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# A high rate test beam of the CMS Phase 1 Upgrade Pixel chip


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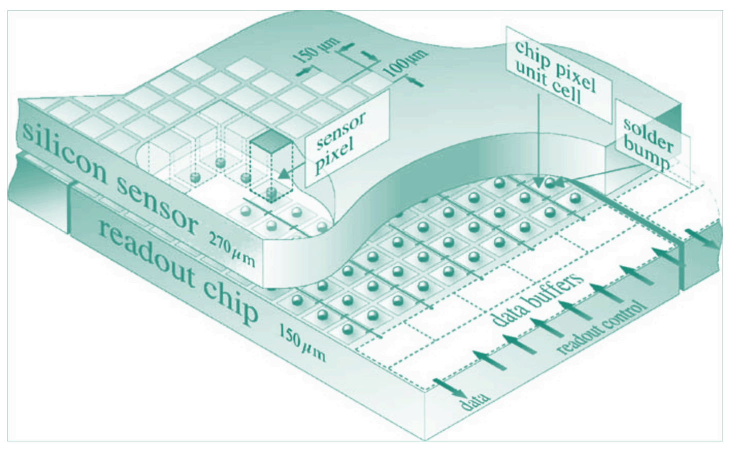
## Motivation and Goals

The innermost part of the **Compact Muon Solenoid (CMS)** detector is build from three layers of **hybrid silicon detectors**. The PSI46 front-end readout chip (ROC) is bump bonded to a 285µm thick n-in-n silicon sensor with a pixel size of 100µm x 150µm and 4160 pixels per chip. The ROC was designed to operate at an instantaneous luminosity of $1 \cdot 10^{34}\ cm^{-2}\ s^{-1}$. At these rates of about 20MHz $cm^{-2}$ the **hit inefficiency** for the inner most layer, due to dead-time effects and random data loss, is already 4%.

The exceptionally good performance of the LHC, reaching higher instantaneous luminosities than originally foreseen, pushes the current ROC far beyond it's intended operational range during the end of RUN 2. It was decided to exchange the entire pixel detector during an extended winter shutdown in 2016/2017. This replacement is called the **Phase 1 Upgrade** of the CMS pixel detector.

The new pixel detector will consist of **four layers** cylindrically arranged around the beam pipe and **three disks** in both forward regions of the detector. A new beam pipe makes it possible to move all layers of the pixel detector closer to the interaction point within CMS. This results in an expected rate of ~120MHz $cm^{-2}$ for the second layer at an instantaneous luminosity of $2 \cdot 10^{34}\ cm^{-2}\ s^{-1}$. To cope with these very high rates a new readout chip was developed, the **PSI46dig chip.** Even higher rates are expected for the first layer at a radius of 3cm from the interaction point. A separate chip is being developed to work under these conditions.

The goal of this work was to test the new readout chip in a high energy **High Rate Test Beam** under conditions as close as possible to the LHC environment, study the ROCs behavior and measure the **hit efficiency as a function of flux**.

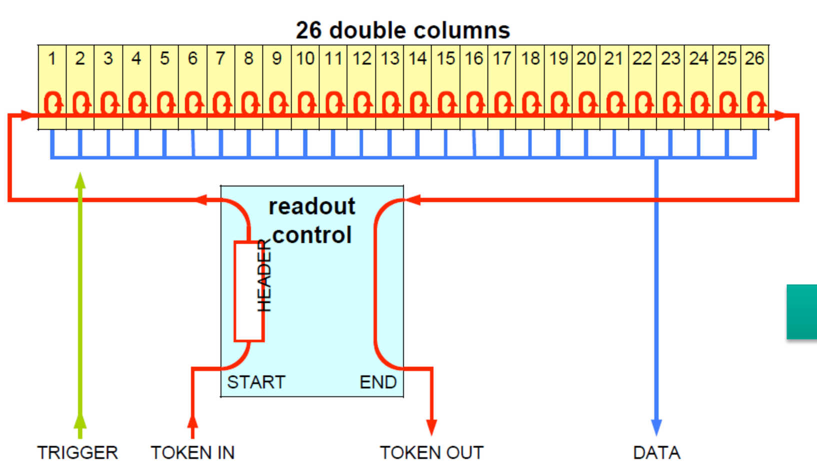


Schematic drawing of the CMS Hybrid Silicon Detector [2]

