Operational Issues of the Present CMS Pixel Detector

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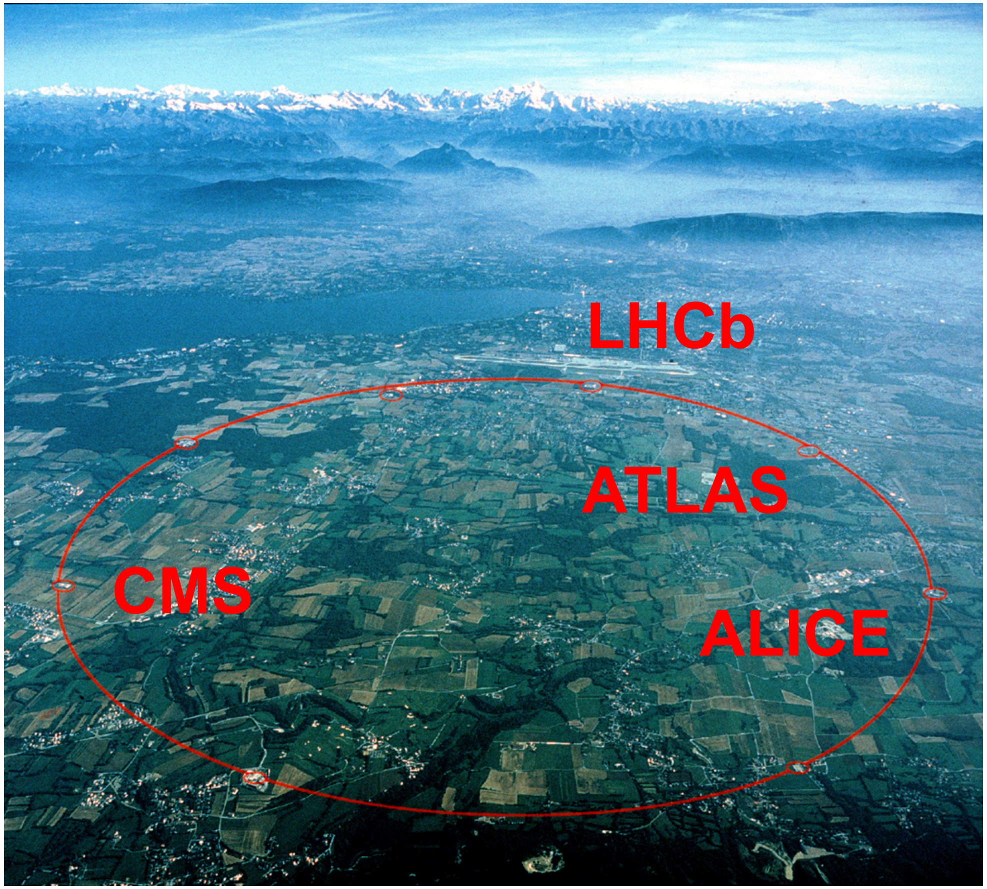
Overview

- LHC, CMS, and Pixel Detector
- Detector Status
- Calibration
- Performance
- Operational Challenges
  - Beam-gas interactions
  - Radiation Damage
- Conclusions

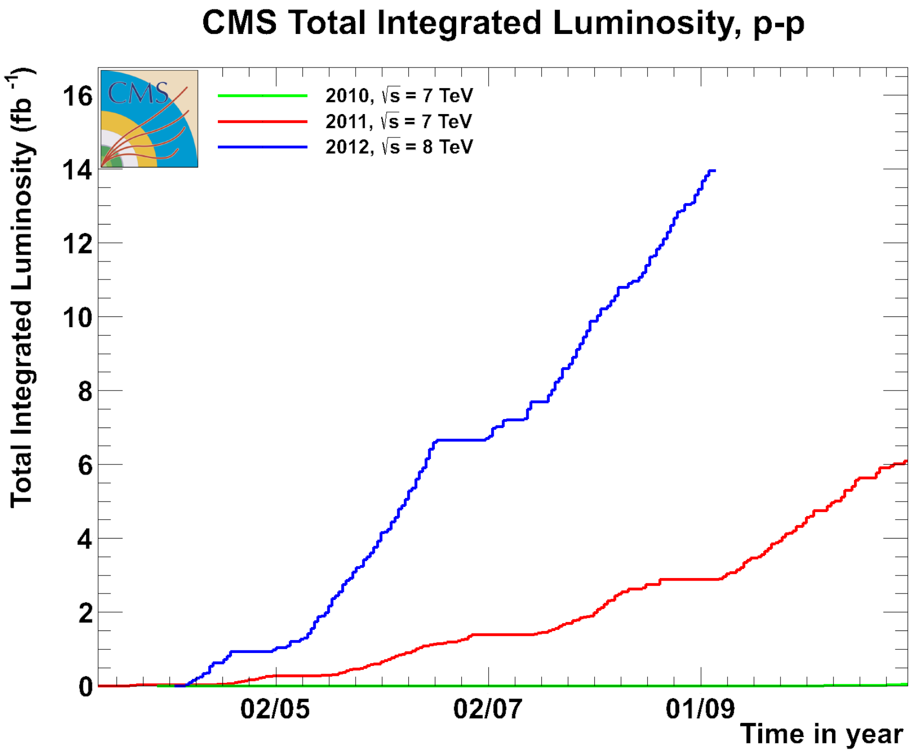
Large Hadron Collider

- Proton-proton, Pb-Pb, (soon) p-Pb
  - p-p: $\sqrt{s}$ = 7-8 TeV, ultimately 14 TeV
  - Pb-Pb: $\sqrt{s}$ = 2.76 TeV / nucleon



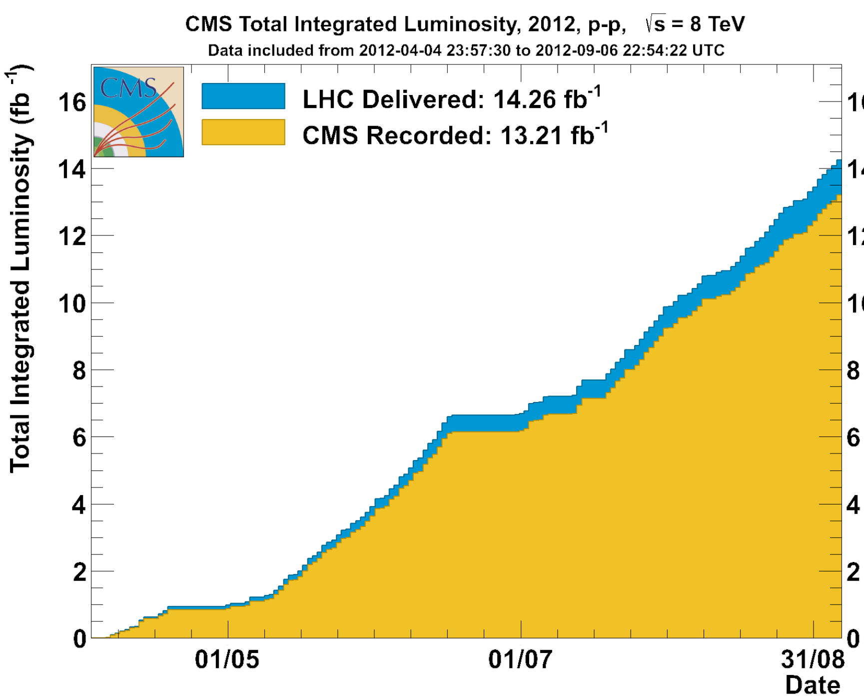
Luminosity
- Current design: ~1 x 10^{34} cm^{-2} s^{-1}
- Max. so far: 7.7 x 10^{33} cm^{-2} s^{-1}

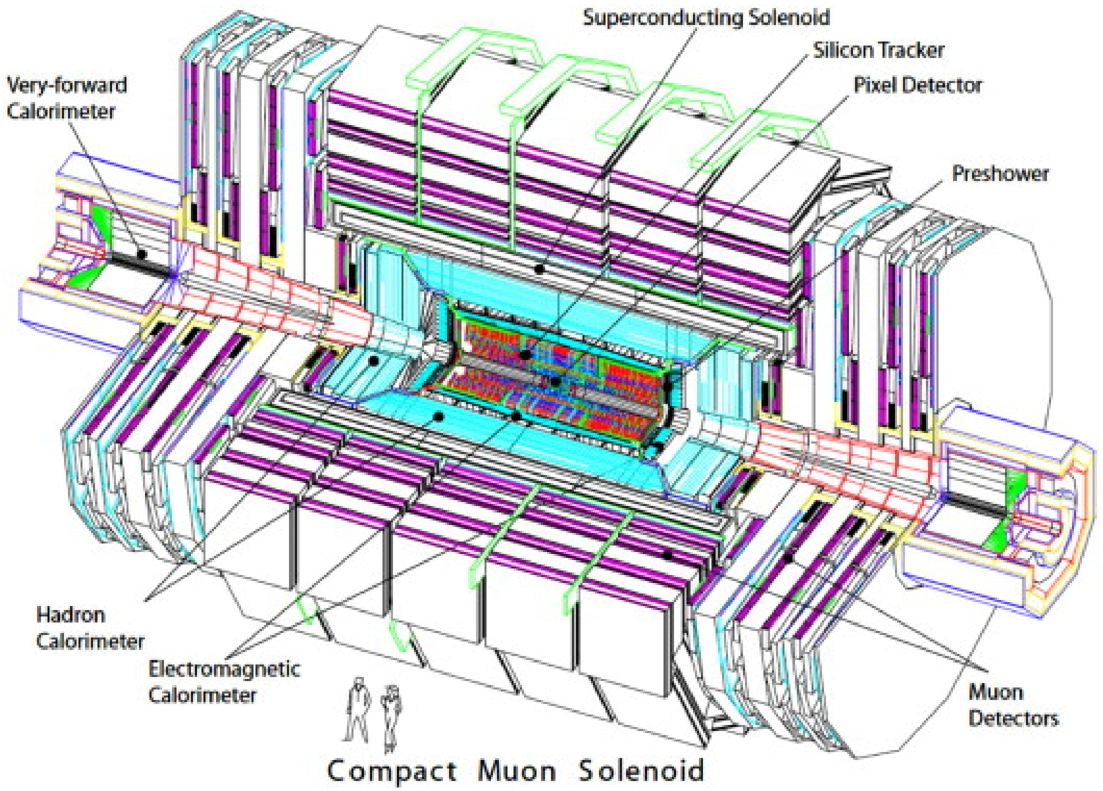
- Bunch spacing 50 ns (ultimately 25)
  - More pileup than at nominal luminosity and bunch spacing!



