CROC_v1 Pixel Chip Calibration for the Phase-2 CMS Inner Tracker

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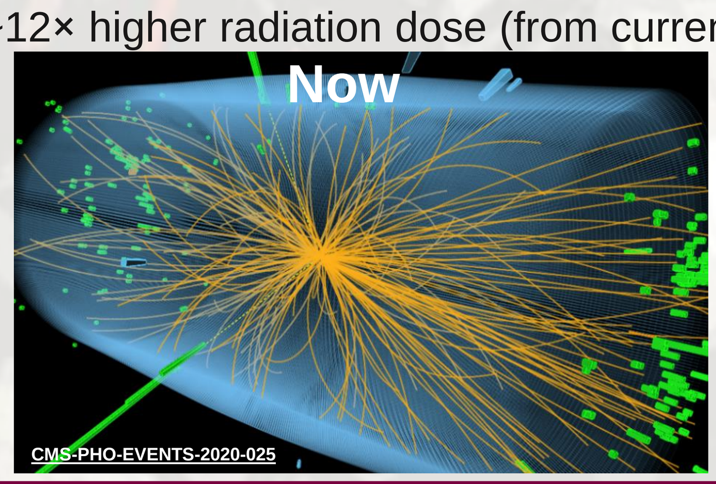
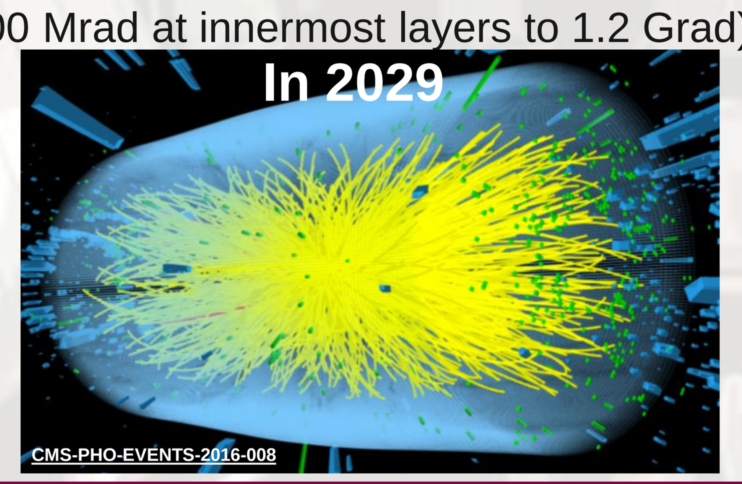
High Luminosity LHC