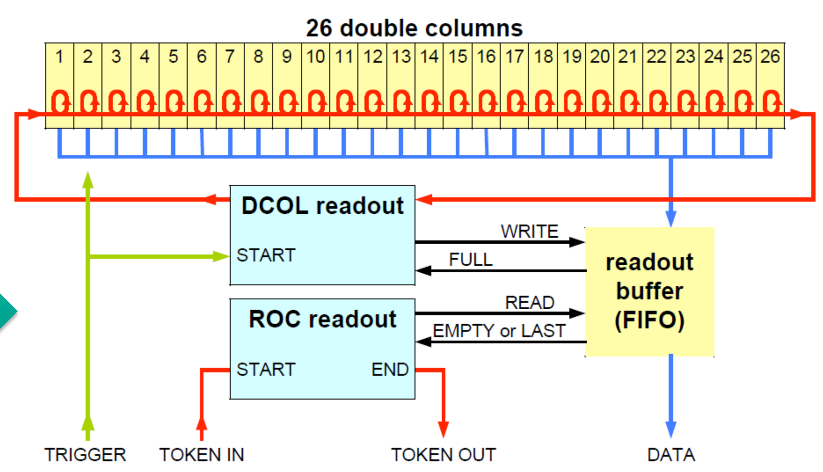
## The PSI46dig readout chip

The new pixel readout chip evolved from it's earlier version currently used in the CMS experiment. Improvements were made at 3 key points: **readout protocol**, **analogue performance** and **data loss**.

1. Readout protocol:
   In order to increase the data transmission speed the readout protocol was changed from an encoding in analogue pulse heights to a digital LVDS signal running at 160MHz.
2. Analogue performance:
   The lowest operational threshold in the current ROC was defined rather by cross talk between pixels than by amplifier noise. An improved power distribution system and an additional metal layer made it possible to reduce the operational threshold to a value below $1800e^-$ [3]. In addition the time walk of signals in the comparator of the pixel unit cell was greatly reduced.
3. Data loss:
   In order to reduce the data loss in the ROC the depth of it's storage buffers had to be increased. The **data buffer**, storing hit information in the periphery of each double column, has been increased from 32 to 80 cells. The number of time stamp storage cells was doubled to 24. An additional readout buffer (see schematics) was introduced. It's purpose is to buffer data that was validated by an external L1 trigger while waiting for a readout token.



Readout of the current pixel detector's analogue ROC



Readout of the new digital ROC

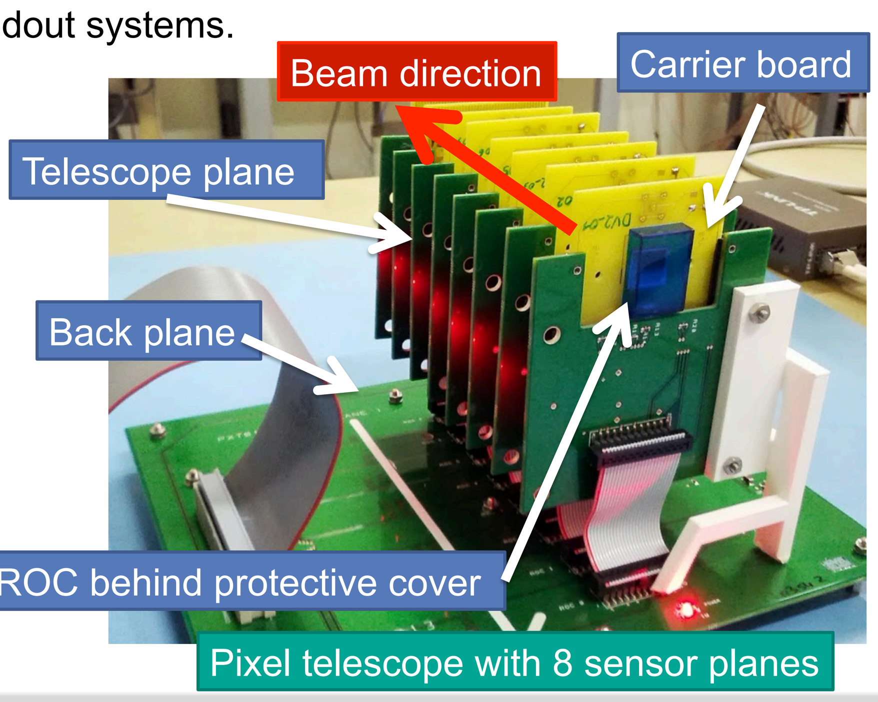
## The High Rate Pixel Telescope and Test Beam Facility