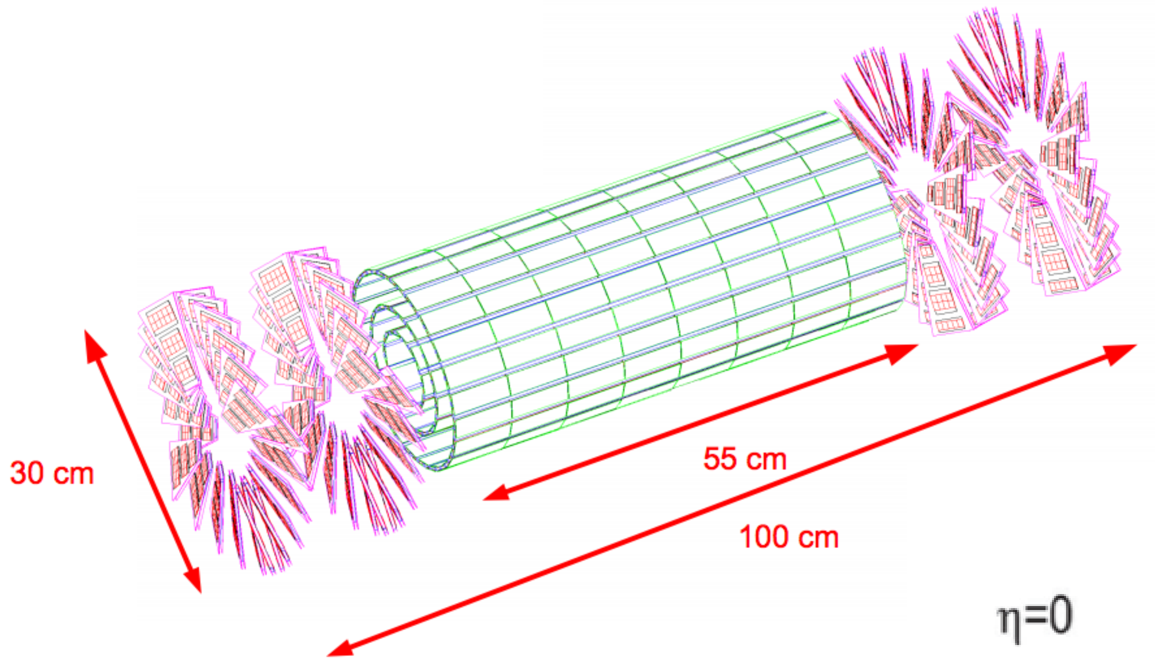
The CMS Detector

- General purpose detector: Higgs, Standard Model, B physics, heavy ions, new physics
- 3.8T solenoidal magnetic field
- Tracking central to all aspects of physics program
- Data-taking efficiency: 93% in 2012
  - Of which Pixels is ~12%



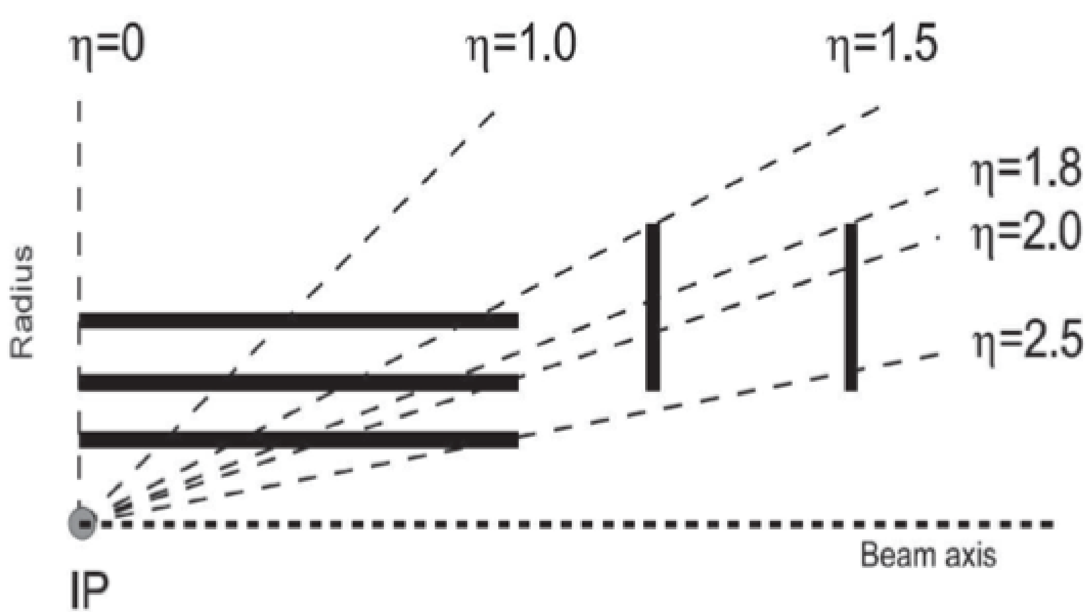


CMS Pixel Detector



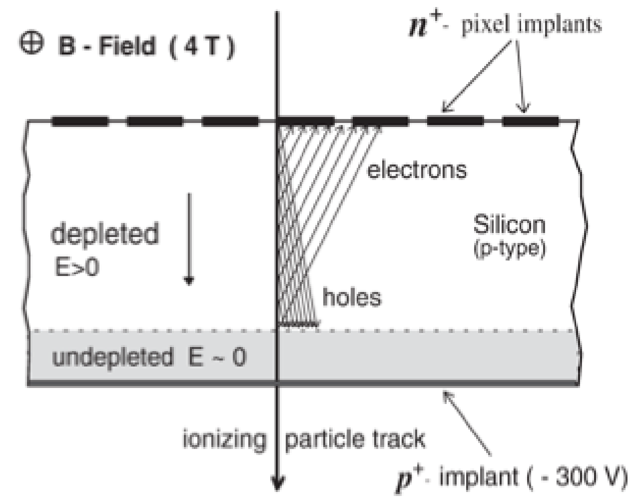
- FPIX (forward)
  - 2 disks / endcap
    - z = 34.5, 46.5 cm
    - 6 cm < r < 15 cm
  - 18M pixels, 0.28 m^2

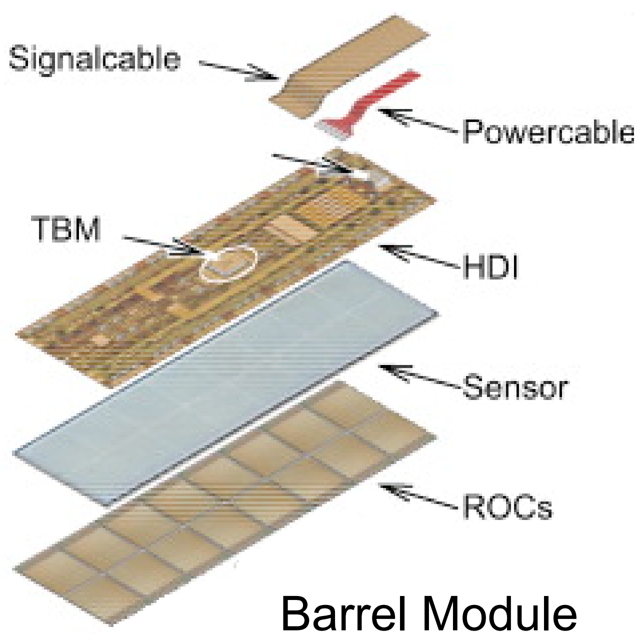
- BPIX (barrel)
  - 3 layers
    - r = 4.3, 7.2, 10.8 cm
  - 48M pixels, 0.78 m^2



Pixel Sensor and Readout

- Si sensors: n-in-n, oxygenated
- Each pixel 100 µm x 150 µm
- Read Out Chip (ROC)
  - 52 x 80 pixels
  - Zero suppression at pixel level
  - Double-column readout
    - Hits read out upon trigger
- Further on-detector electronics:
  - Token Bit Manager (TBM) chip: Receives triggers, controls ROCs
  - Portcard/supply board: auxilliary electronics, e.g. conversion to optical signal
- Detector total: 15840 ROCs, 1320 optical readout channels