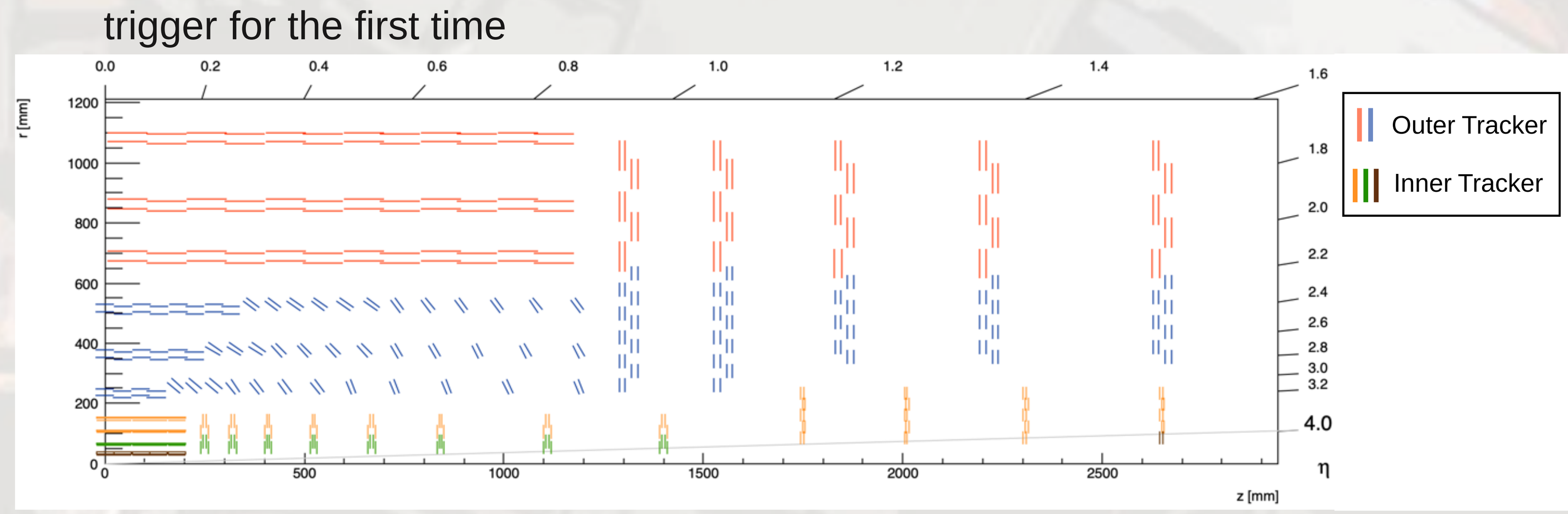
- The High-Luminosity LHC will start operation in 2029, with greatly improved physics potential
- Expected instantaneous luminosity of 7.5×10^{34} Hz/cm^2 is 7.5× larger, compared to the nominal LHC luminosity of 10^{34} Hz/cm^2
- Expected pile-up up to 200 [1]
- CMS collaboration is working on Phase-2 upgrades to suit the HL-LHC conditions:
  - ~8× larger number of tracks (from LHC nominal 25 PU vertices to 200)
  - ~7.5× higher trigger rate (from CMS nominal 100 kHz at L1 to 750 kHz)
  - ~12× higher radiation dose (from current 100 Mrad at innermost layers to 1.2 Grad)





Phase-2 CMS Tracker

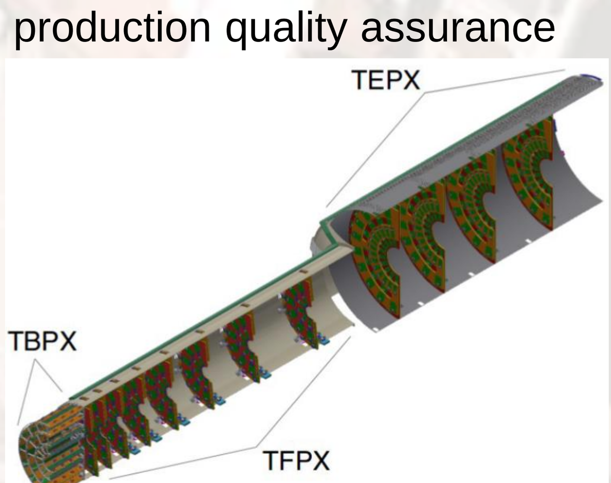
- A completely new silicon tracker is in preparation for the Phase-2 upgrade
- The tracker will consist of two parts: Inner and Outer
  - Inner tracker, consisting of very-high-granularity silicon pixel detectors, will extend up to |η| = 4.0, instead of the current |η| < 3.0
  - Outer Tracker, consisting of silicon strip and macro-pixel sensors will be used in L1 trigger for the first time



CMS Phase-2 Tracker layout. Green, yellow and brown show the Inner Tracker, blue and red – the Outer Tracker [2]

