# Performance and lesson learned with the CMS Pixel Detector

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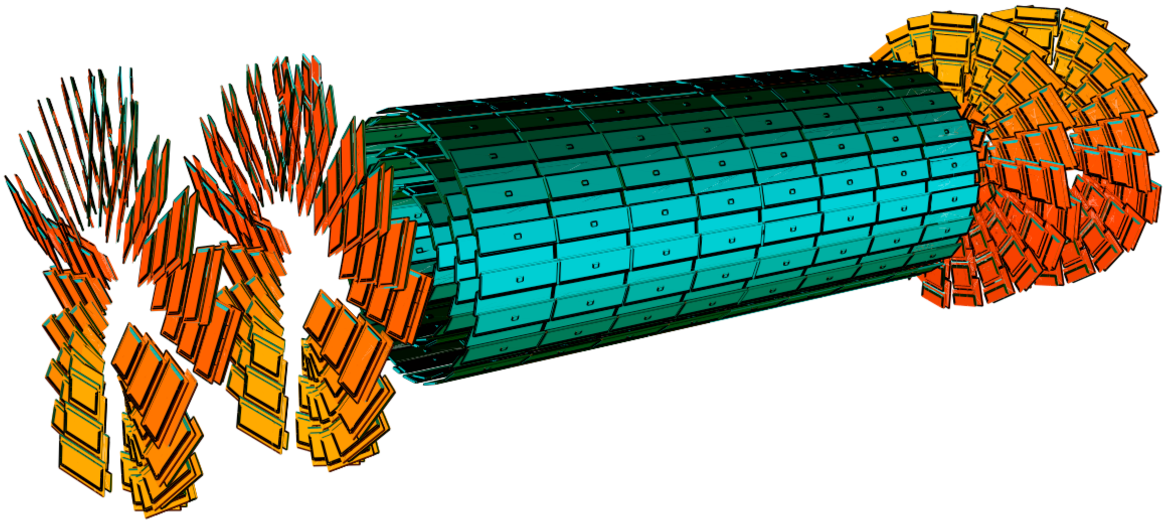
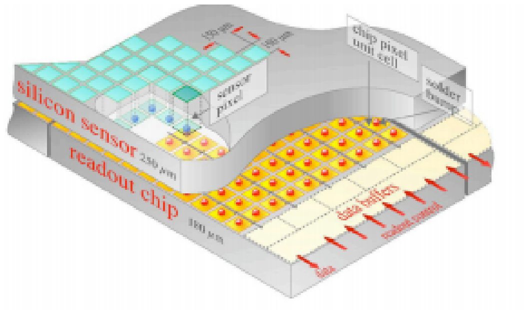
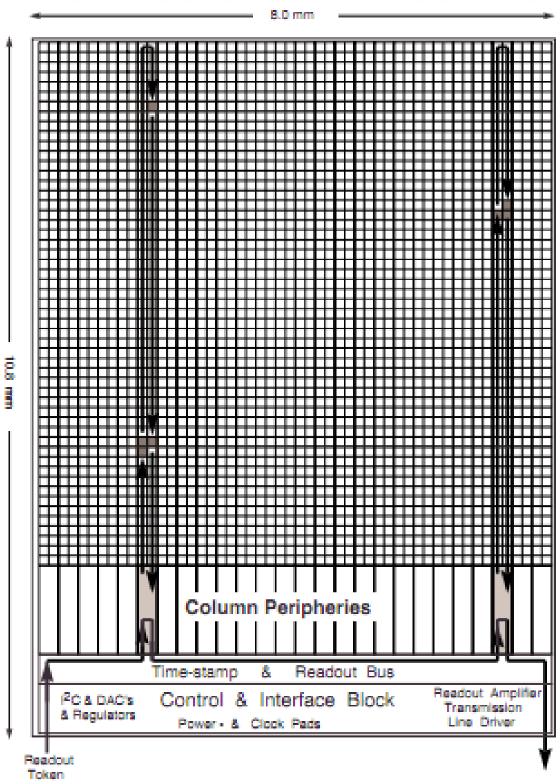
For the CMS Pixel Group



## Schematic view: ROC (Read-Out-Chip)

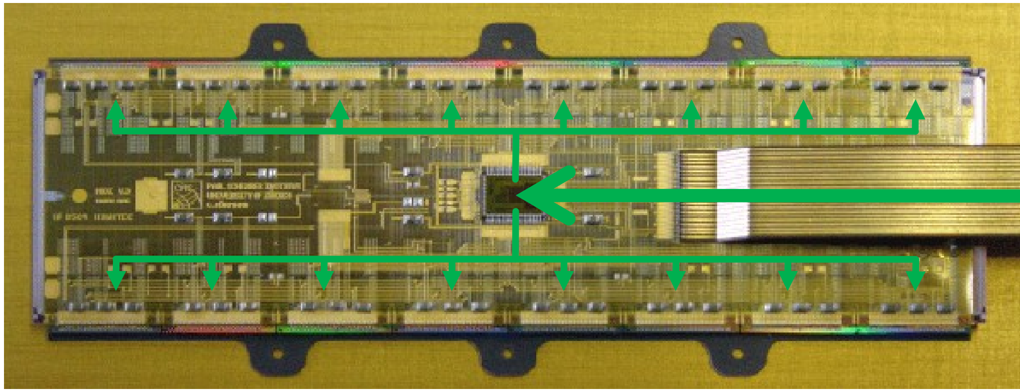


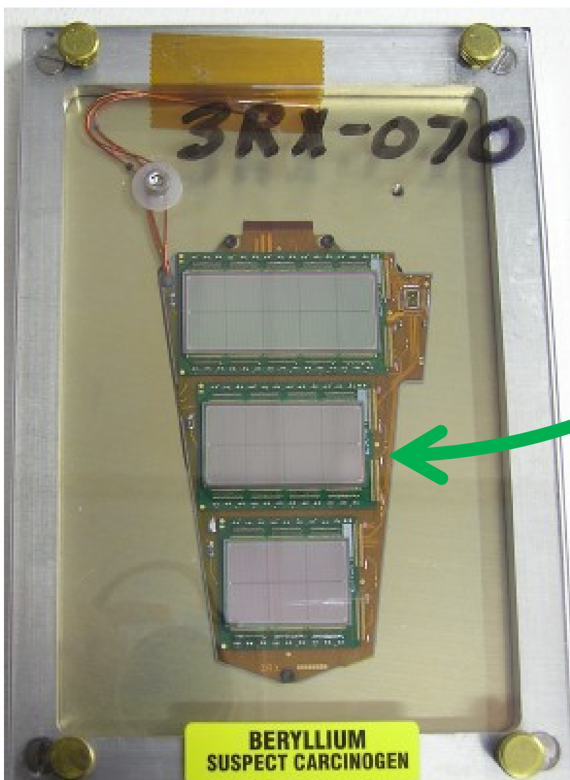




- PSI design, manufactured by IBM
  - 0.25 µm process, ~1.3 million transistors
- 15840 ROCs, 4160 pixels/ROC
- Automatic zero-suppression
- Double column drain architecture
  - Hits buffered until trigger decision arrives
  - Single 25ns-wide bunch-crossing (BX) readout
- 40 MHz analog readout
  - Analog pulse height
  - Other info encoded in analog signal
    - e.g. hit pixel address in base-6