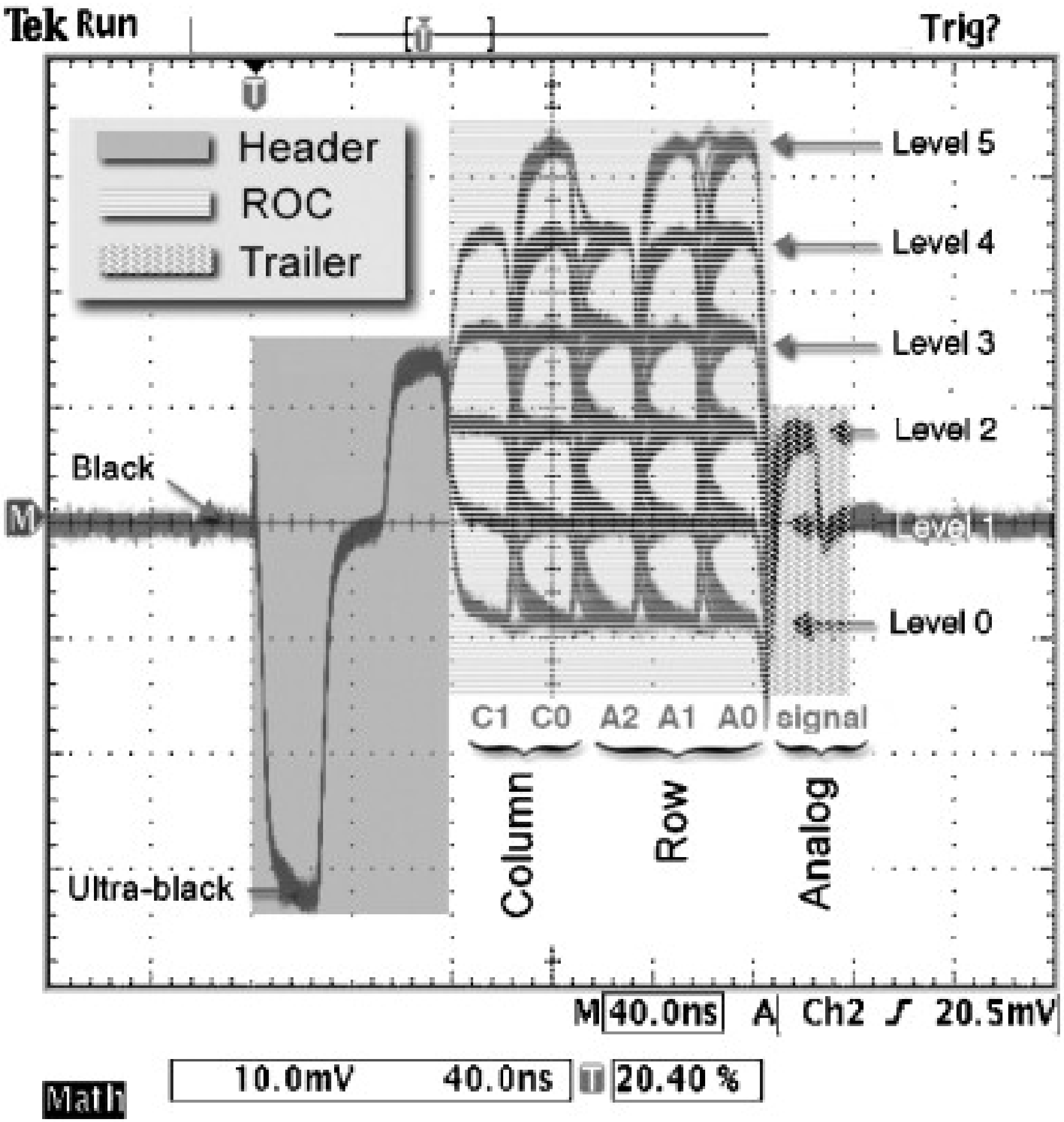




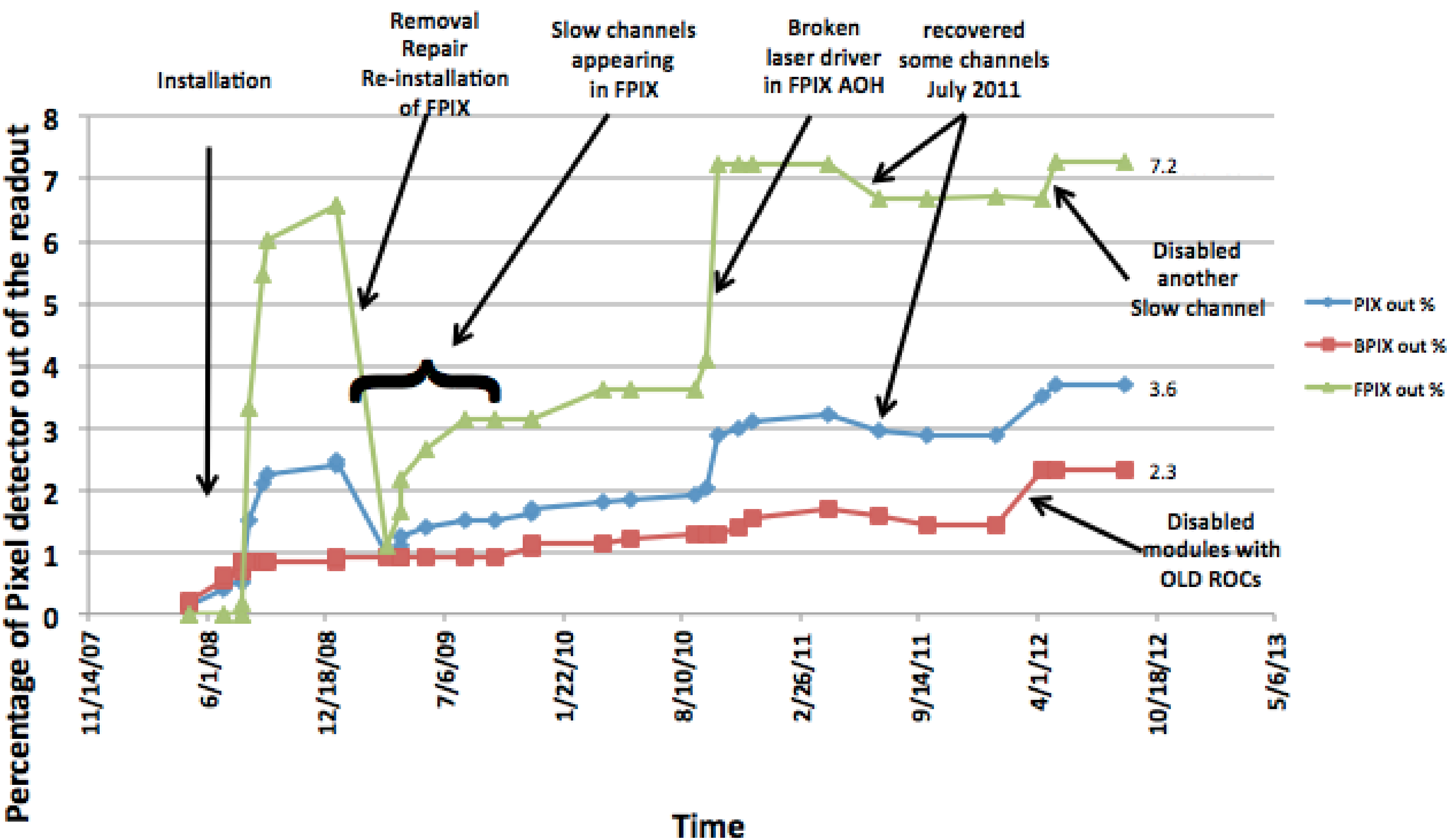
Barrel Module

Analog Readout Structure

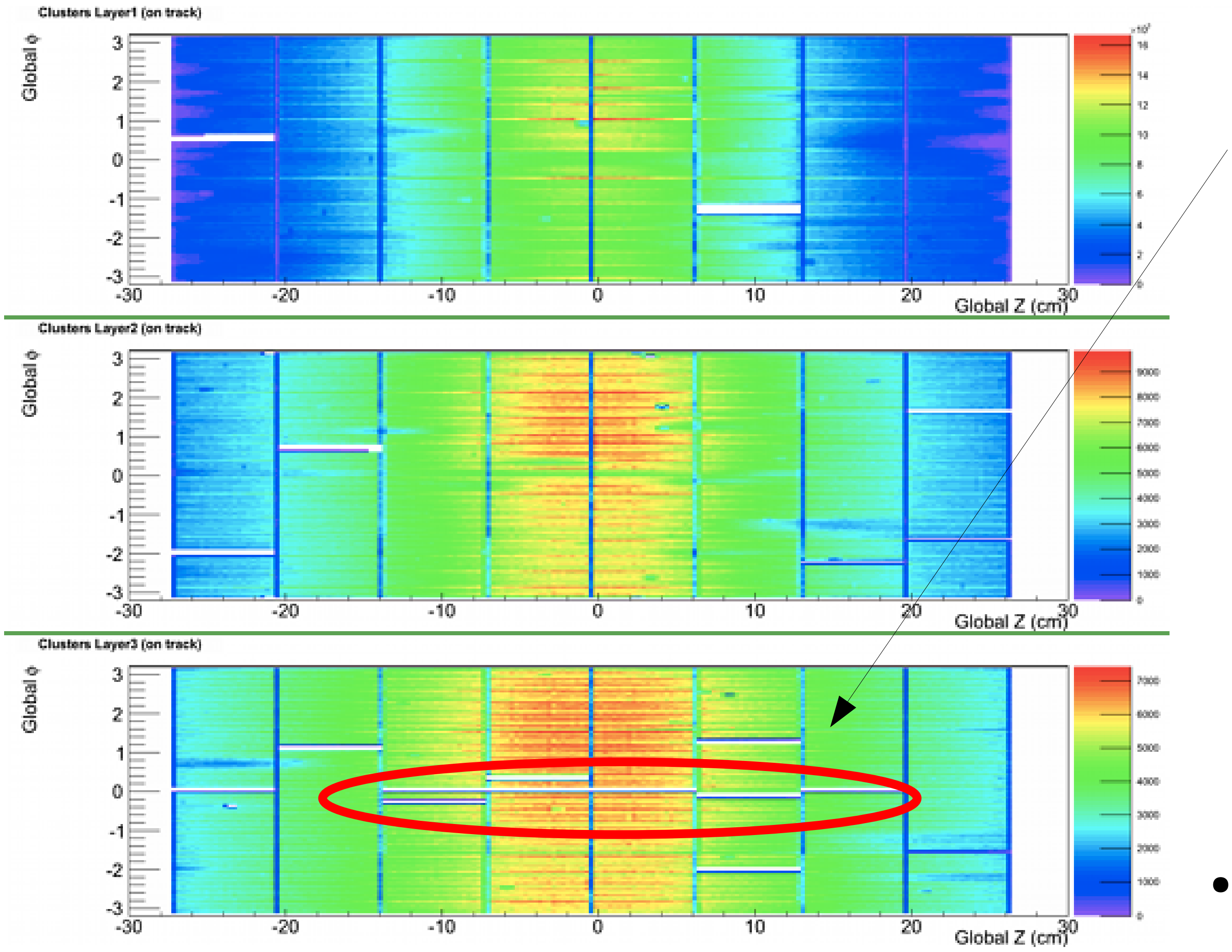
- Hit pixel triggers readout of double column to buffer
- Double columns read out sequentially when trigger received
- ROC header followed by address and analog signal for each pixel



Detector Status (1)



Detector Status: Barrel

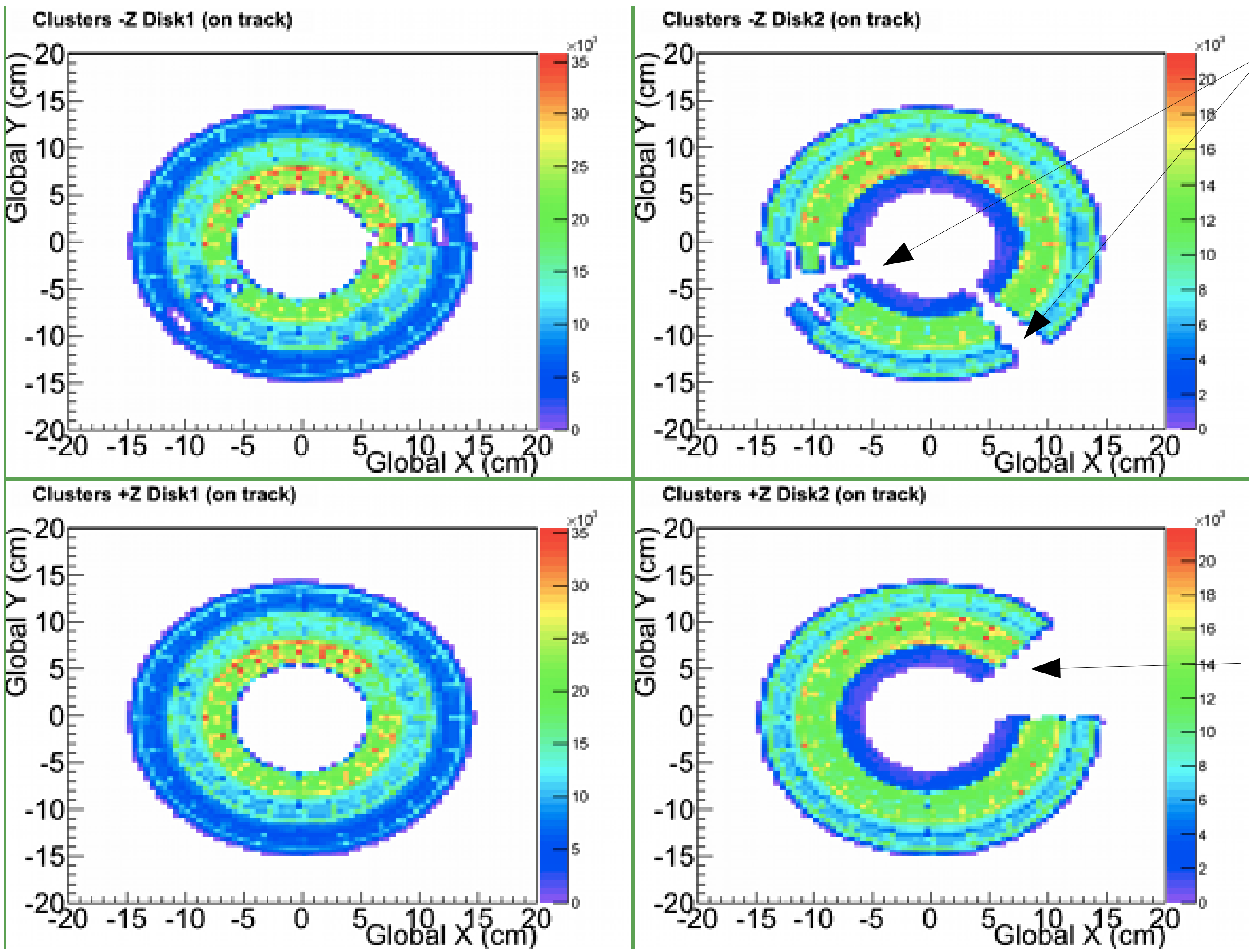


Modules with old ROC design

- Rare readout error that requires module reset
- Increased with occupancy, eventually caused too much downtime