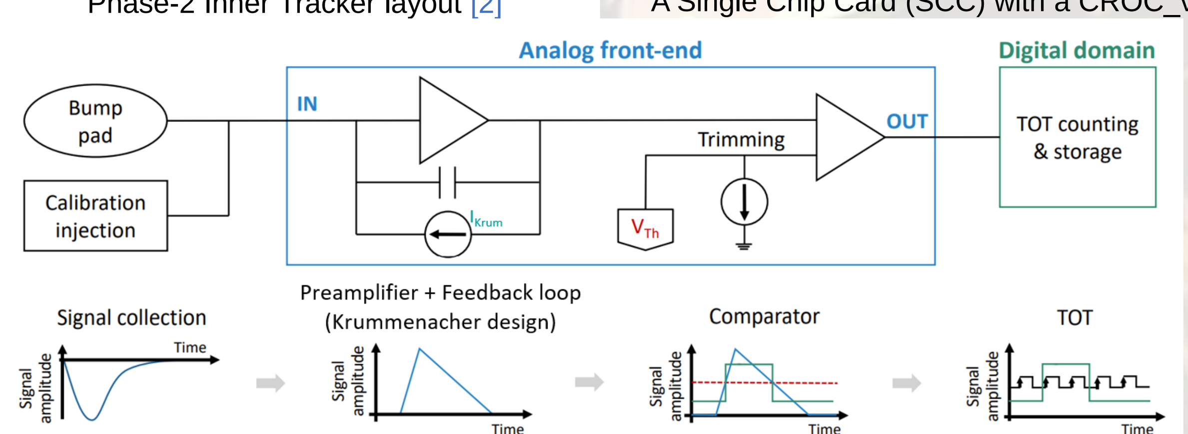
Phase-2 CMS Inner Tracker

- 25×100 μm^2 pixel cells with 150 μm active thickness, ~2 billion pixels in total
- 2 different sensor technologies: 3D pixel sensors on TBPX layer 1, planar n-in-p pixel sensors everywhere else
- 12 forward disks instead of the current 3 – improved forward event detection
- Will use the radiation-hard RD53 chip, radiation tolerant up to 1 Grad
- CMS ReadOut Chip or CROC_v1 (RD53B CMS) is the 2nd gen prototype that features a linear analog front-end
- Ph2_ACF – new data acquisition and control software used for system tests and production quality assurance



Phase-2 Inner Tracker layout [2]

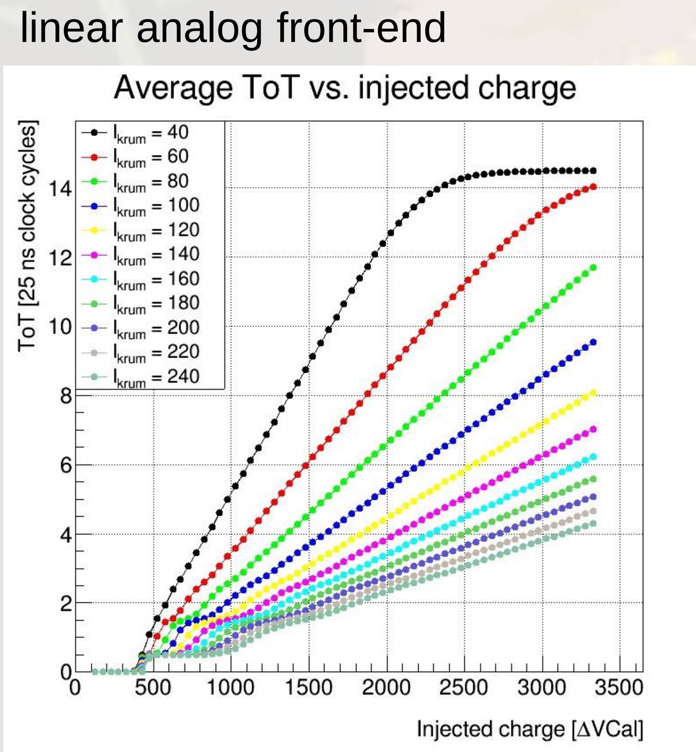
A Single Chip Card (SCC) with a CROC_v1 chip



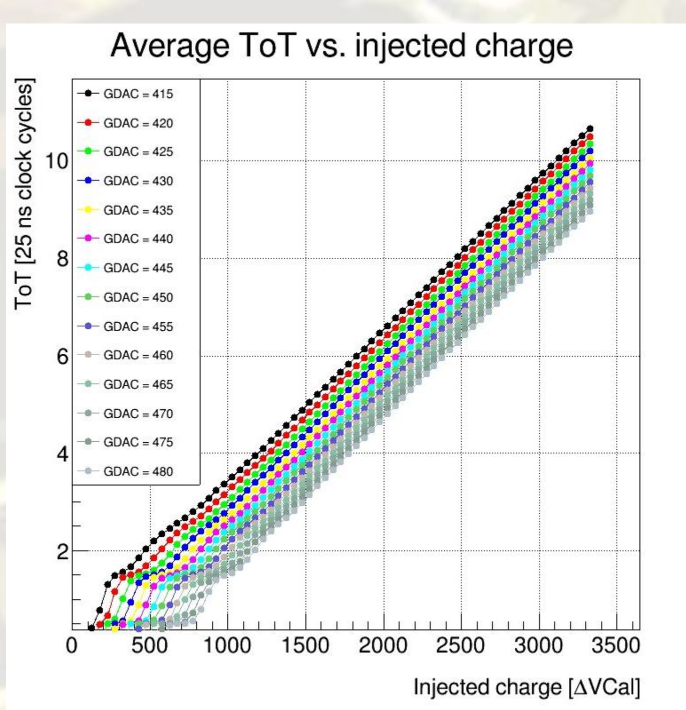
Basic analog front-end structure [3]