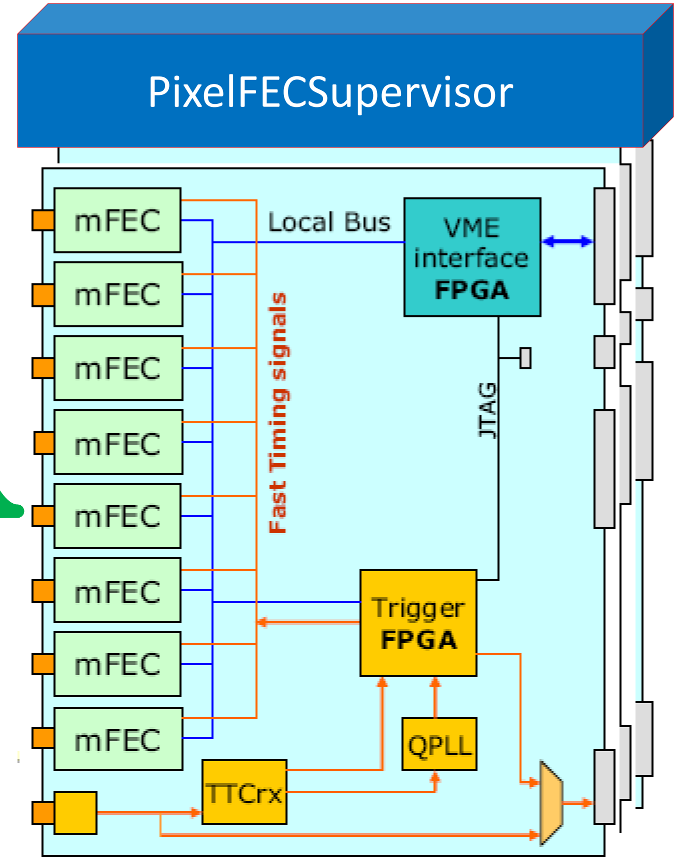
**~ 66 Millions Pixels in the system**

# Controller









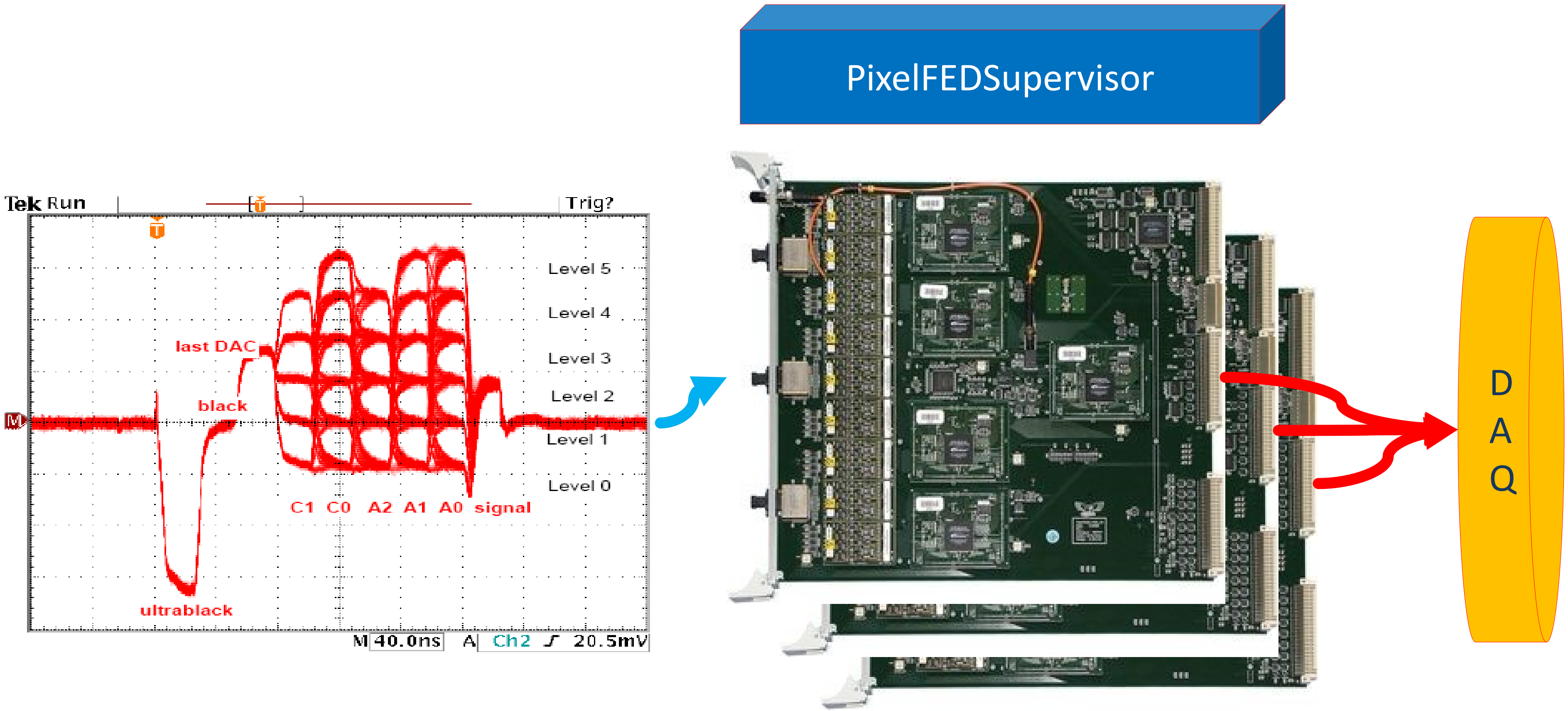


- Control signals consist of
  1. Clock & L1 Trigger
  2. $I^2C$ Commands for programming

- Using $I^2C$ commands we can program various DACs on each ROC, set trim bits on each pixel and inject charges for calibration purposes.


3

# Digitizer and data readout



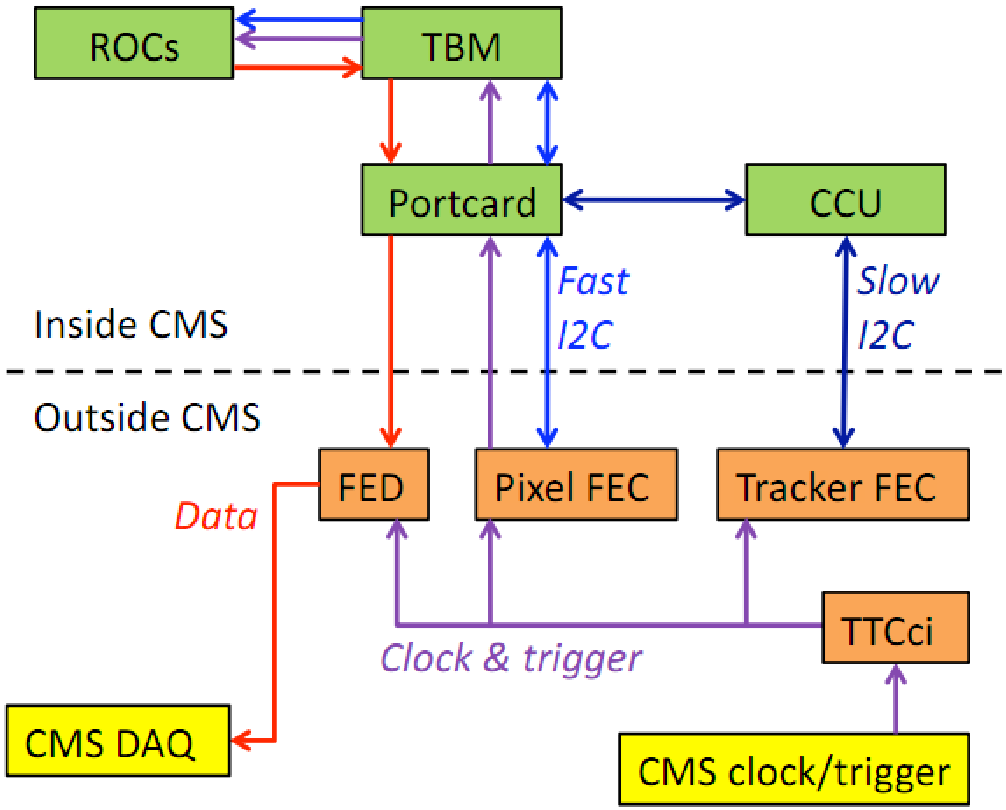

•Pixel Front End Driver (FED) digitizes analog signals given the level thresholds for decoding.

•One crate of FED boards is controlled by one PixelFEDSupervisor application. 40 FEDs in Pixels.

•FEDs send digitized data down S-Link cables to the Data Acquisition System (DAQ).

•FED data may also be read out via VME by the PixelFEDSupervisor.

# Schematic view: DAQ




**Pixel Online Software**

- Configures ROCs & DAQ before running
- Monitors DAQ status while running
- Implements calibrations

The Pixel Online Software controls these **VME devices**.

**Front End Driver (FED):**

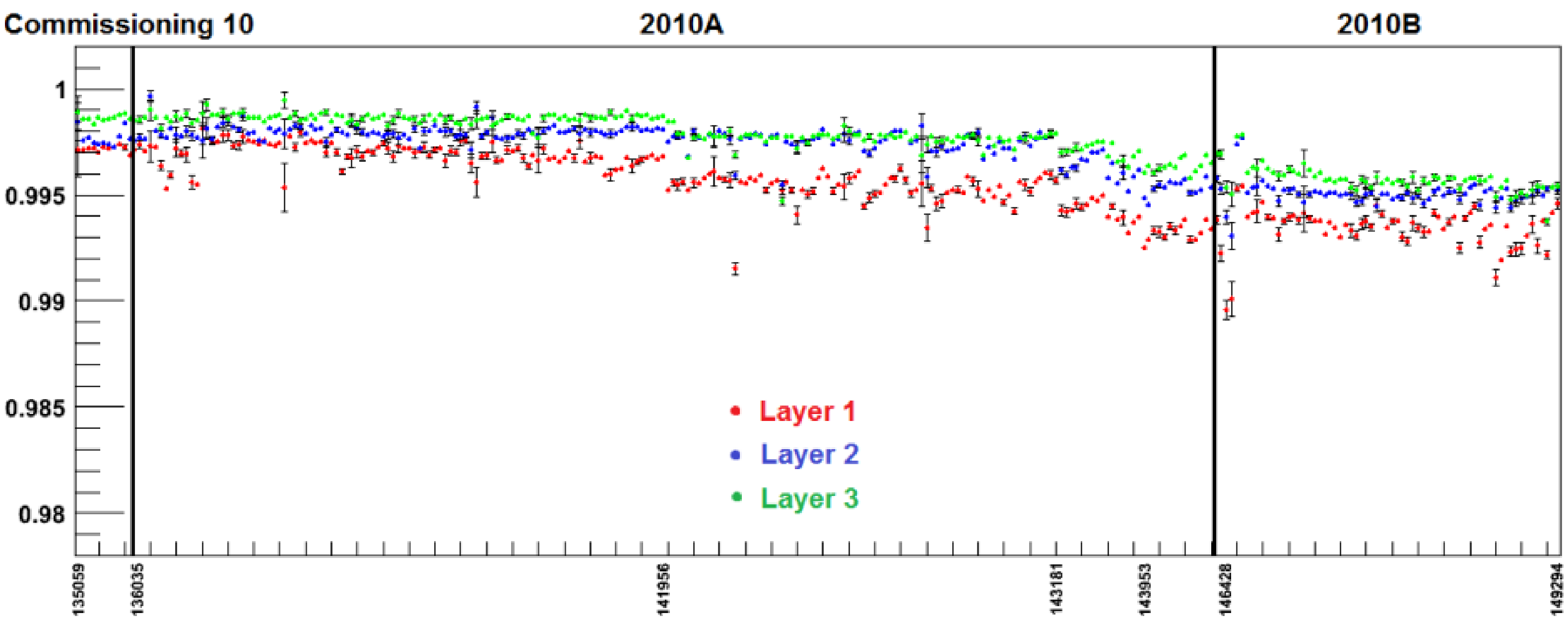
- Receives optical data signal
- Digitizes and sends it to CMS DAQ
- Must be triggered to read & send data!