- Other lost modules mostly since installation

Detector Status: Disks

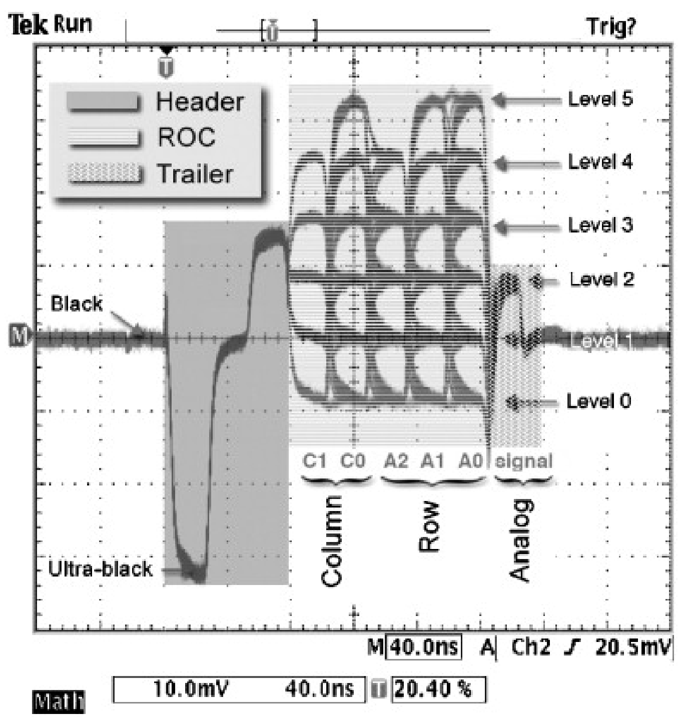


"Slow" channels

- Long rise time in analog readout
- Pixel addresses misread
- ROCs or events miscounted if headers lost

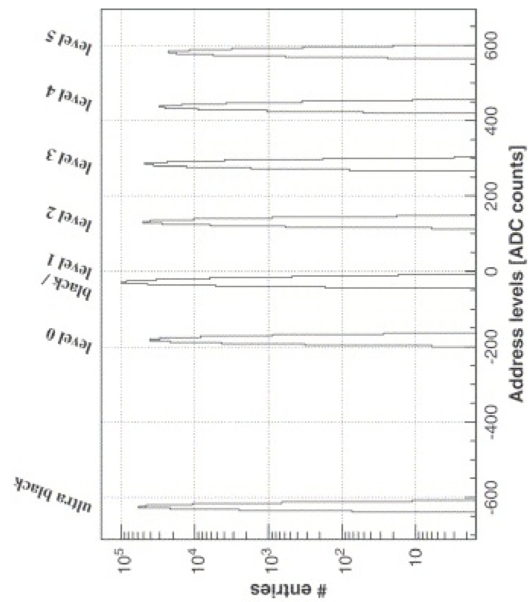
Broken laser driver in optical readout

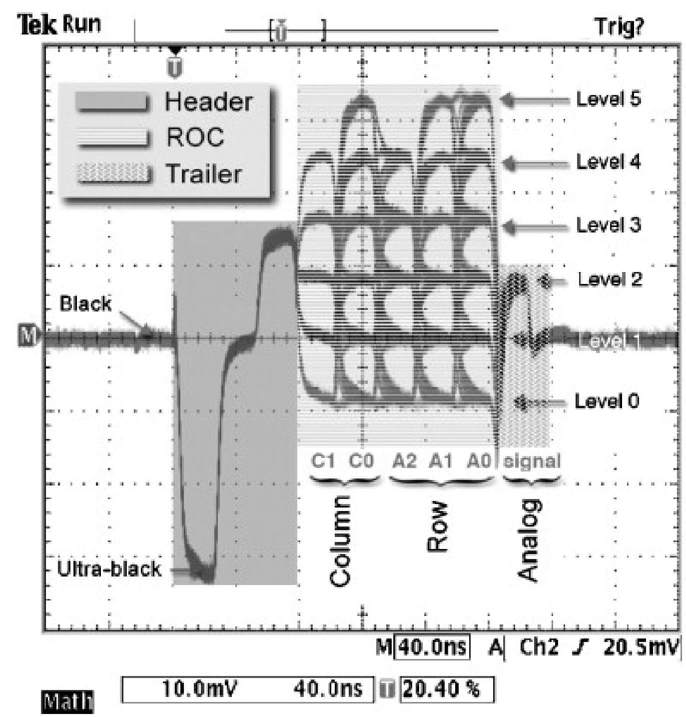
Weekly Calibrations (1)



- Baseline Calibration
  - Adjust optical receiver so “black” level in middle of ADC range
  - Very temperature sensitive
  - Small adjustments automatic
- Address Level Calibration
  - Separation between address levels

Weekly Calibrations (1)





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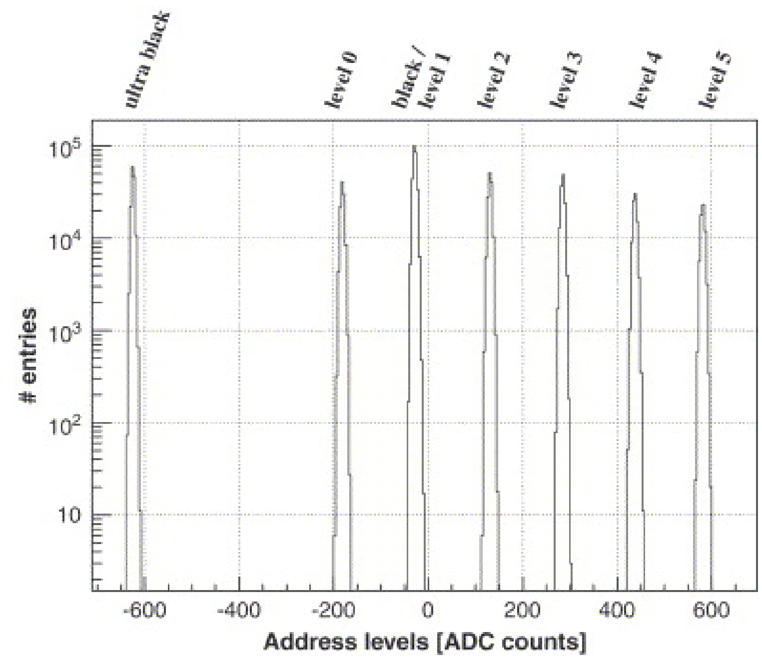

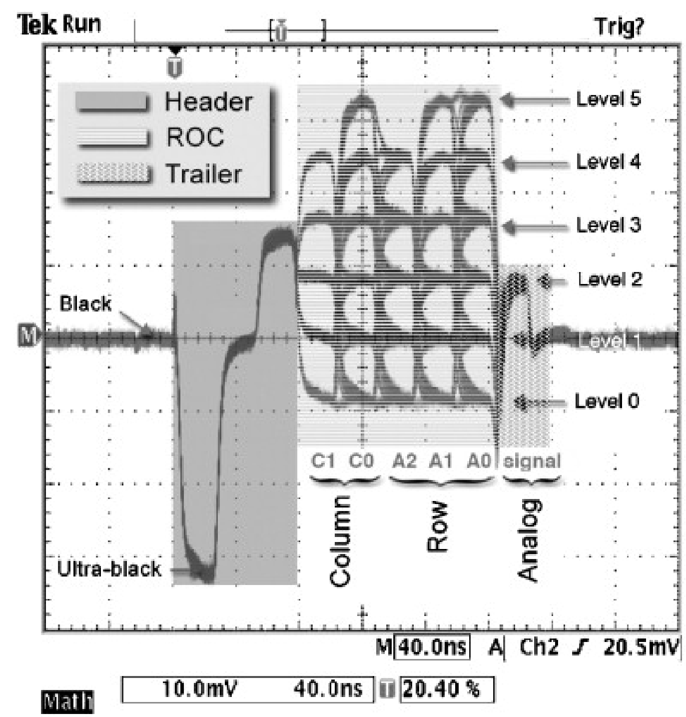

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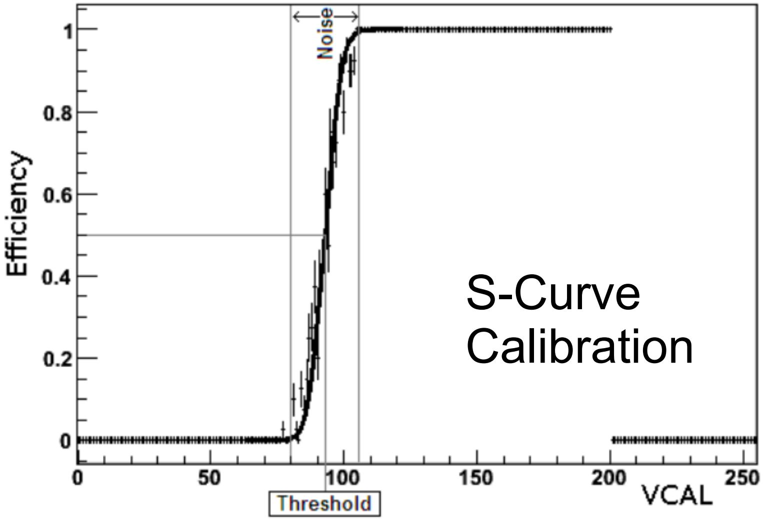
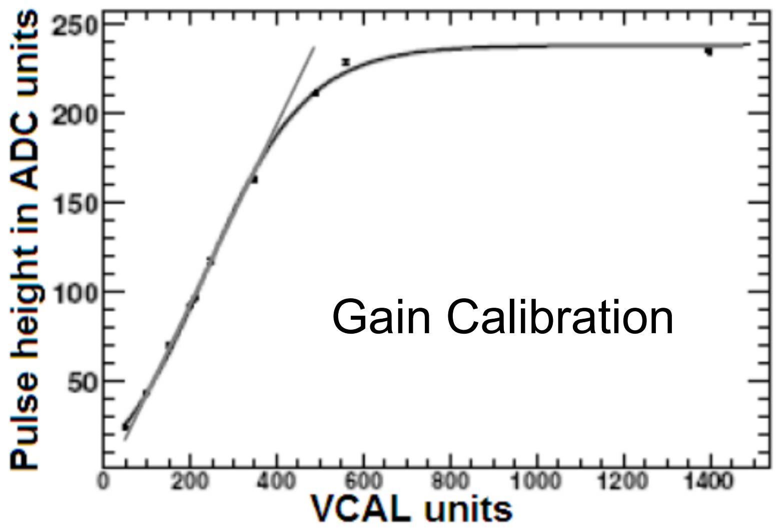
Weekly Calibrations (2)