A beam telescope and it's corresponding **data acquisition system** (DAQ) was designed by the CMS group at the Rutherford Appleton Laboratory. Every telescope consists out or **8 planes** of PSI46dig readout chips. 7 of these planes are used for tracking, while the remaining plane is used as device under test (DUT).

The DAQ system was build from an commercially available **Xilinx Spartan SP605** evaluation board (test board) with a custom made extension board (bridge board). While the FPGA on the test board handled the sending of signals to the ROCs and the programming of DAC settings, the bridge board held two DC/DC converters needed for powering the ROCs. Additionally the bridge board had an input for a TTL trigger signal and the capacity to synchronize two readout systems.

The test was conducted in the "High Rate Tracking Area" of the **MTest beam line** at Fermilab, Chicago II. With all accelerators at CERN performing maintenance, this was the only beam line world wide with the capability to provide the particle rates we wanted for our experiment.

The Fermilab Main Injector provides a 120GeV **proton beam** bunched on the 53MHz accelerator clock, creating straight tracks and ensuring minimal scattering of particles in the sensor and readout chip material.



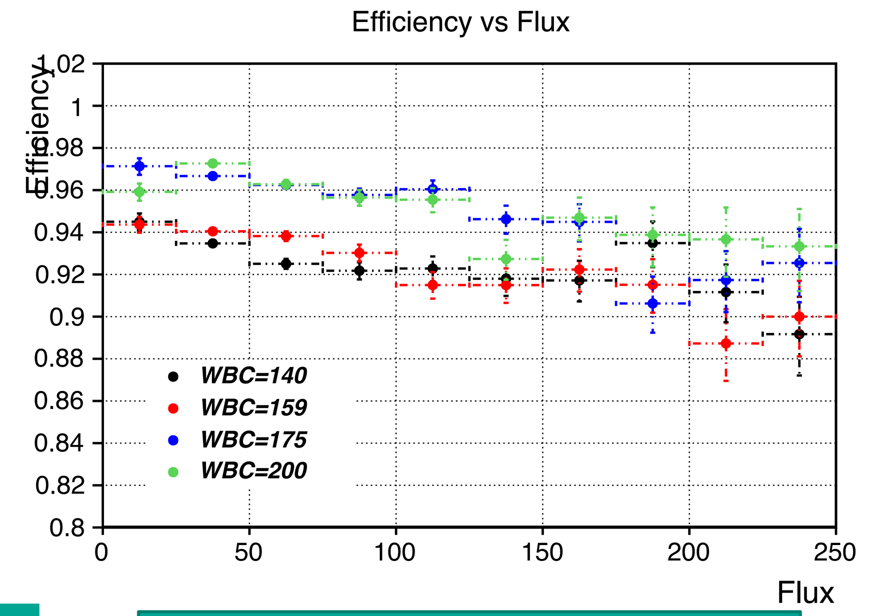
Pixel telescope with 8 sensor planes

## Results from the test beam

The analysis of the data collected during the test beam was performed using the **EUTelescope** analysis framework. It is a modular and easy to adapt framework, developed to be compatible with many beam telescopes. EUTelescope provides algorithms for clustering, alignment and tracking.