Important note: there is no internal (to the pixel system) communication from the FED to the FEC. Such communication exists only via TTS (Trigger Throttling System)

# Detector Performance: Efficiencies

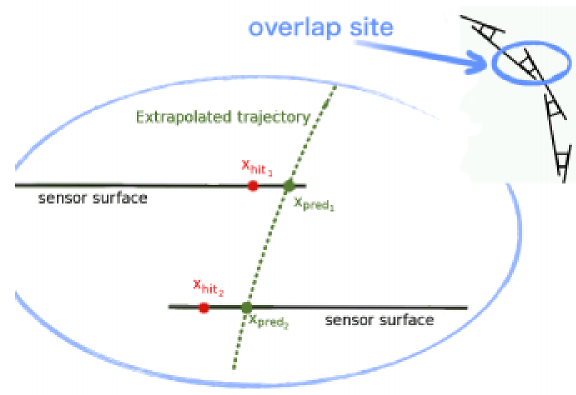
## Efficiencies in 2010 (new)

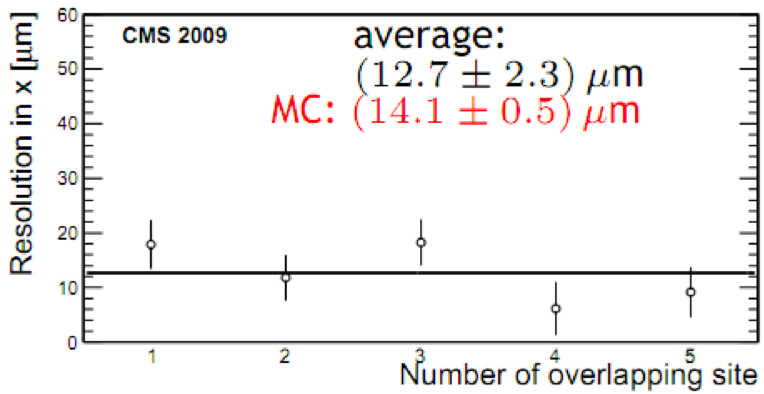
- 1% drop experienced starting with CMSSW 3_6_X is recovered
- Overall pattern similar to old efficiency – efficiency loss as function of luminosity is visible
- Inner layers experience consistently larger efficiency loss

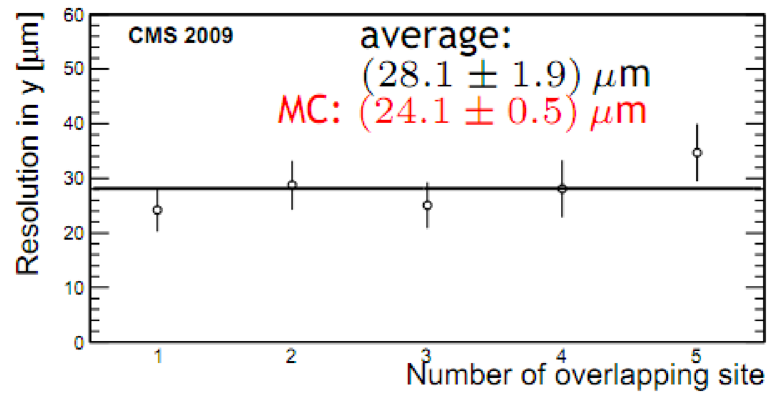


# Detector Performance: Resolution

- Method: Compute double difference
  - ▷ difference of measured hit positions
  - ▷ difference of extrapolated hit positions
  - ▷ difference of the two differences
  - → reduces sensitivity to
    misalignment
    extrapolation errors

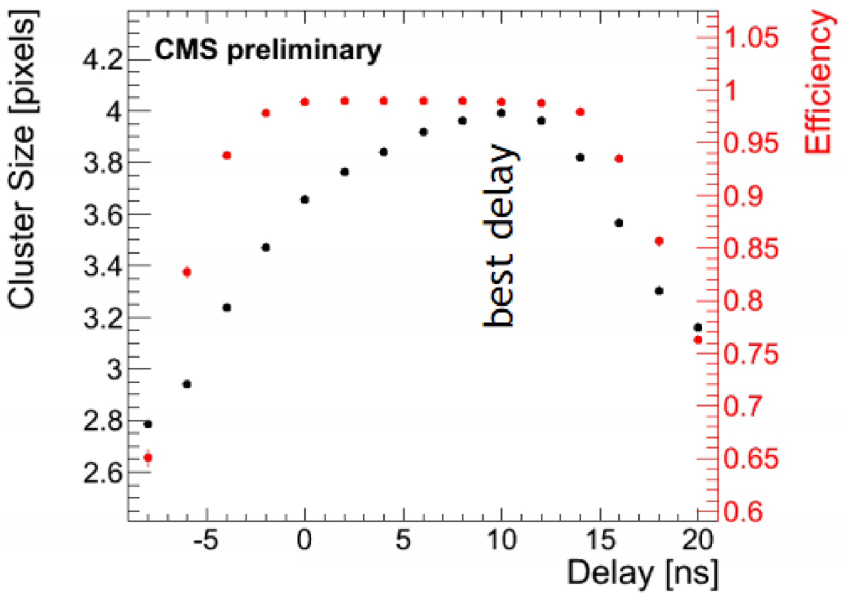



- Caveat: overlaps only at the edges of the track $\alpha$-acceptance
  - ▷ cluster $x$ sizes deviate from the optimal size (of two)
  - → the $x$ resolutions are somewhat worse than the typical $x$ resolution

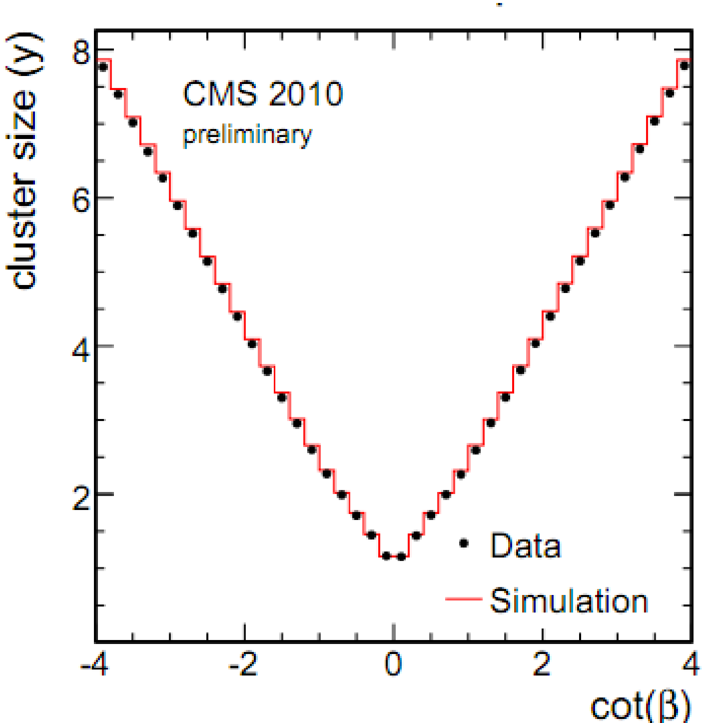
# Detector Performance: General




The detector is well calibrated

- absolute thresholds: $\langle T \rangle = 2457$
- in-time thresholds: $\langle T \rangle \approx 3200$

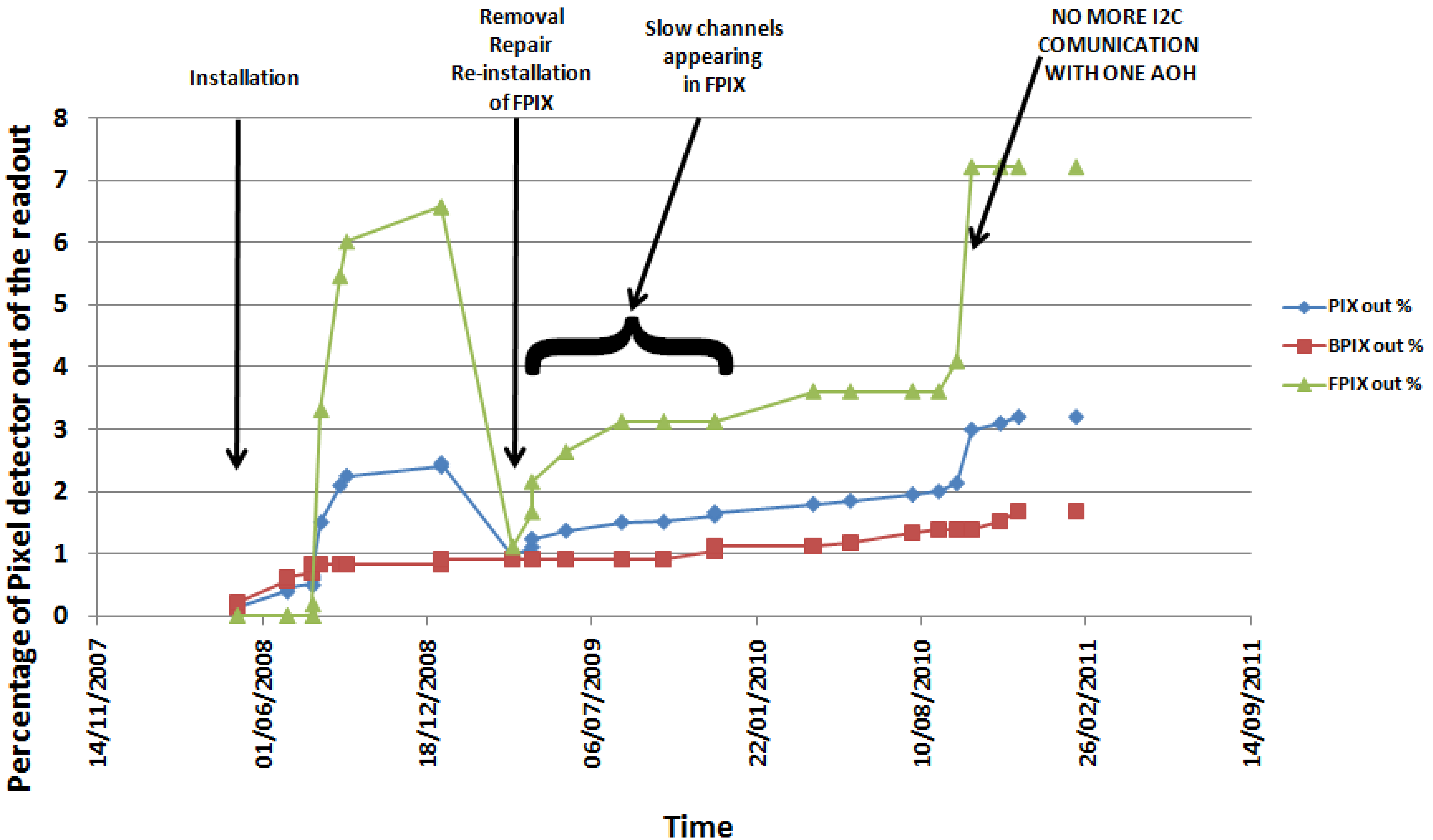
The detector is timed in with the experiment and with the accelerator