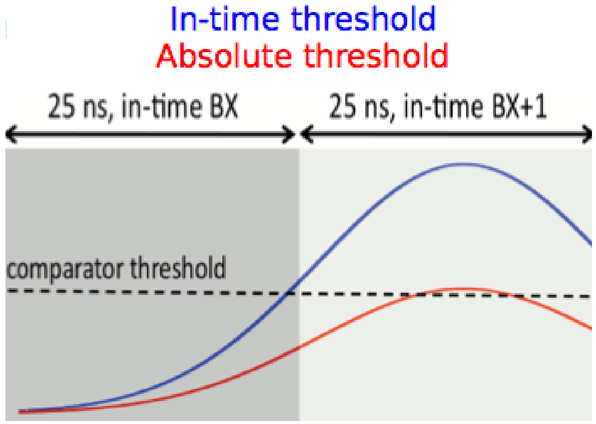
- S-Curve Calibration
  - Check efficiency vs. injected charge on subset of pixels
  - Target threshold: ~2500 e^- (~45 VCAL)



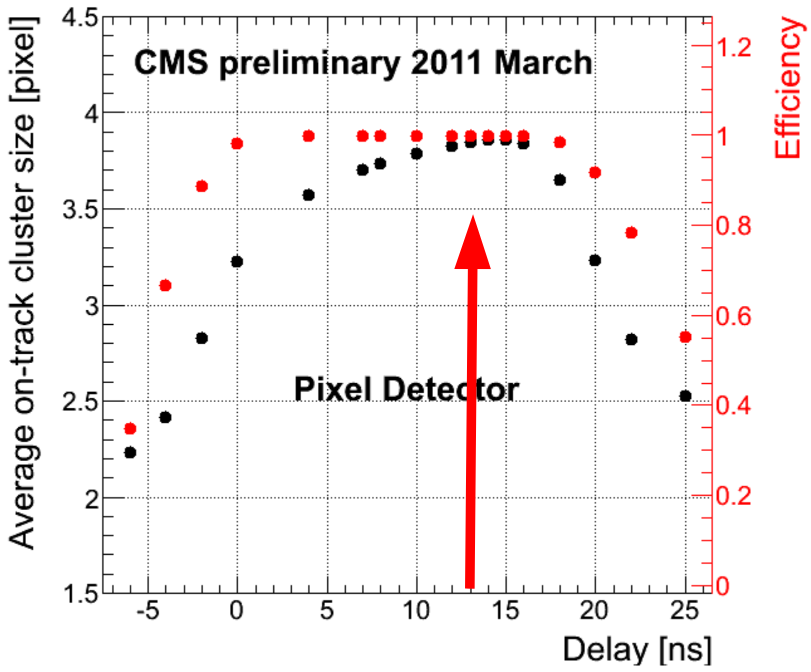
- Gain Calibration
  - ADC counts vs. injected charge
  - Linear pixel response

Calibrations & Scans

- Calibrations run once or a few times a year determine full range of readout settings
  - E.g. adjusting analog voltage → changes preamplifier rise time → changes timewalk



- Timing Scan
  - Vary timing during LHC running; confirm that readout delay settings are on plateau for good efficiency
- High Voltage Bias Scan
  - Cf. Radiation damage section

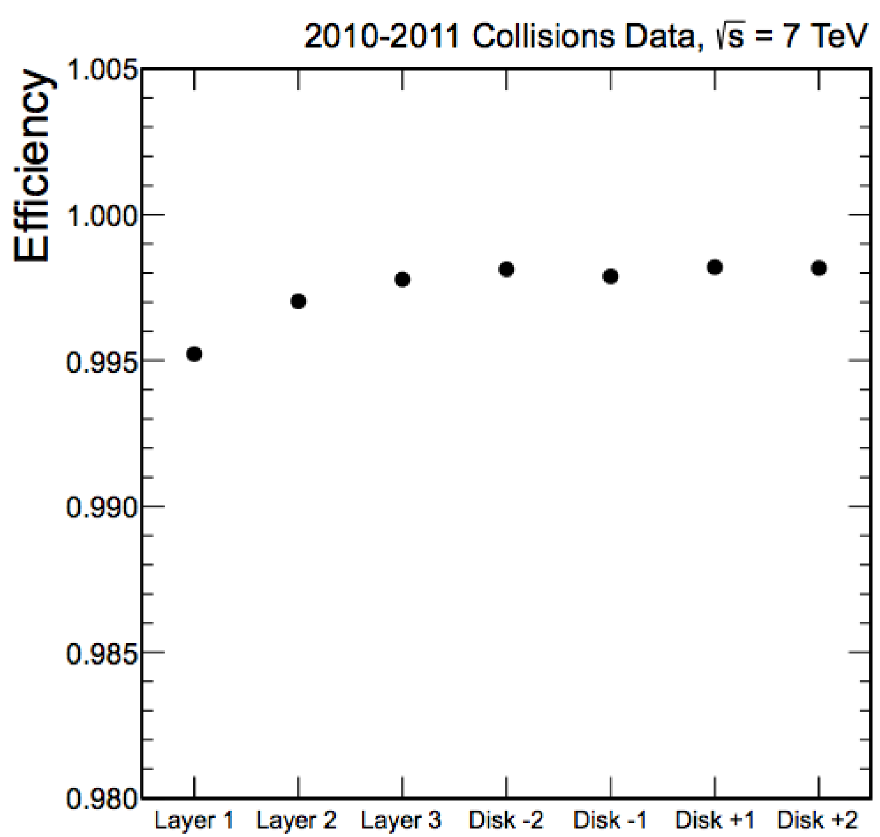


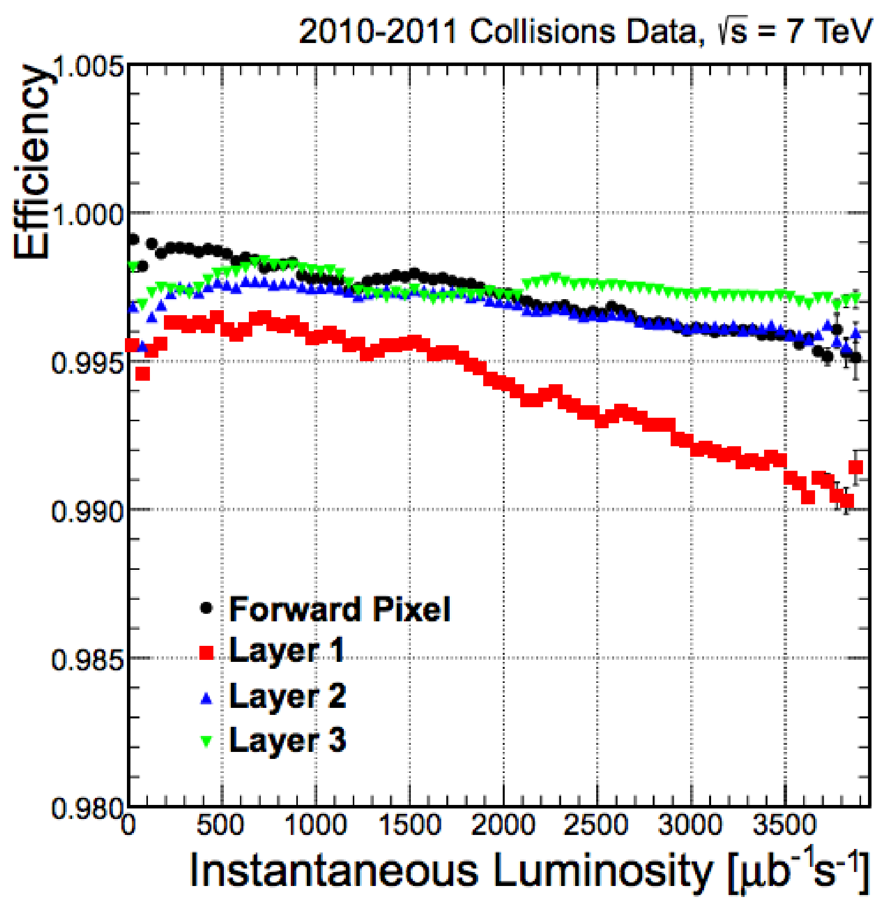
Temperature & Recalibration

- To limit impact of radiation damage and minimize leakage current, design temperature is -20ºC
- Imperfect sealing of pixel volume → issues with humidity → cannot go below 0 ºC for coolant (sensors are ~10 ºC warmer)
- Coolant temperature 2008-2011: 7.4ºC
- Coolant temperature 2012: 0ºC
- Detector recalibrated for temperature change
  - Analog voltage for ROCs adjusted: balance minimizing timewalk with power supply limits on current
  - ROC-by-ROC thresholds re-minimized

Pixel Hit Efficiencies

- Pixel efficiency determined from missing hits on track
- Efficiency (for all working ROCs) above 99.5%
- Efficiency reduced at high luminosity due to occupancy