Gain tuning

- Signal strength is measured by the number of 25 ns clock cycles spent above the threshold – Time Over Threshold or ToT
- Preamplifier feedback ("Krummenacher") current can be tuned to obtain different ToT gain curves
- ToT saturates at 14 by design and can run in single-slope or double-slope modes (only single-slope mode shown)
- ToT response is visibly non-linear for Krummenacher currents >60 and charges close to the threshold, which is the expected behavior
- ToT gain slope does not depend on the threshold itself, as expected with the linear analog front-end



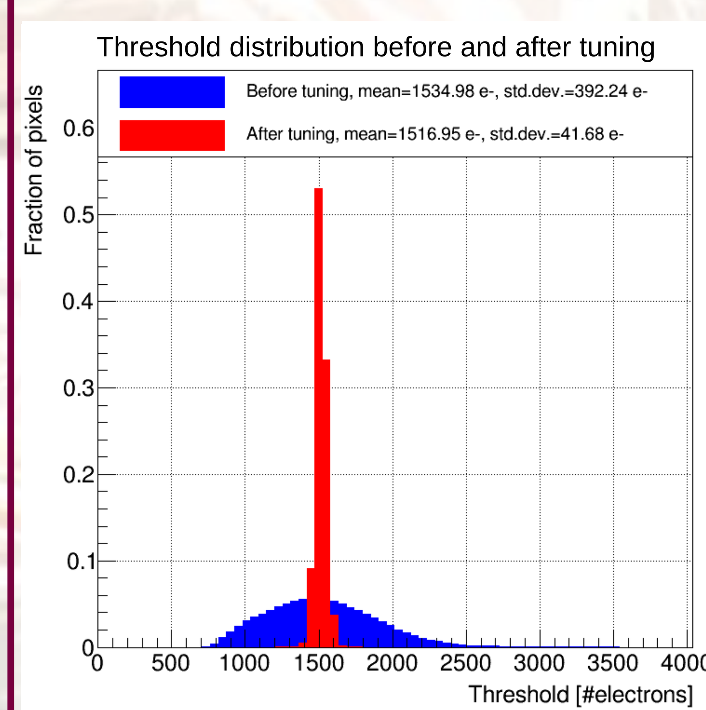
ToT response to injected charge amount for different Krummenacher current values using single-slope mode.



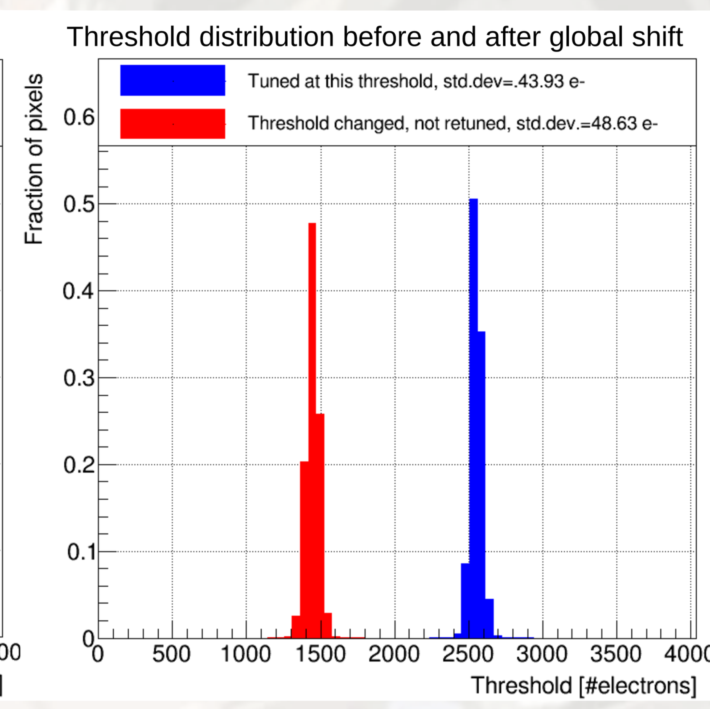
ToT response to injected charge amount for different threshold values using single-slope mode.

