrade.

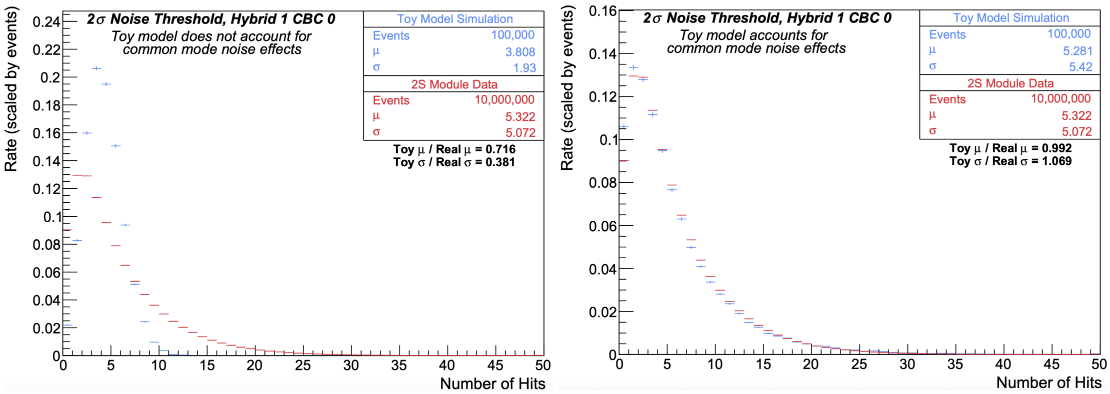

Figure 6: Number of hits recorded by a 2S module (red) at a noise threshold of 2σ, compared to the toy model simulation (blue), both before (left) and after (right) the inclusion of common mode noise effects in the toy model.

References

[1] CMS Collaboration, "The Phase-2 Upgrade of the CMS Beam Radiation Instrumentation and Luminosity Detectors", Technical Design Report, CERN-LHCC-2021-008, CMS-TDR-023 (2021).