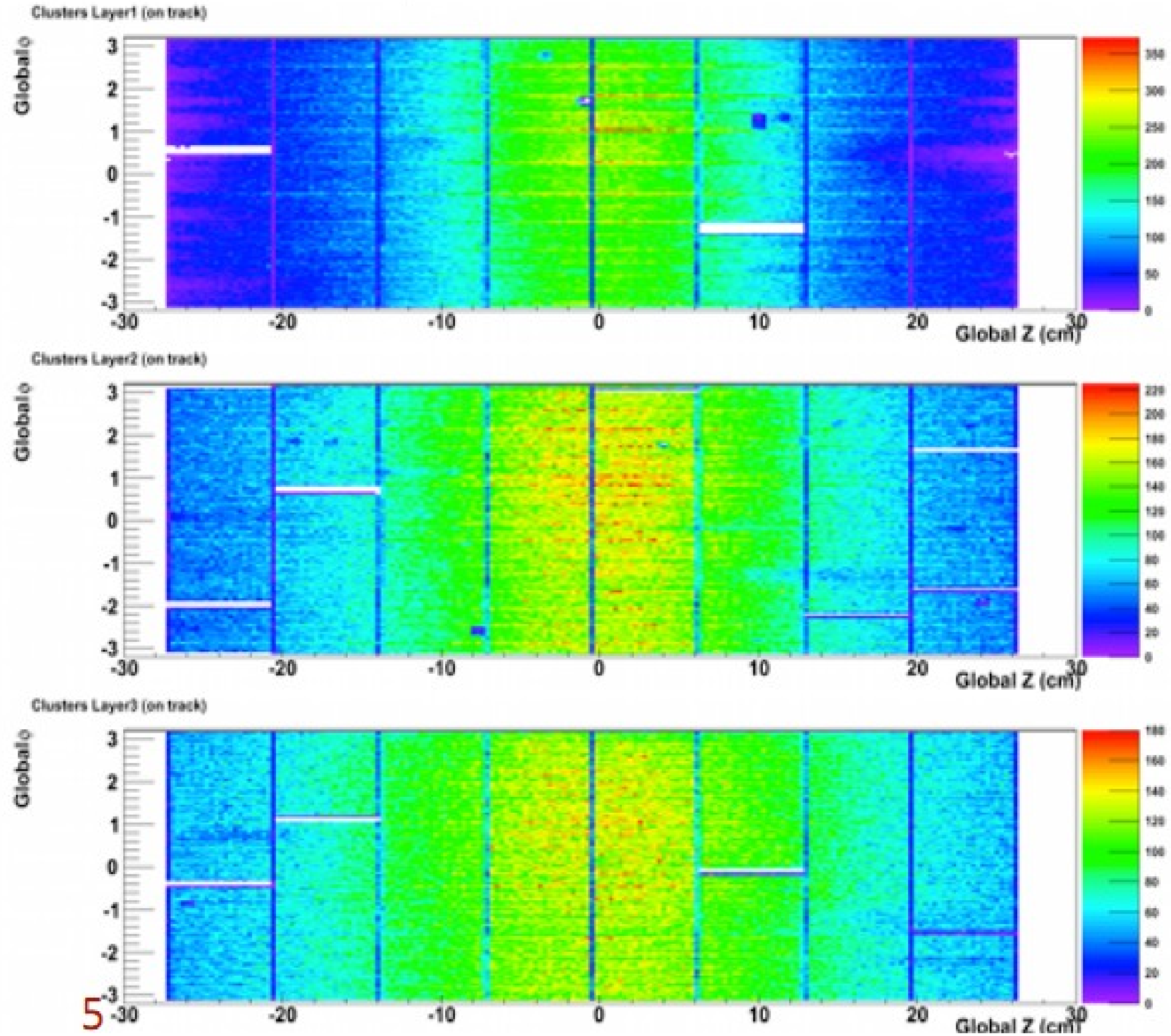

The detector is also well understood in simulations.

The detector is providing high quality data for physics analisys.

# Detector status



# Detector Status: Pixel Barrel




**Very few holes More than 98% operational.**

**Most holes are likely due to single wirebonds failures**

# Detector Status: Pixel Forward Disks

**Total of 14 panels out of 192 (7.3%) is not functioning**

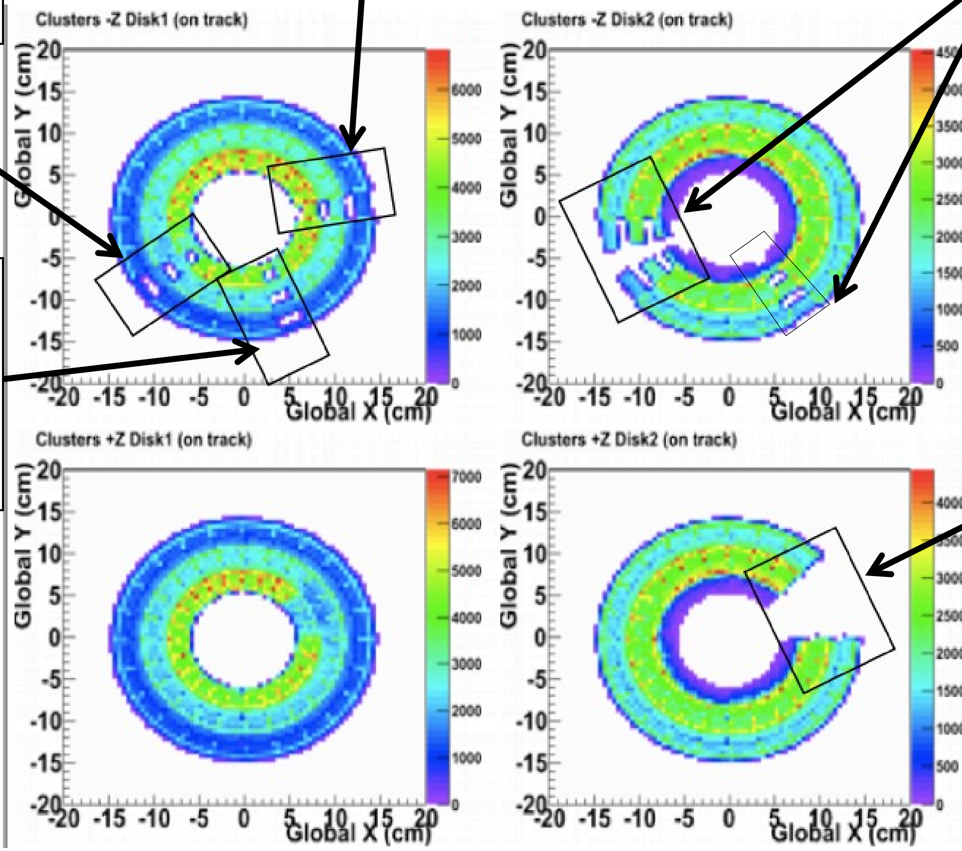
Too Low signal amplitude (TBM): 1/192 (0.5%)

No signal output: 1/192 (0.5%)

Slow panels: 5/192 (2.6%)

One ROC no-signal: 1/192 (0.5%) Recoverable with software effort.

No I2C communication with AOH: 6/192 (3.1%)



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# Some general remarks from operations (1)

**<u>Power supply system</u>.**

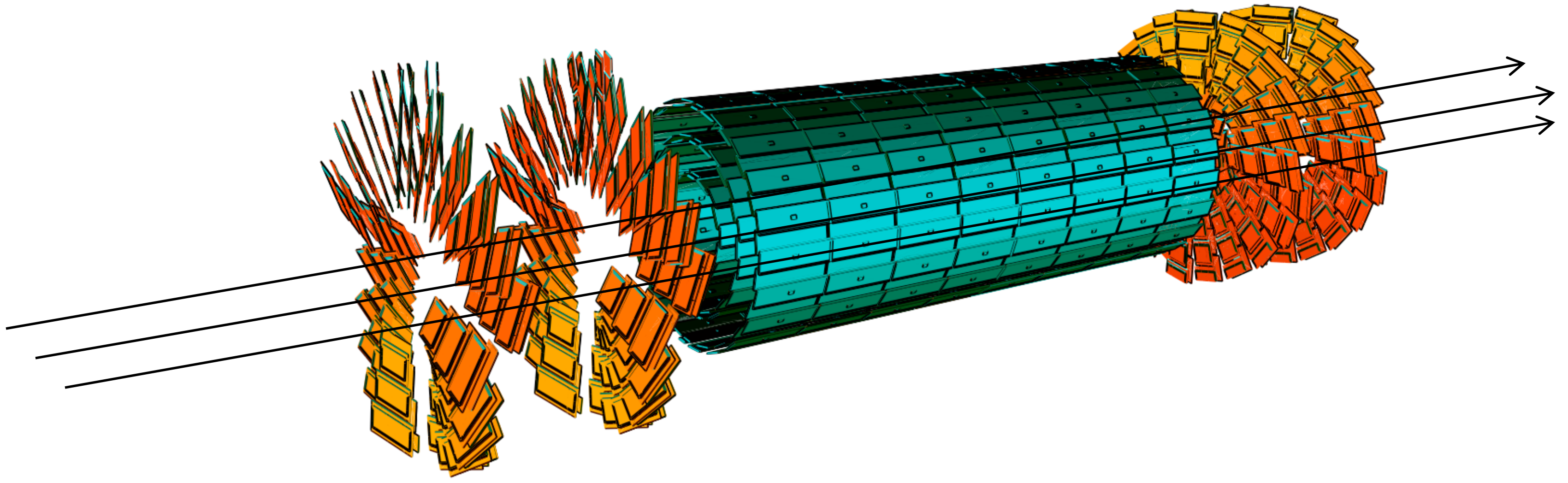
- **Very solid and robust.**
  - **19 months since the last replacement**
- **Low resolution on the current meters is hurting us**
  - **Vana DAC to set the current for the analog part should be tuned to ~25 mA per each ROC.**
    - **Quite hard to do with a resolution of 15 mA**
      - **Done by optimizing the difference between absolute and in-time thresholds (very lengthy process)**
  - **1uA resolution on the HV current makes it hard to monitor early radiation damage.**
    - **Operating now close to room temperature so leakage current changes are anyway visible**