Threshold tuning

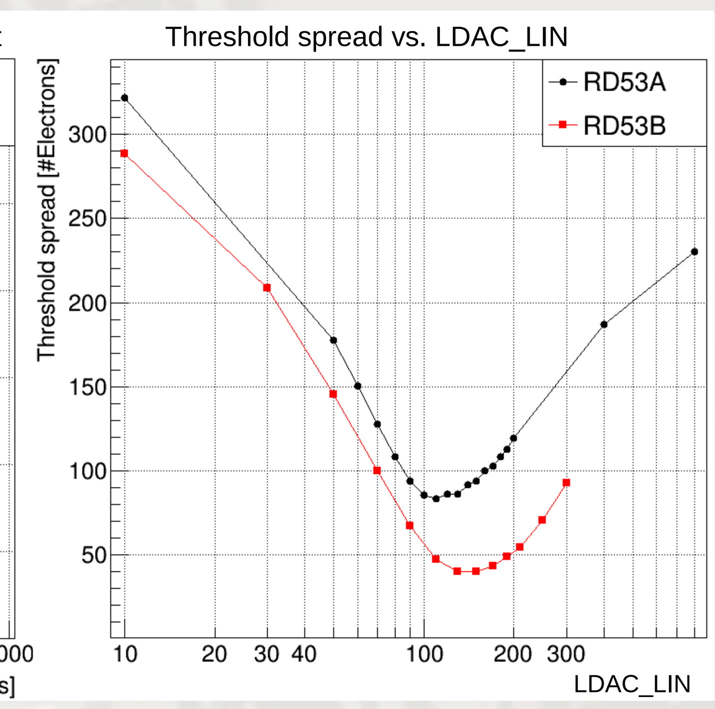
- 5 threshold trimming bits (TDAC) for each pixel can reduce the threshold spread between different pixels down to only 50 electrons – 2× better than RD53A, which had only 4 bits
- Threshold spread is not correlated with the threshold value and per-pixel threshold tuning
- LDAC_LIN global register can be used to adjust the trimming bit strength for optimal tuning precision and dynamic range



Hit detection threshold distributions of a tested pixel sensor on the RD53B chip before and after threshold tuning



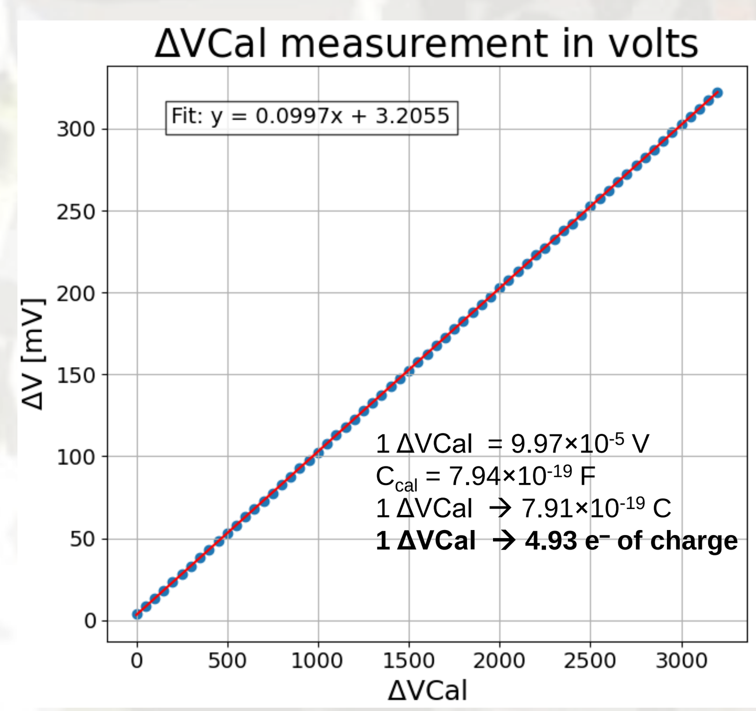
Threshold distributions after threshold tuning to ~2600 electrons, and after shifting the global threshold to 1500 electrons and keeping all TDACs the same