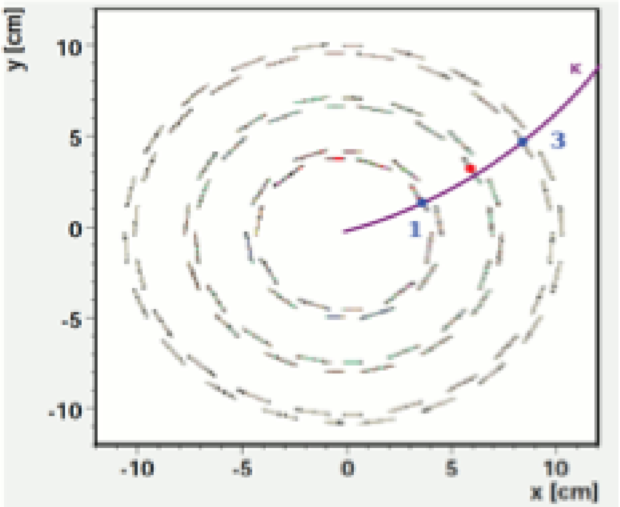


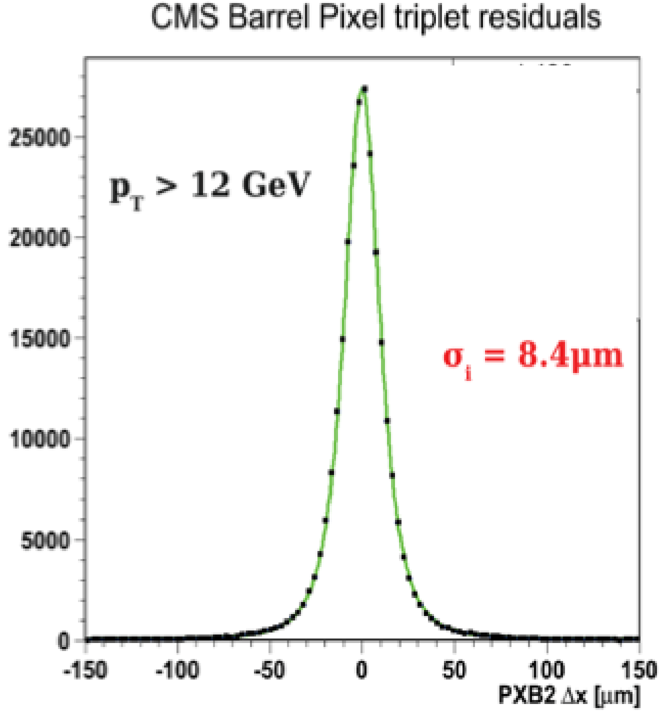


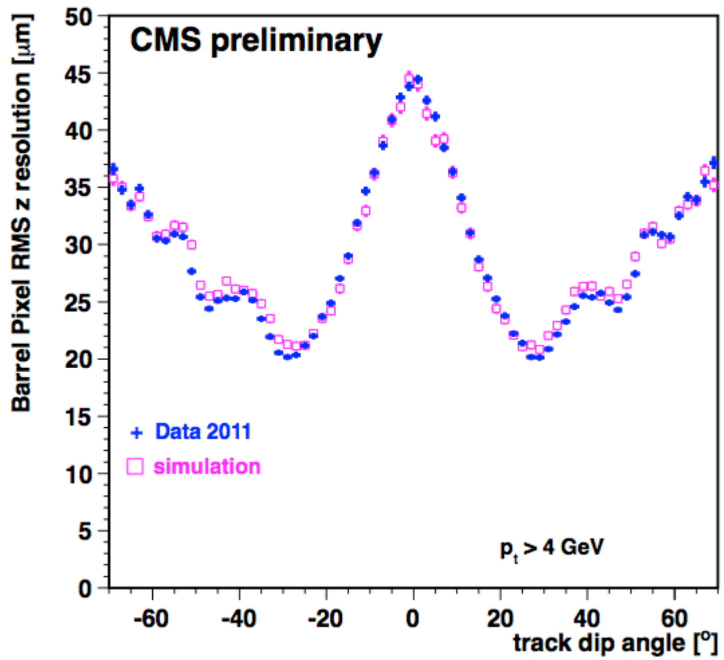
Pixel Hit Resolution

- Tracks with 3 hits in pixel barrel are used
- Use curvature of full track
- Positions, angles from layers 1 and 3
- Interpolated to layer 2; measure hit residual
- Studies with overlapping components on the same layer give consistent result

$$\Delta x = x_{hit} - x_{extrapolation}$$

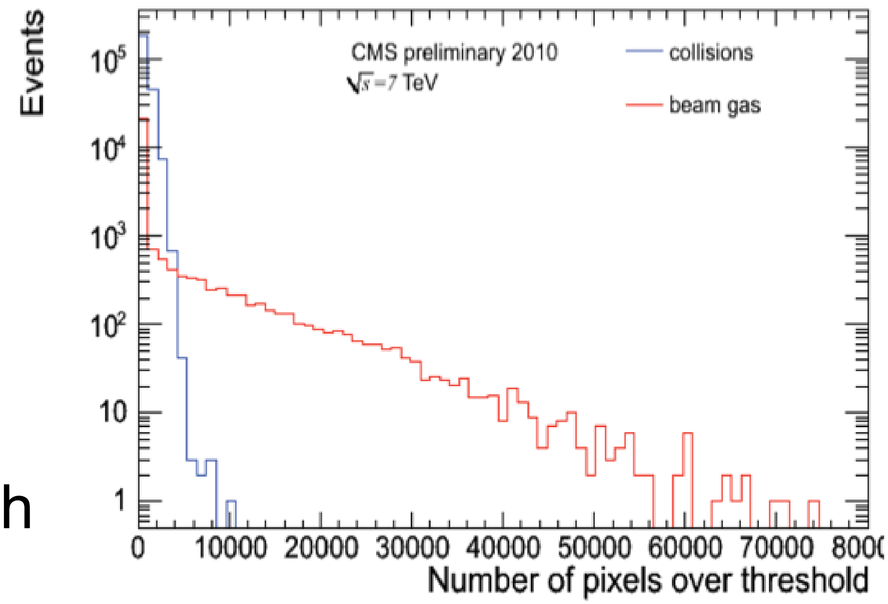


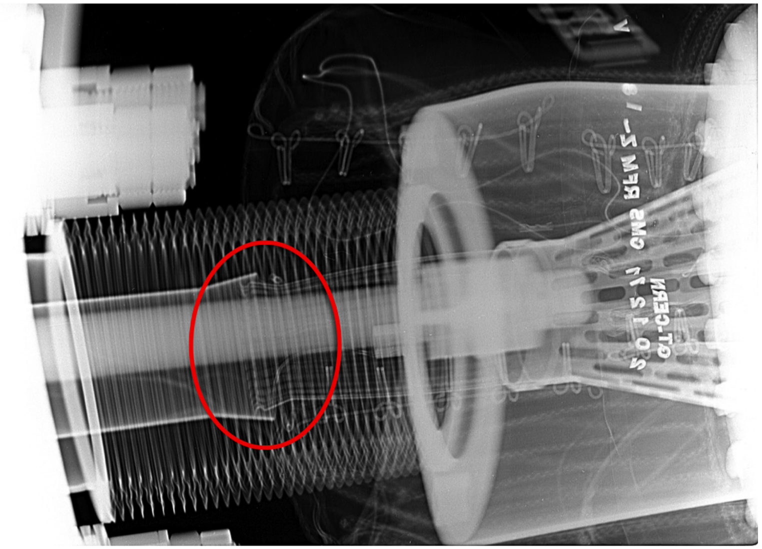




Beam-gas events

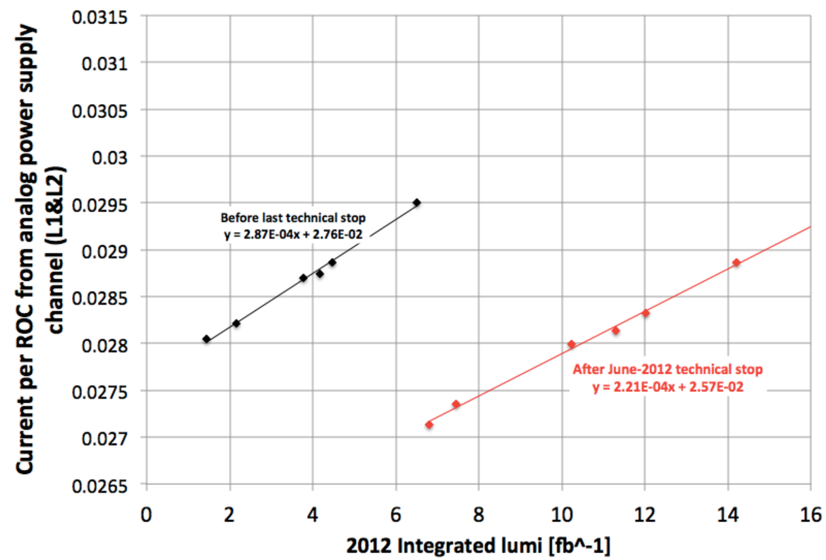
- Beam-gas interactions: particles graze BPix modules, creating many hits
- Excessive occupancy in a single channel
- Solved with “busy mechanism”
    - Stop triggers until channel can catch up
    - Further optimization done on data acquisition settings and firmware to minimize dead time from mechanism
- LHC joint 18.5m from interaction point fixed during 2011-2012 shutdown: significant improvement

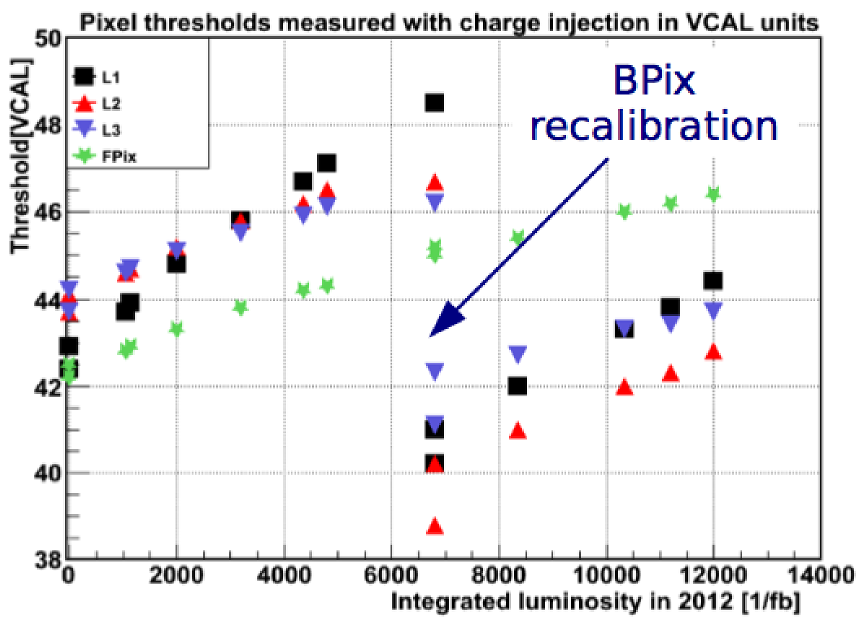




Impact of Radiation Damage

Analog Current & Threshold

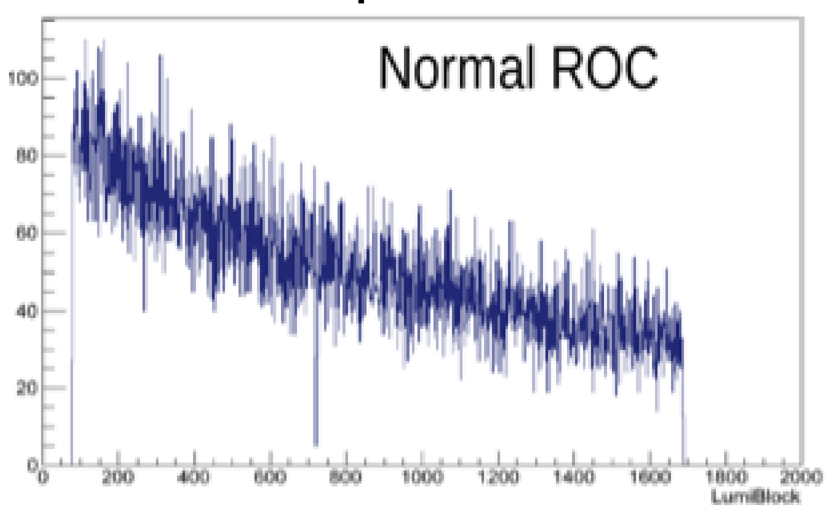


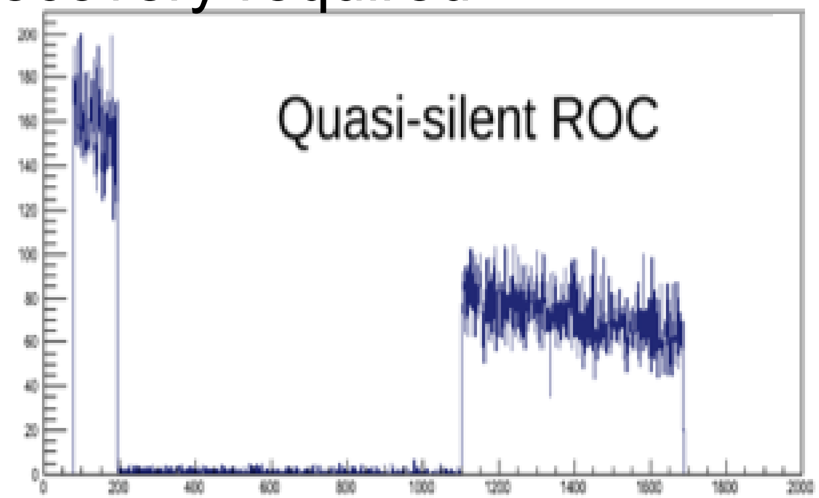


- Analog current increases linearly with radiation damage
  → Slower preamplifier rise time
  → Higher pixel threshold
- Biggest operational concern: power supply current limit per channel
  - Limit 6A, operate ~5.5A
- Fixed by recalibration
- Not anticipated!
- Possible mechanism:
  - Meaning of fixed analog voltage DAC setting changed
  - Caused by bulk damage in diode used for reference voltage?