The most important measurement, the hit detection efficiency as a function of the flux on the detector, showed two unexpected results:

1. The **efficiency** never reached the expected 99.3% at very low beam rates as one would have expected from a previous test beam at DESY, Hamburg [3].
2. One would expect the efficiency to **decrease with higher L1 latencies (WBC)**. But we observed the opposite behavior in the test beam.



Efficiency vs. Flux measurements for different trigger latency (WBC) settings

| | expected ROC behavior | observed ROC behavior |
|---|---|---|
| Efficiency at low fluxes | > 99% | < 98% |
| Efficiency vs. WBC | Decreasing | Increasing |

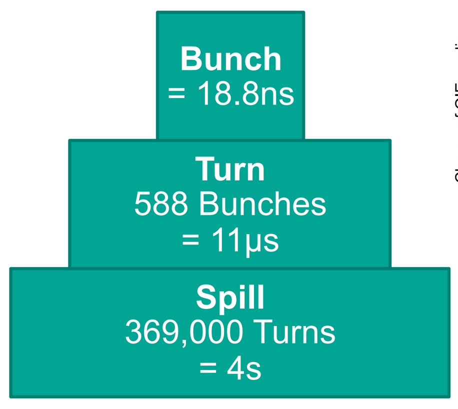
The most likely explanation for these discrepancies is the miss-match in clock frequencies between the readout chip running on 40MHz and the beam running on 53MHz and big variances in the bunch-by-bunch intensity of the beam.

## Difficulties of the high rate test beam environment

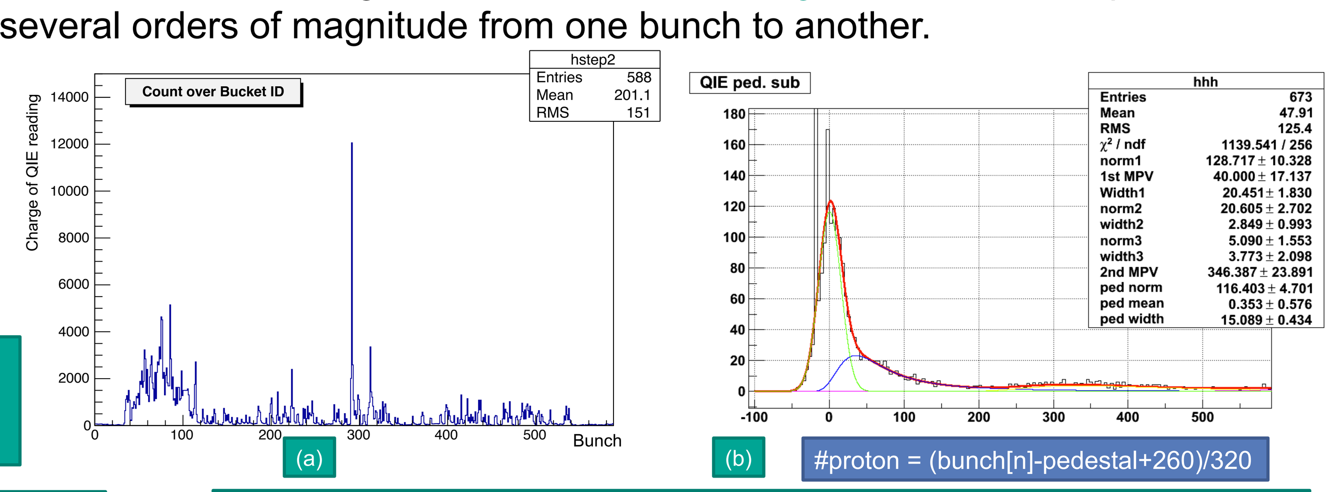
The most difficult measurement to make during the beam test was the **particle flux**. While the beam instrumentation department of Fermilab provided a measurement of the total number of protons in a single spill and the beam shape, the time distribution of how the particles arrive during the 4s long spill was completely unknown.

Together with experts form the SeaQuest experiment at Fermilab we set up a 1cm x 1cm scintillator, covering the telescopes surface in the beam, connected to a photomultiplier tube. The output signal of the photomultiplier was connected to the **QIE device**, an ADC with a high dynamic range and high time resolution. This enabled us to count the number of particles on a bunch-by-bunch basis by measuring the charge of the pulses from the photomultiplier and converting this charge to the number of protons.