**<u>Optical system.</u>**

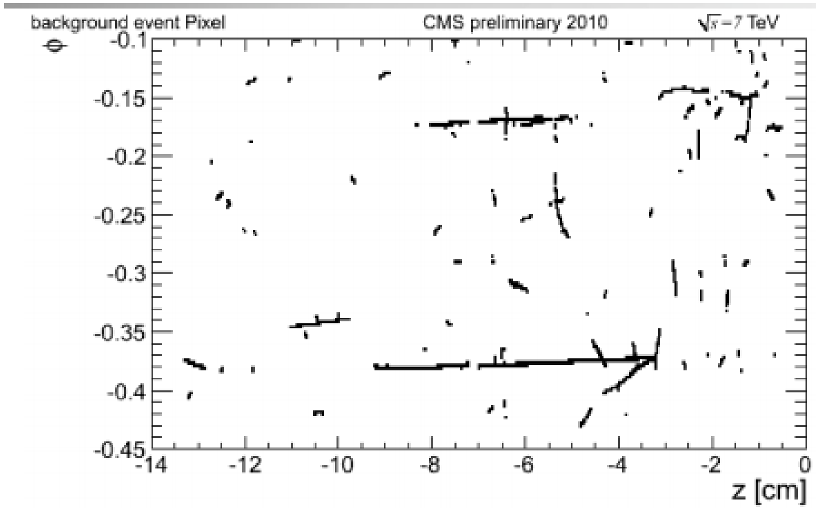
- **Very solid and robust.**
  - **Only one failure (could be the CCU).**
- **Long time to stabilize the output once the system is powered up.**
  - **1-2 hours before any useful data can be taken.**
  - **It would be nice to have some sort of active compensation circuit.**
- **Probably worth mentioning the long process of connecting/measuring/cleaning/reconnecting/remeasuring at every installation**

# Operational issues: Beam-gas interactions (1)

- **Beam gas interactions in the straight session of the LHC close to the experiment generates shower of particles that enter the pixel detector along the beam line.**
  - **Large number of pixel above threshold in the barrel if the track hits the sensor**
  - **Visible since early 900 GeV collisions (and even with single bunches passing by).**
  - **Implemented new FED firmware to dump the long events and hold-off triggers.**



# Operational issues: Beam-gas interactions (2)



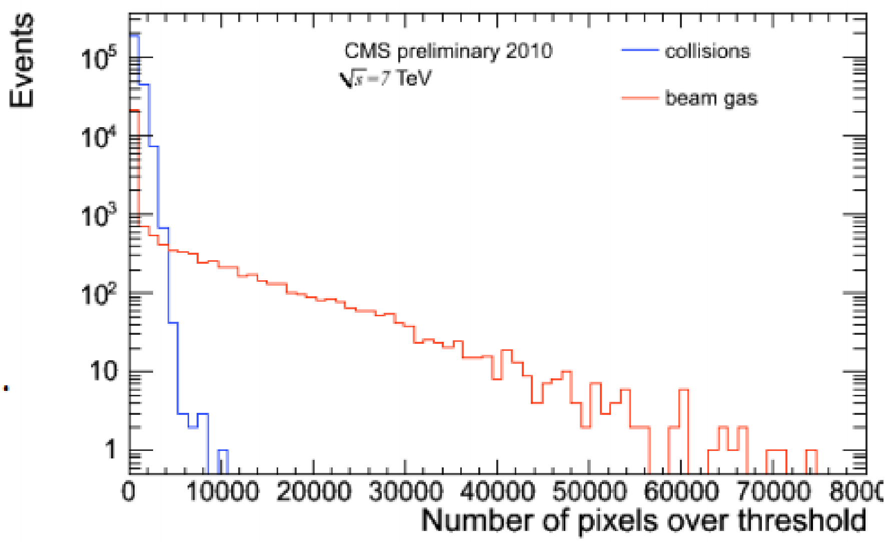

*occupancy map from a single event*

**Beam-background events:**

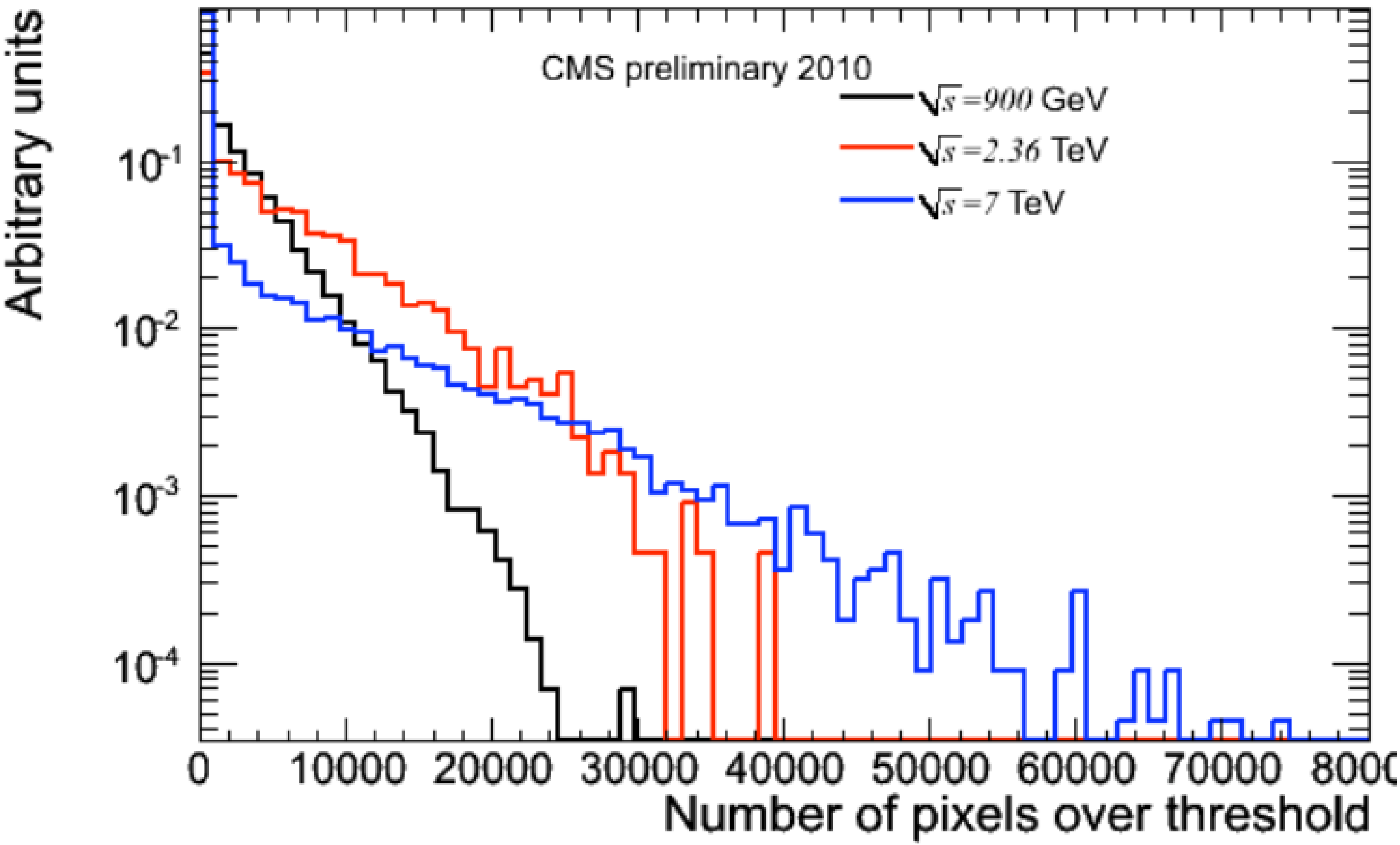
- We observe showers of particles that graze the detector along the beam axis (z).
- They occur coincident with bunch crossings.
- These events are consistent with beam interactions with gas in the beam pipe.

**These events:**

- lead to a *huge* occupancy, especially in the barrel layers.
- impose challenges to maintaining event synchronization, especially at high trigger rates.