Single Event Upsets (SEU)

- Ionization from charged particles → bit flip in memory of on-detector electronics
  - Measured indirectly only: we define SEUs if symptoms recovered by reprogramming
- May disrupt functioning of...
  - Pixel: no action needed
  - ROCs: may become "silent" or "quasi-silent" (at worst, <0.1% of detector total); reprogrammed when possible
  - TBM or portcard: immediate recovery required



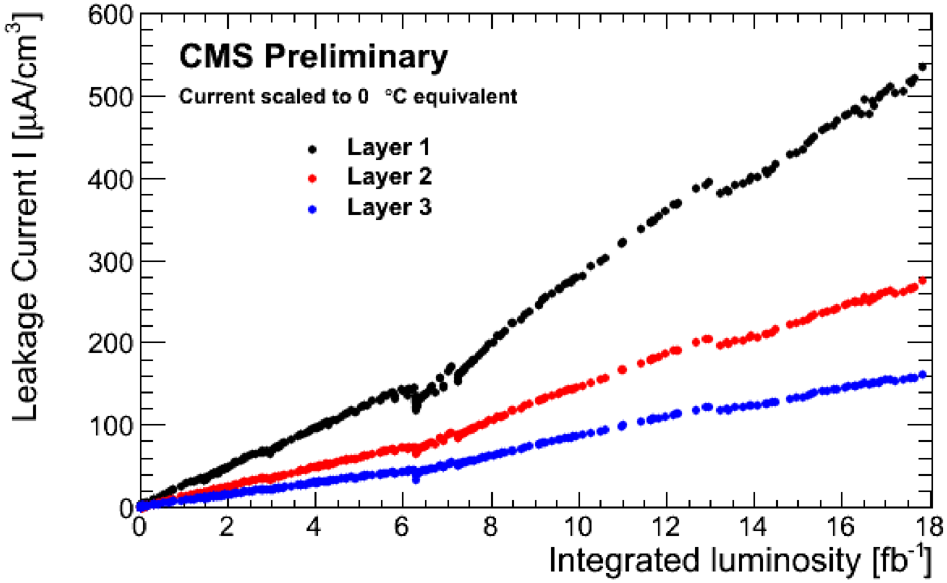


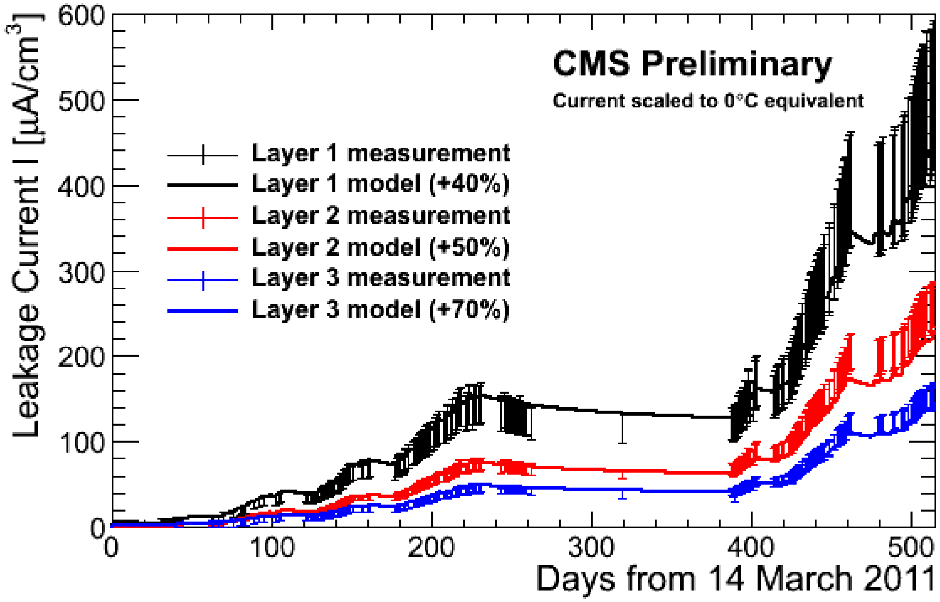
SEU Detection & Recovery

- SEU detection
  - Readout channel timeout
    - Channel shut off after consecutive timeouts
    - Left off after 3 tries at recovery with no result, and indicate expert intervention needed
  - Out-of-Sync (OOS) errors: use recovery mechanism if X errors during Y events
  - Much work done on optimization!
    - Example from OOS: (X,Y) = (8, 100k) minimizes downtime
- SEU recovery procedure
  - Central trigger stopped
  - ROC's, TBM's, and portcards all reprogrammed
  - Total time: a few seconds (no individual pixels)

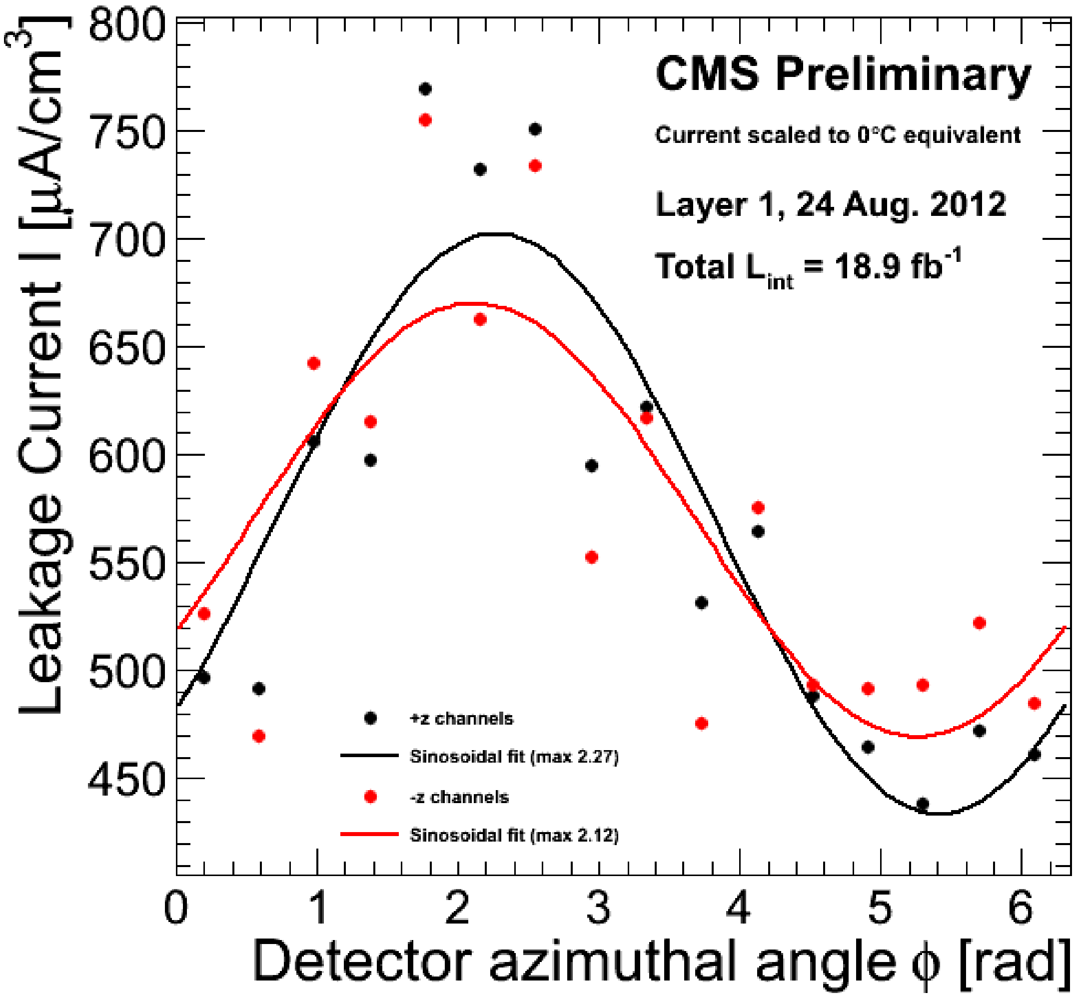
Leakage Current

- Leakage current expected to increase linearly with fluence
  - Due to bulk Si damage
  - Partial recovery due to annealing
- Good shape agreement with models – magnitude low by 40-70%
- For more on bulk properties and models, see talk wednesday from S. Gibson