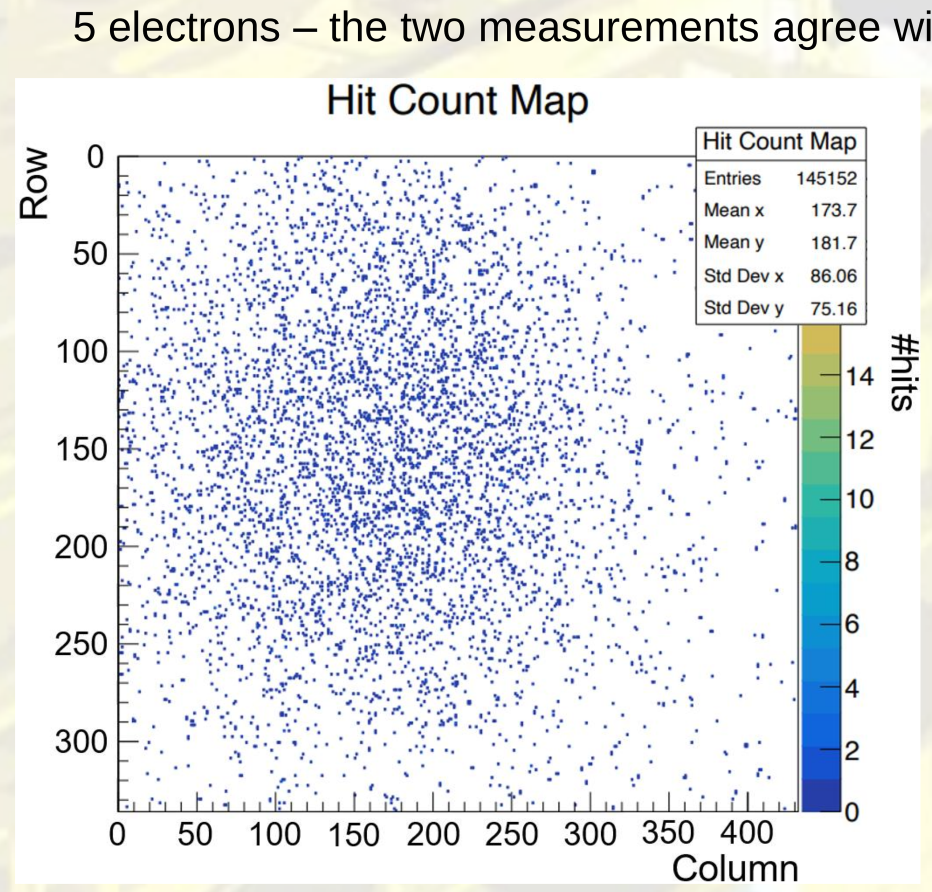
Comparison of the threshold spread (std. dev.) as a function of trimming bit strength (LDAC_LIN) between RD53A and RD53B