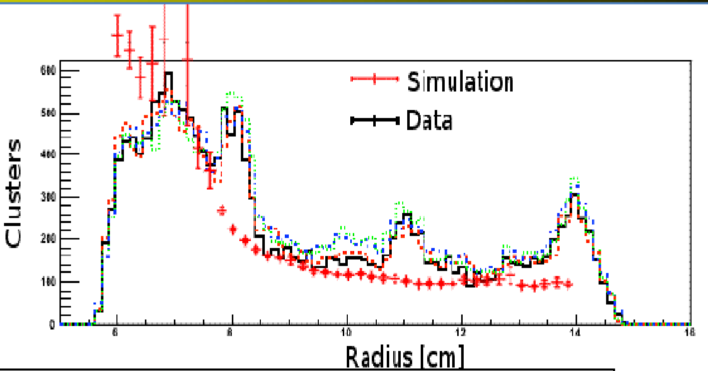


# And the effect will gets worse in the future



# Operational issues: Beam-gas interactions (4)

- **This effect is predictable with Simulation**
  - **But was not taken into account during the construction.**




- The problem: Reading in a large beam background event can block one or more FED inputs for a long time. All of the hits must be read in! Meanwhile, the FED is triggered for the events that follow the beam background event.
- The effect: The events that follow the beam background event eventually come, but not when they are expected. If nothing is done, the FED inputs are out of synchronization forever.
- The solution:
  - Part 1: Drop the events that did not arrive when expected.
    - Synchronization is regained once all of these events have been dropped.
    - Works well at lower trigger rates. However, at higher trigger rates, more and more events must be dropped.
  - Part 2: If many events must be dropped, pause the CMS trigger so that no more events must be dropped and the FED can take the time required to resynchronize itself.
    - Works well at high trigger rates.
    - Causes only ~ 0.5% deadtime.

# Operational issue: Data corruption in the FEDs

While going through several interactions on the FED firmware to deal with the Beam-background events we started to experience several form of internal (to the FED) data corruption.

- Increasing luminosity (trigger rate and occupancies) imply higher data traffic in the boards

At first the we pointed to new bugs being introduced during the firmware upgrades. (long saga of deploying/rolling-back firmware)

This was a major source of downtime for the experiment.

- CMS DAQ (central) does not forgive any mistake
  - Single Event number out of sequence for example.

- Problem was solved in August 2010
  - Simply by lowering the slew rate of the FPGAs output.
    - Pointing to internal noise in the board.

- From a (the) major source of downtime for the experiment the pixel disappeared from the accounting sheets.
  - Good strategy to “push” the CMS system to the highest possible trigger rate since the beginning (trigger on anything that moves).
    - Problems were found and solved before the “high” luminosity period of 2010.
      - Integrated lumi lost in the 0.1% level.

# Operational issue: TRE Trapped Readout Error

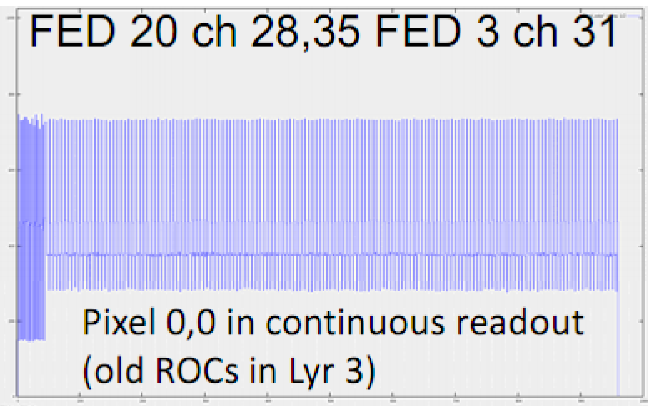
Trapped Readout Error (TRE)

This is a problem with the ROC that was identified and solved back in 2005.

Implied a new ROC submission

Unfortunately due to schedule constrains a handful of modules with the "old" ROC where installed in the barrel L3.

FED 27 ch 36, FED 21 ch 34, FED 20 ch 28,35 FED 3 ch 31



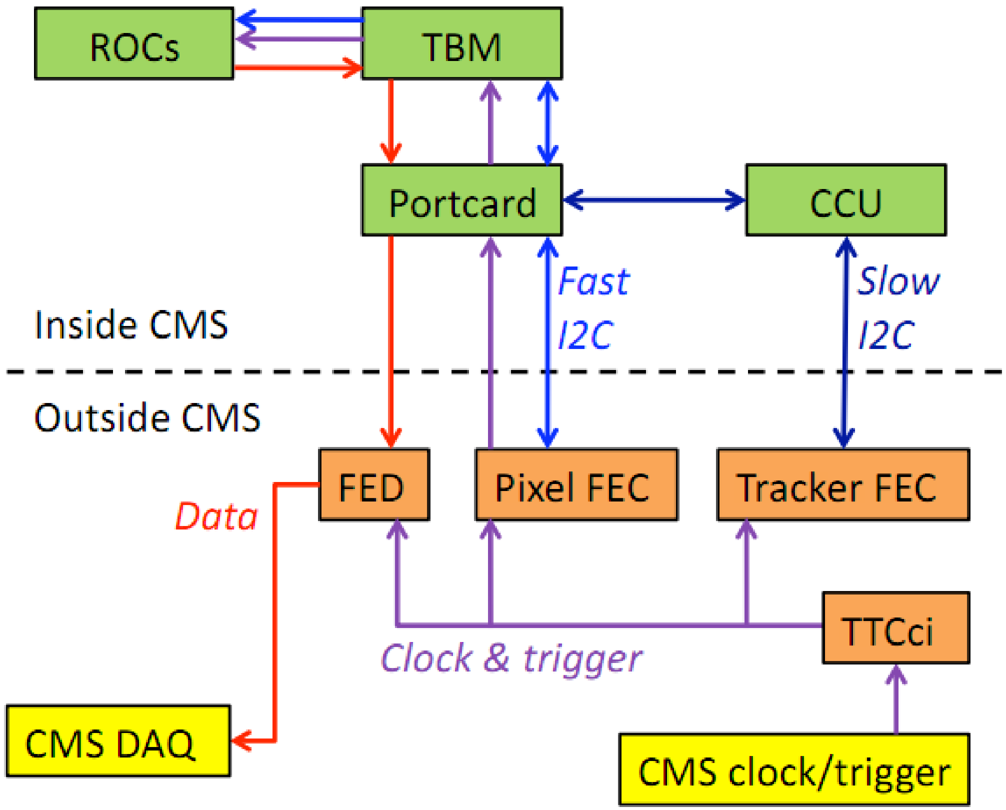

While reading out an event the ROC start sending out a illegal repeated pattern of data.

The only way to exit the infinite readout is to send the ROC a reset.

We are still working on the most efficient mechanism to detect the problem when it appears (FED) and to send a ROC reset.

- Work ongoing this days.
- Would be much easier if controller and data-receiver were in the same board.

# Schematic view: DAQ




**Pixel Online Software**

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**Front End Driver (FED):**

- Receives optical data signal
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- Must be triggered to read & send data!

Important note: there is no internal (to the pixel system) communication from the FED to the FEC. Such communication exists only via TTS (Trigger Throttling System)

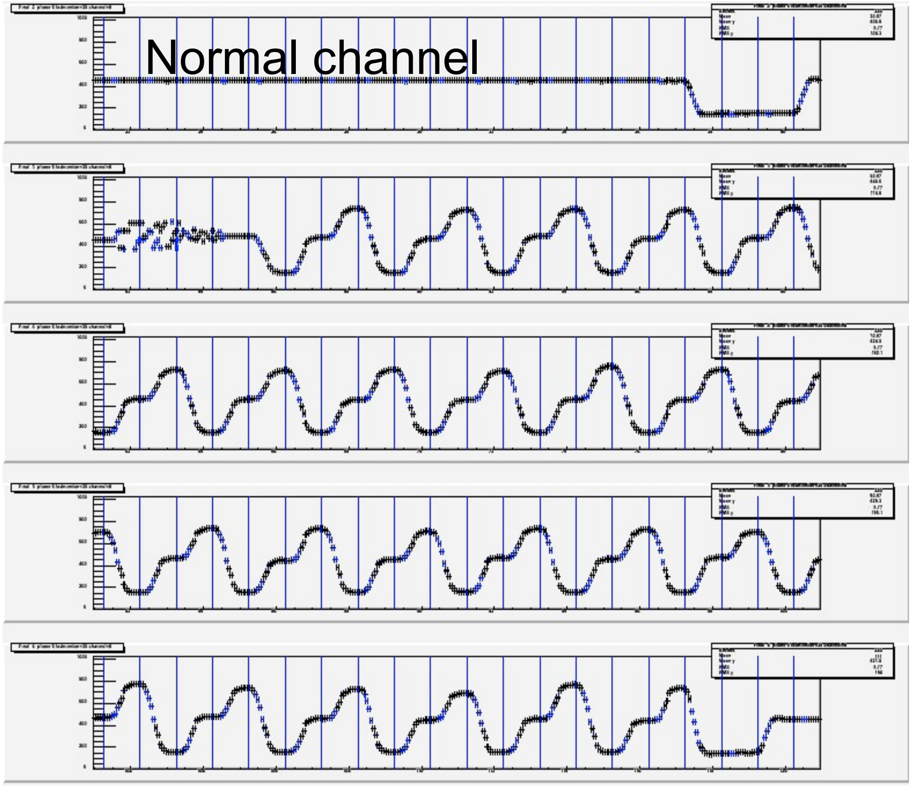
# Some final remarks: I cannot call it conclusions