The measurements showed that the bunch filling **fluctuated considerably**. The number of particles in the beam could change by several orders of magnitude from one bunch to another.



Nomenclature for the Fermilab beam structure



Beam intensity fluctuations within a turn (a) and conversion of QIE data to number of protons (b)

## Simulation Work

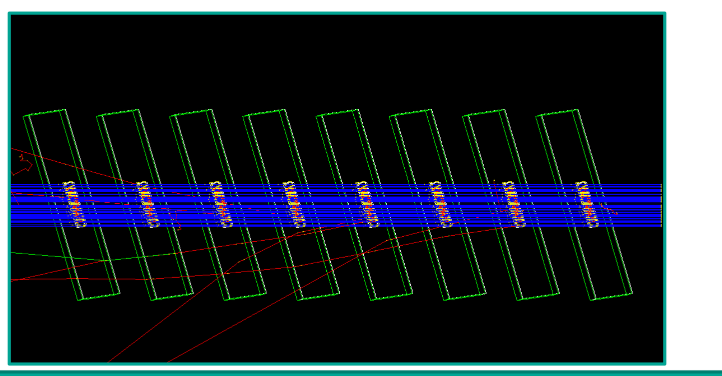
In order to understand the discrepancies between test beam measurements and expectations a simulation study was started. A full simulation of the test beam should give insights on where the observed inefficiencies originate from.

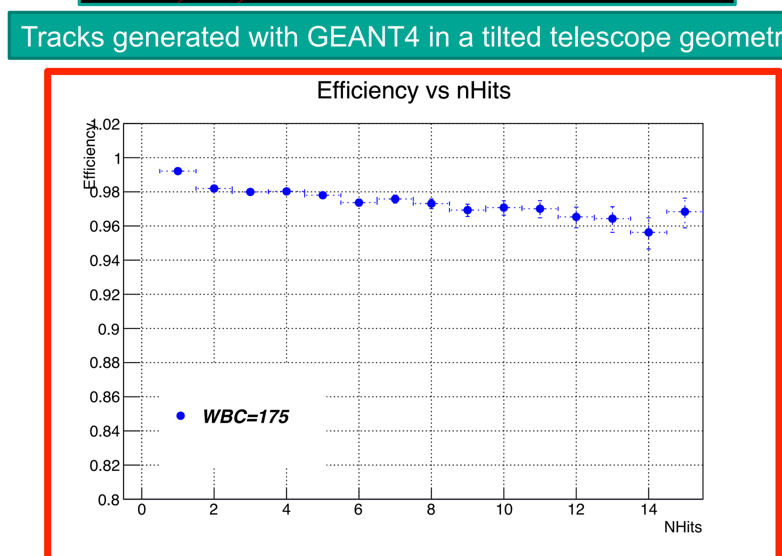
**GEANT4**
- 8 silicon sensors and ROCs
- Creates physically correct charge distribution and charge sharing

**DataFlow**
- Mimics functionality of ROC and DAQ
- Reproduces same conditions as in test beam
  →Clock mismatch (40MHz for ROC and 53MHz for beam)
- Same particles-per-event distribution as in test beam

**Converter**
- Converts to LCIO format used in analysis

**Analysis**
- Same analysis software as used for measured data


Tracks generated with GEANT4 in a tilted telescope geometry



Prove of principle: Efficiency over average number of hits in telescope plane.
The simulation chain works, but still work in progress!


Literature and picture reference:
[1] CMS Collaboration. CMS Technical Design Report for the Pixel Detector Upgrade. Technical Report CERN-LHCC-2012-016, CERN, 2012
[2] G. B. Cerati et al. Radiation Tolerance of the CMS Forward Pixel Detector. Nucl. Inst. & Meth. in Phys. Res. A, 600(2):408 - 416, 2009
[3] Daniel Pitzel, Pixel ROC tests at Hamburg, Pixel ROC and TBM review, March 28th 2014 https://indico.cern.ch/event/305865/session/0/contribution/2/material/slides/0.pdf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