Threshold calibration

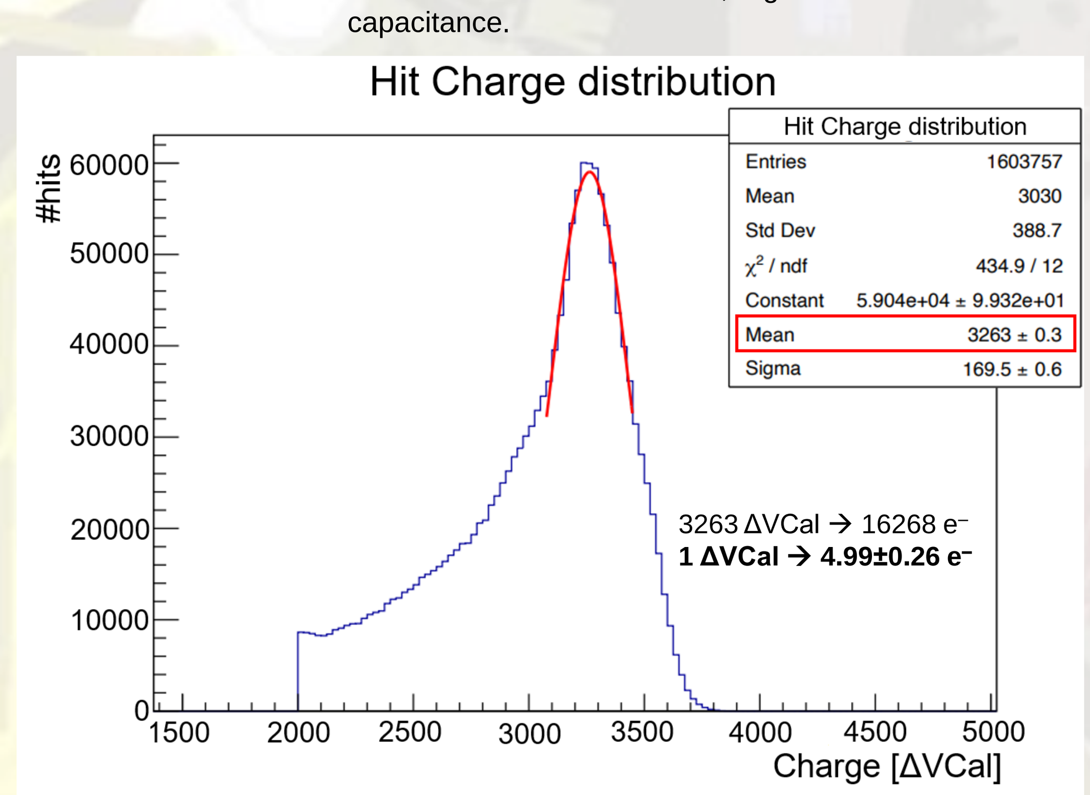
- Threshold can be measured by injecting calibration pulses of known amplitude
- Calibration pulse strength (and consequently the threshold) is measured in DAC units, called ΔVCal
- The physical ΔVCal value expressed in the number of electrons of signal was measured in 2 ways:
  - Using the chip's internal voltage multiplexer (VMUX)
  - Using a radioactive X-ray source ^{241}Am (59.54 keV). One X-ray photon with 59.54 keV of energy is expected to create 16268 electron-hole pairs in silicon
- In both cases, the measured ΔVCal value is very close to 5 electrons – the two measurements agree within errors



Calibration voltage in millivolts is shown as a function of ΔVCal value. This is used to calculate the size of the ΔVCal unit in electrons, given the calibration capacitance.



Hit map of the recorded X-ray hits in the pixel matrix. The shown hits had their signal strength measured to obtain the physical ΔVCal value.



Charge distribution of the recorded X-ray hits. Only single-hit clusters with charge >2000 ΔVCal were selected to achieve high X-ray hit purity. A Gaussian fit is applied on the peak, using the mean value to calculate the ΔVCal value.

Conclusions

- A new tracker is in preparation for the CMS Phase-2 upgrade, featuring high radiation tolerance and high granularity – big improvement over the current tracker
- Pixel chips for the inner tracker are developed by the RD53 collaboration, with a second-gen prototype called CROC_v1 undergoing tests
- Chip performance tests show good results: (a) 2× smaller threshold spread compared to the previous gen chip,
  (b) signal gain response behaves as expected,
  (c) 2 different measurements of the calibration voltage unit agree within errors

[1] [2] [3]

Bibliography

[1] O. Aberle, I. Béjar Alonso, O. Brüning et al., High-Luminosity Large Hadron Collider (HL-LHC): Technical design report, CERN-2020-010 (2020).
[2] CMS Collaboration, The Phase-2 Upgrade of the CMS Tracker, CMS-TDR-014 (2017).
[3] The Tracker Group of the CMS Collaboration et al., Comparative evaluation of analogue front-end designs for the CMS Inner Tracker at the High Luminosity LHC, JINST 16 P12014 (2021)