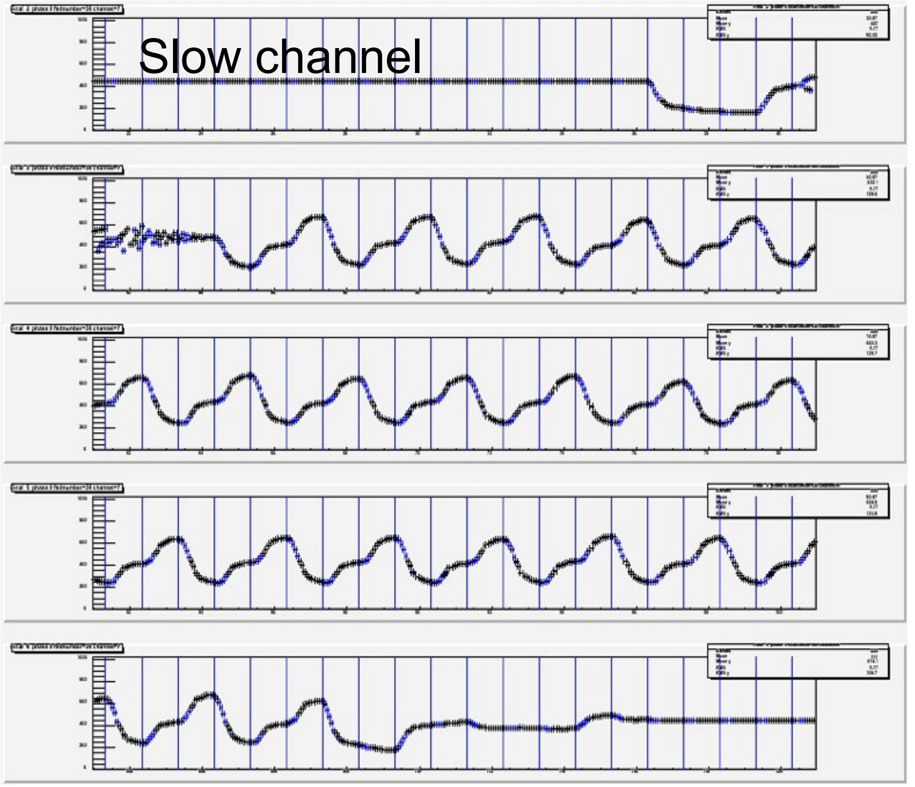
- The detector is performing well even if there is a non-zero mortality rate
  - CMS can take advantage of 3-4 months shutdown to perform maintenance to the system
    - Extraction/maintain/insertion/re-commissioning
- Infrastructures (power supply and VME hardware) are very robust and reliable.
  - For budget reasons the power supply system was copied from the strip system and it is not optimal for the pixel.
- The CMS pixel struggled during early operation.
  - Large occupancy induced by beam-background events were not fully considered during the design phase.
- There is a potential benefit by changing the architecture of the readout electronic by combining in a single board the controller and the data-receiver.

# SPARE SLIDES

# The "slow" channels

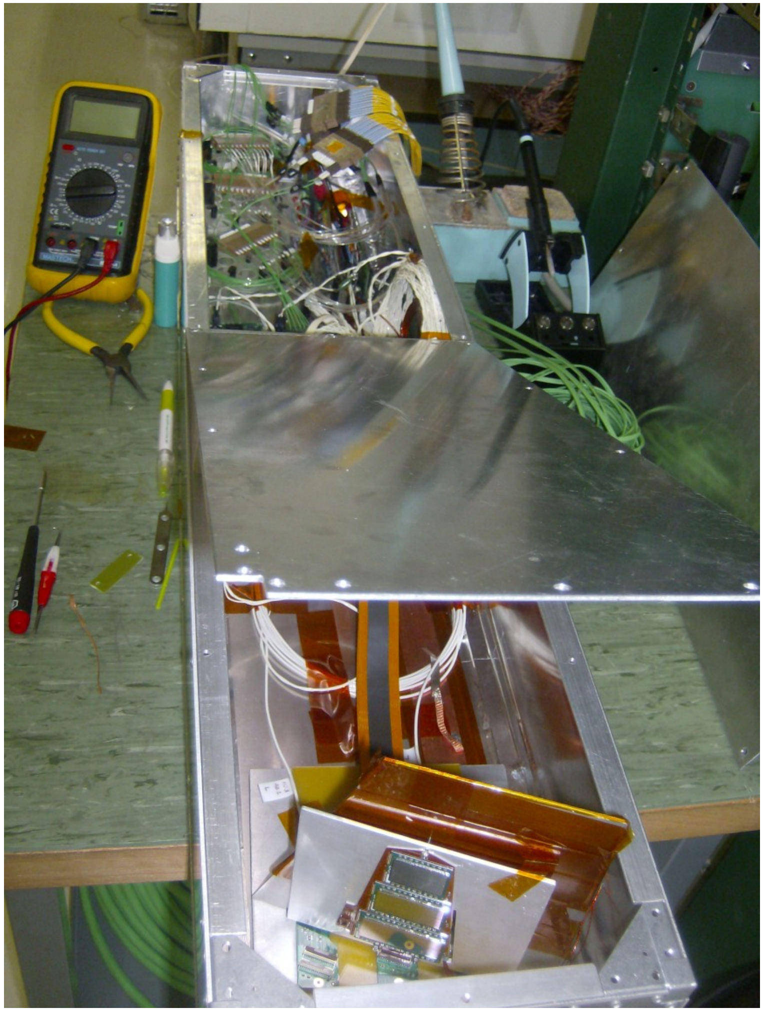
- 75% of the FPIX failures suffer from the same symptoms.
  - Low rise-time of the analog output signal.
- It is impossible to separate the address levels (Undecodable information)
- The CMS pixel system was inserted in CMS last summer



# The "slow" channels (2)

- **Long list of tests performed in the lab with spare components**
- **We managed to generate a long list of scenarios to be investigated**
  - **but none of them reproduce the symptoms as measured in the experiment.**
- **We are now trying to deal with the problem in situ**
  - **developing FED firmware modifications to:**
    - **measure the rise-time on the fly event by event from the TBM header (3 clock cycles long)**
    - **Event by event apply the measured correction to the address levels.**
- **Also considering removal/diagnose/repair of the FPIX MINUS during the 2012 shutdown.**



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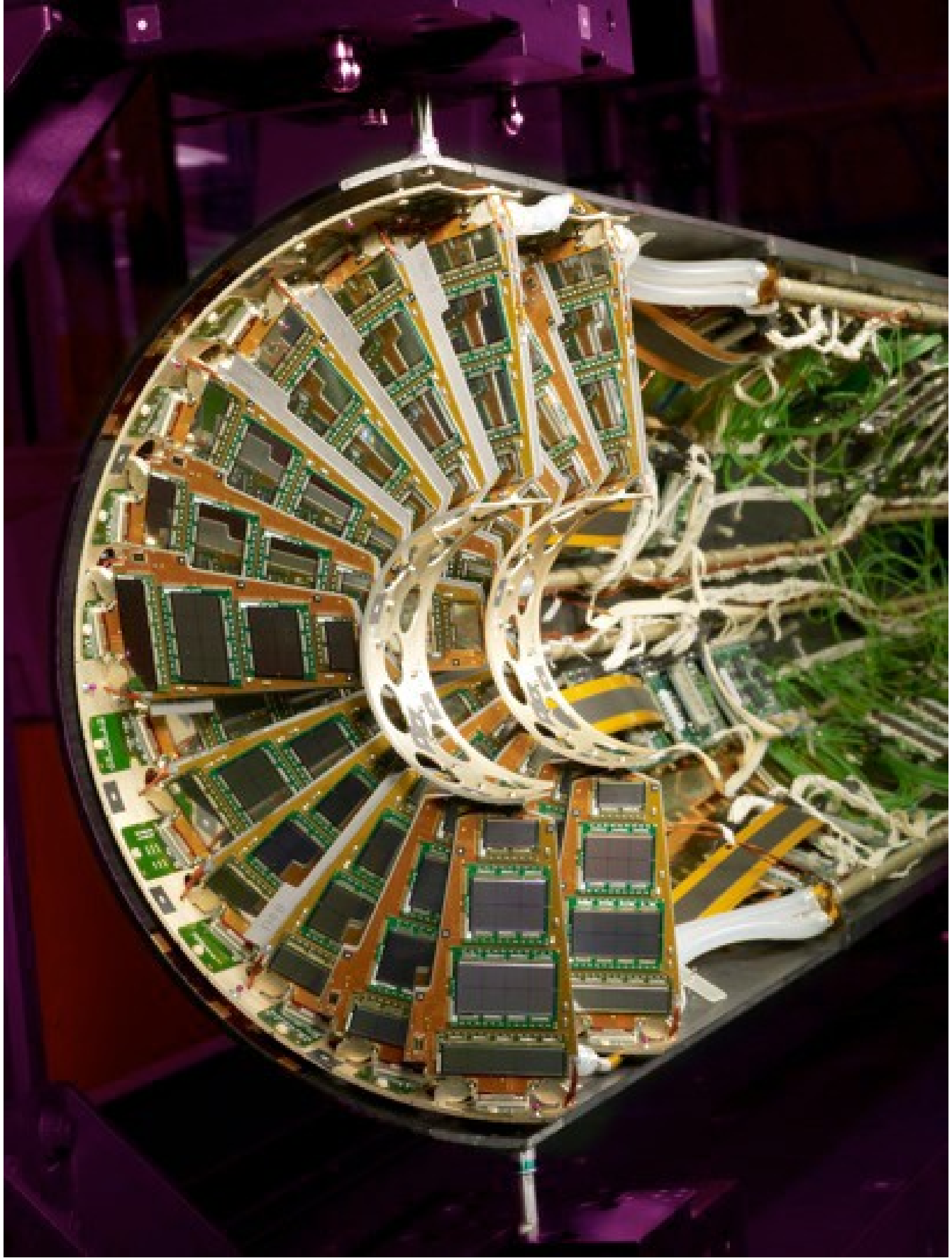
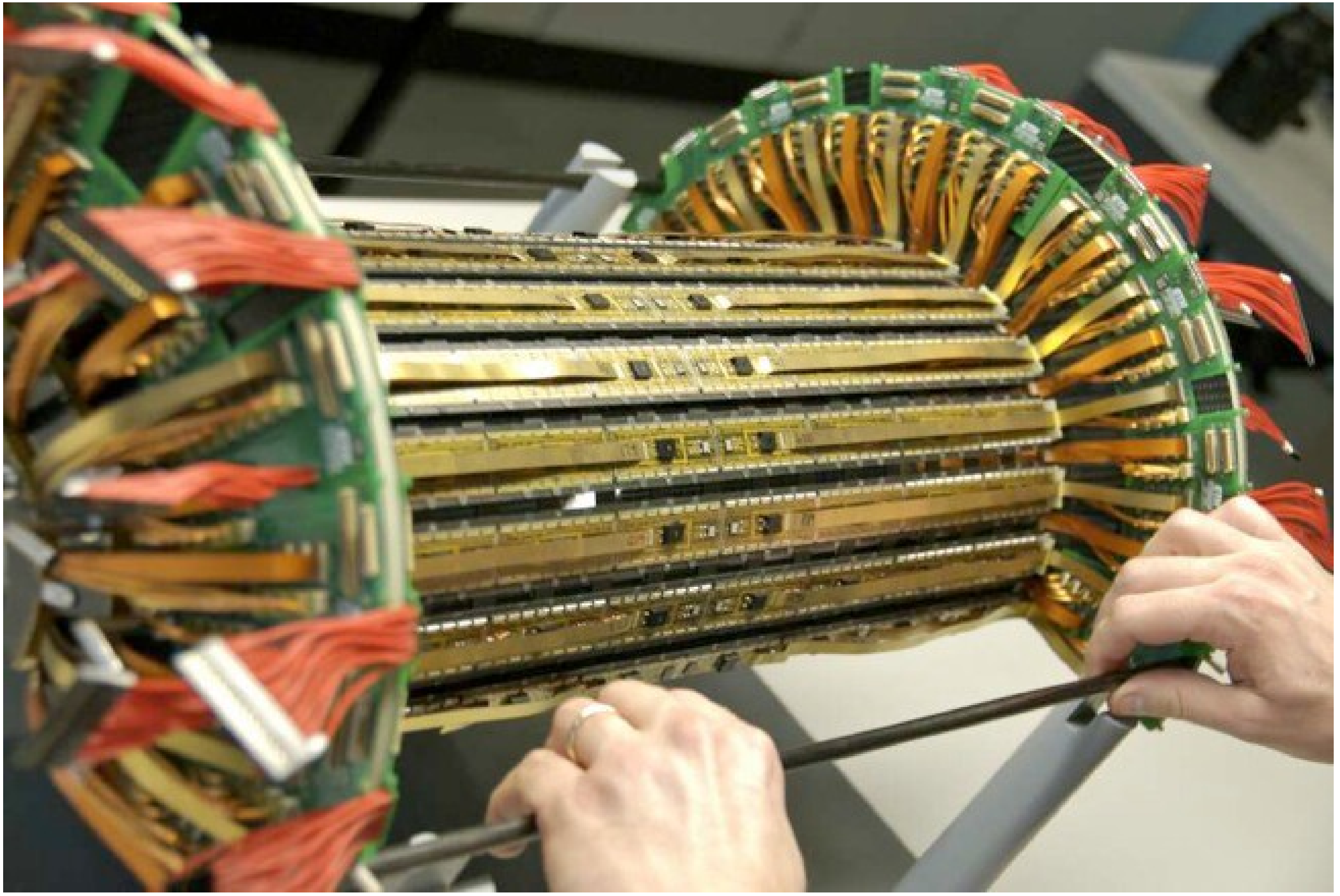
# CMS Pixel Disks