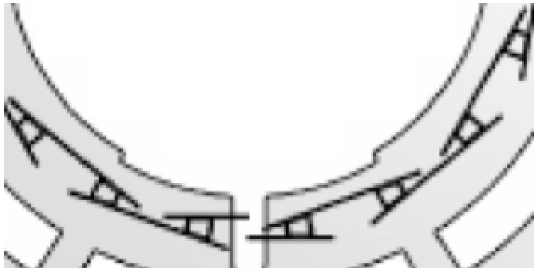


Azimuthal Dependence

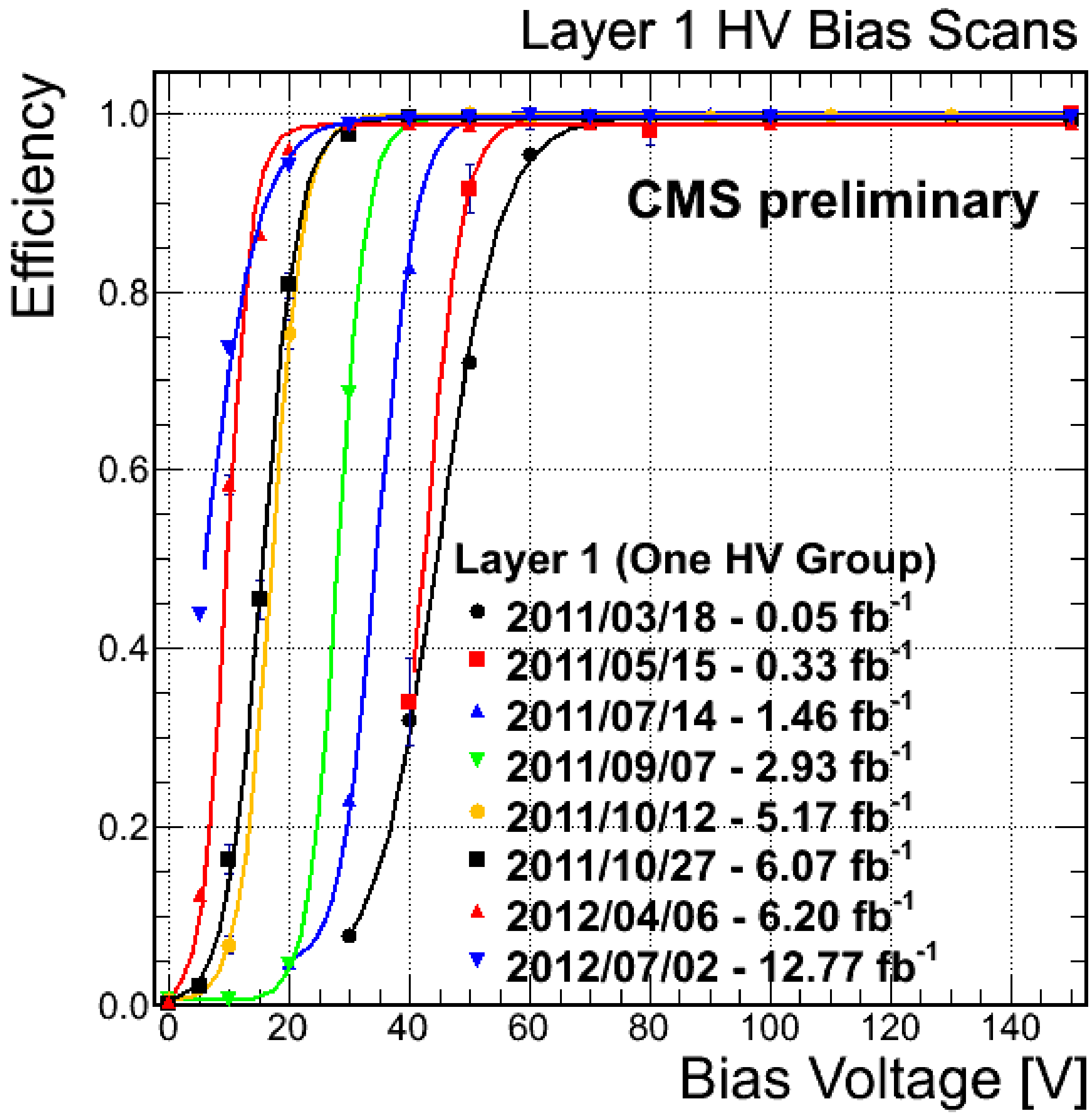


- LHC Beam Spot is not at center of Pixel Detector!
- W.r.t pixel, LHC beam spot (x,y) = (-2.4mm, 3.9mm) → φ ~ 2.12
- 30% effect on potential Layer 1 lifetime!
- Geometric issues also impact data rates → where readout issues emerge

Can also see impact of staggered geometry



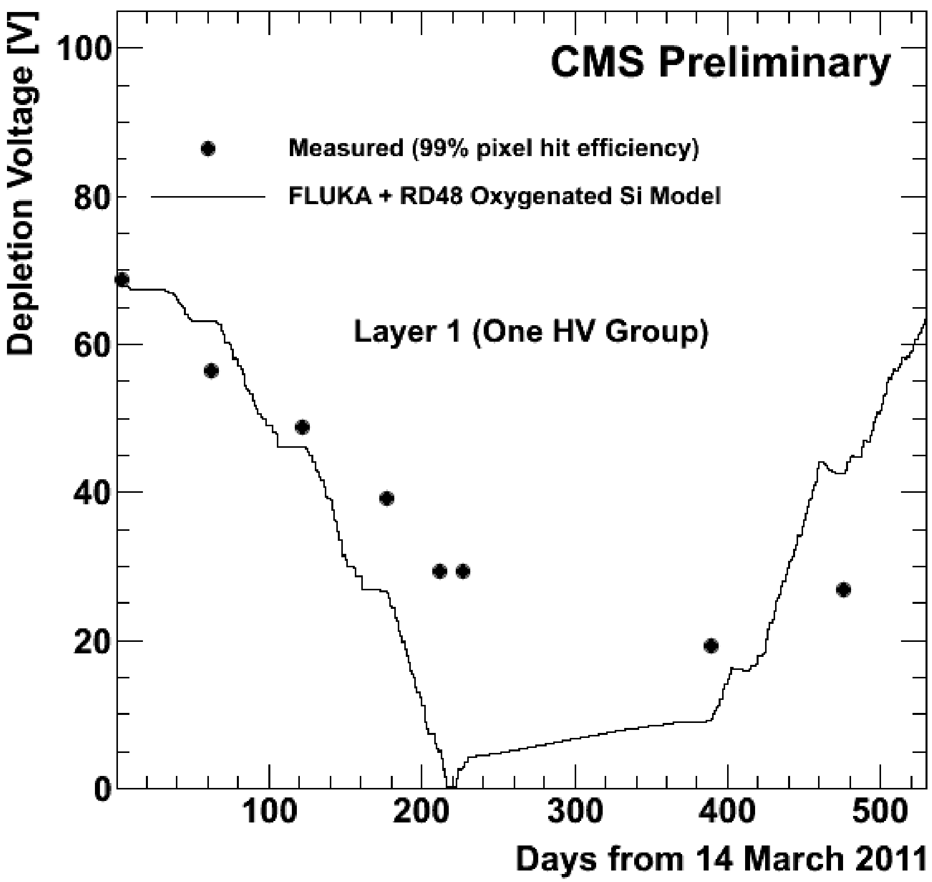
Bias Voltage Scan

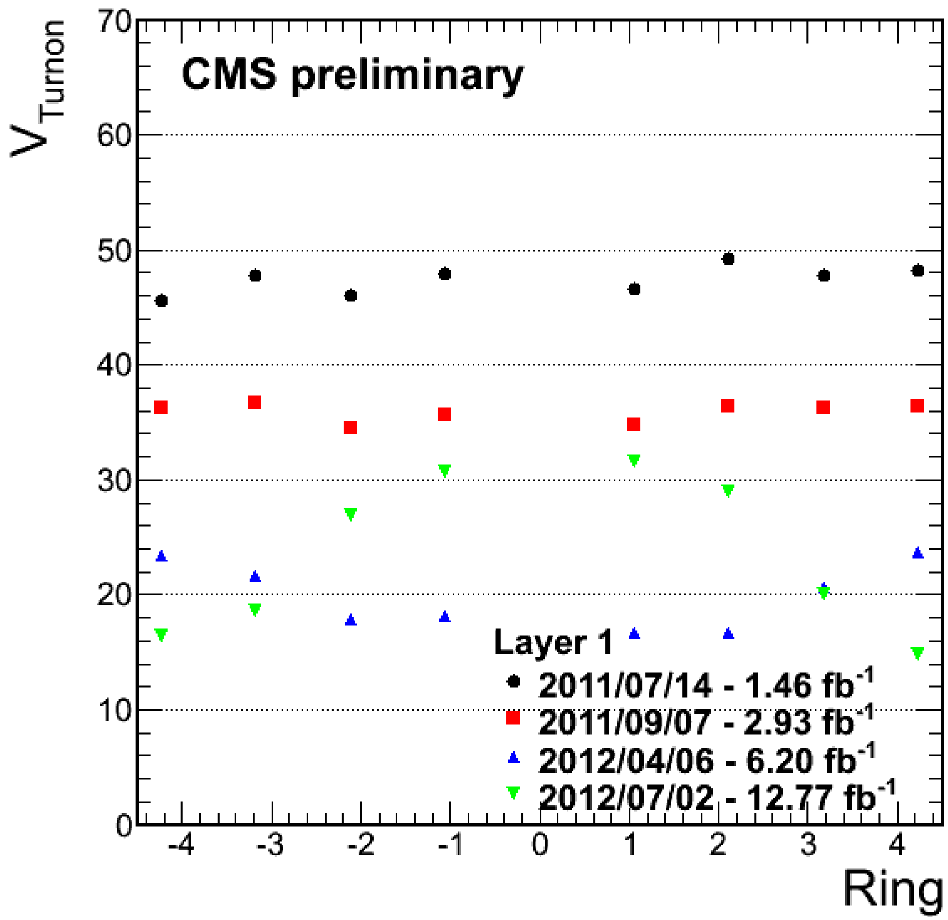


- Vary voltage during LHC running
  - Use small area of detector or non-physics datataking
  - Current nominal voltage:
    - 150V for BPIX
    - 300V for FPIX
- Measure efficiency for hits on track
- When silicon is fully depleted, hit efficiency should reach plateau!
  - Choose 99%

Type Inversion

- Depletion voltage measured (99% efficiency) → silicon has reached type inversion
  - Evolution seems slower than models predict so far





Future Plans

- Spring 2013, after current run has ended: pixels to be extracted
  - Opportunity to study slow channels and other issues
- Most non-operating channels likely can be repaired on the surface
- Cooling and humidity infrastructure will be upgraded for design temperature of -20ºC
- Start of 2014: pixels to be reinserted and recalibrated for next LHC run
  - Pixel position to be adjusted for better centering with the LHC beamspot
- For further in the future, see Thursday's upgrade talk by R. Lu

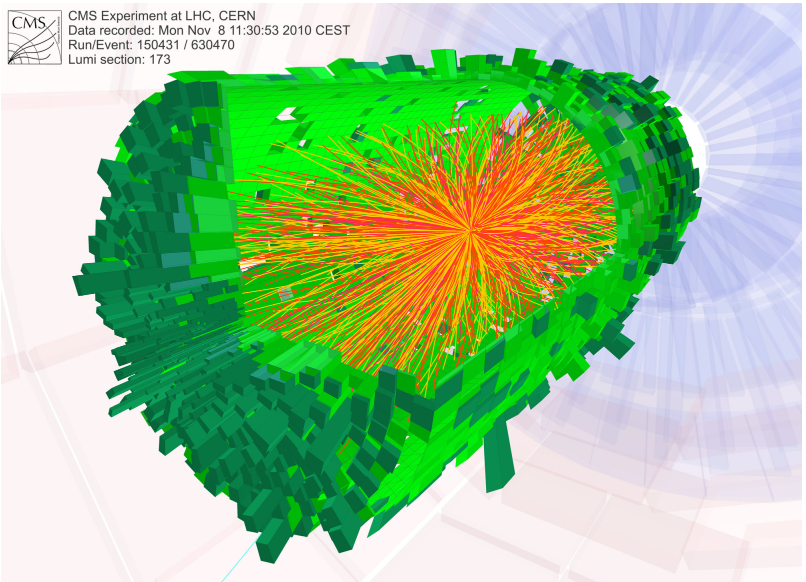
Conclusions

- Pixel detector performance in during 2009-2012 LHC running has been very good
  - Stable running, small contributions to downtime
    - Pixel detector accounts for ~12% of 2012 CMS downtime
  - Hit efficiency (>99.5%) and resolution excellent as expected
- Ongoing work required to maintain performance
  - Adjustment for high-occupancy events
  - Minimization of downtime
  - Recalibration with changing temperature and radiation damage, etc.
- Some surprises, but bulk radiation damage so far as expected
  - Depletion voltage to be monitored as it increases

Extras

Heavy Ion Running

- Very low luminosity: ~5 x 10^{26} cm^{-2} s^{-1}
- But very high track multiplicity: up to 30k hits in the most central collisions
- Readout buffer sizes increased
- Good performance in 2010 and 2011 HI runs!



Fuller List of Calibrations

- Calibrations run once or a few times a year determine full range of readout settings
  - Optical readout levels (bias, gain)
  - ROC analog voltage ($\rightarrow$ timewalk)
  - Black/ultrablack levels at each readout step
  - Delay for sending and returning commands
  - Charge injection timing & response
  - ROC pulse height
  - Individual pixel threshold trim bits