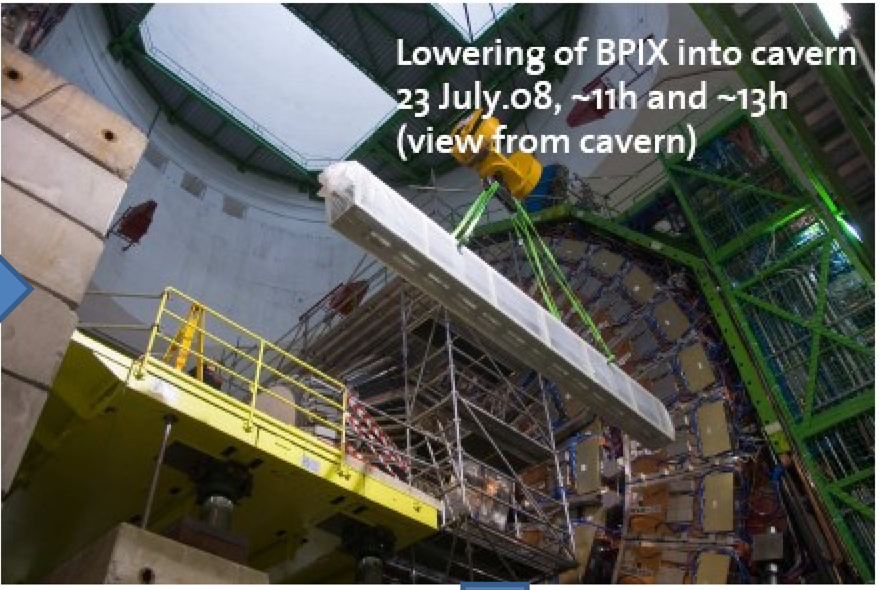
CMS
Compact Muon Solenoid



# CMS Pixel Barrel



# Installation in CMS

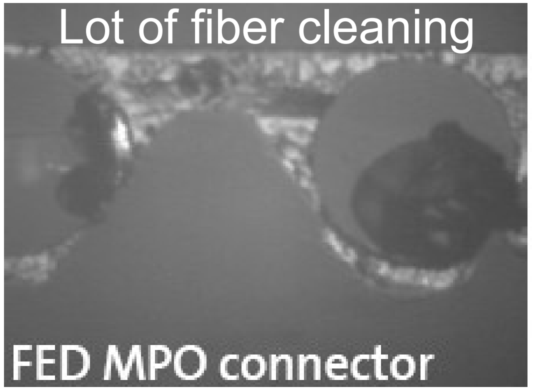


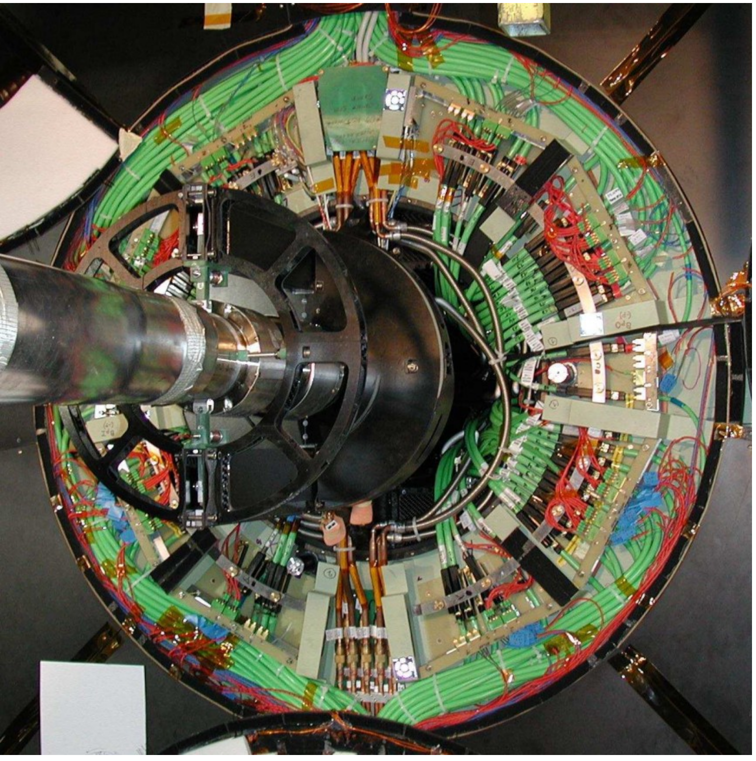
# Installation

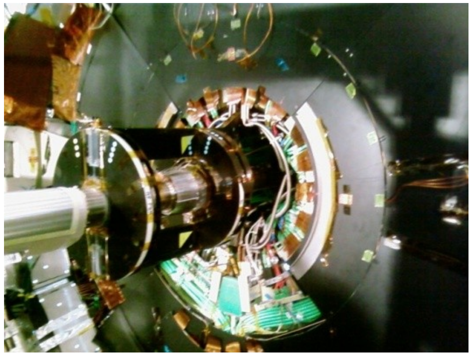
- Systems (BPIX and FPIX) slide on pre-build rails into the strip tracker bore.
- System latches in final position.
- Procedural process to the minimal detail.

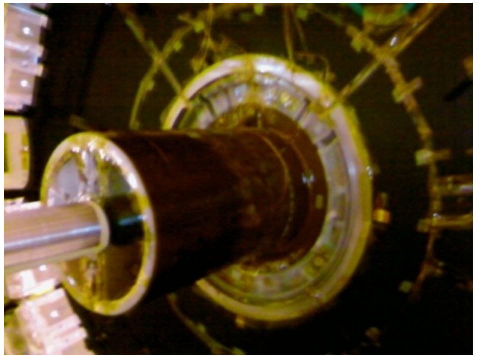
# Timeline (less than a couple of weeks total)

- Barrel Pixel (5 working days)
  - July 23th lowered in the cavern
  - July 29 green light for the insertion of the FPIX
- Forward Pixel
  - Lowered install and connected in 1 working day/side

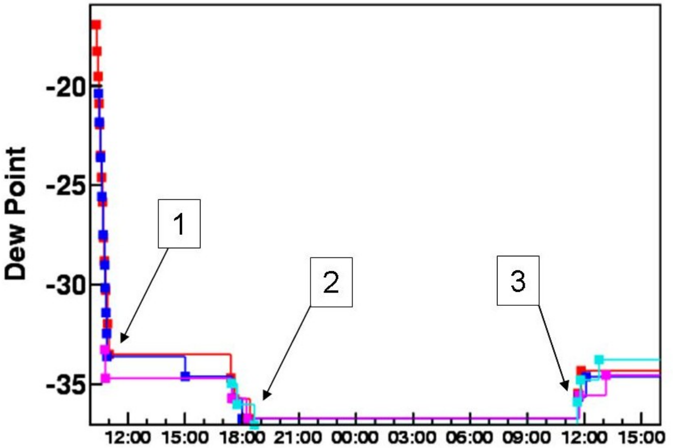




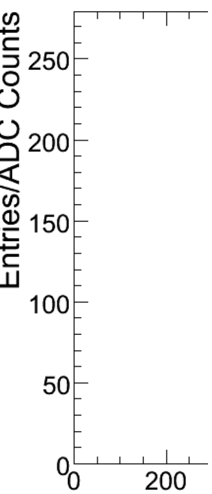


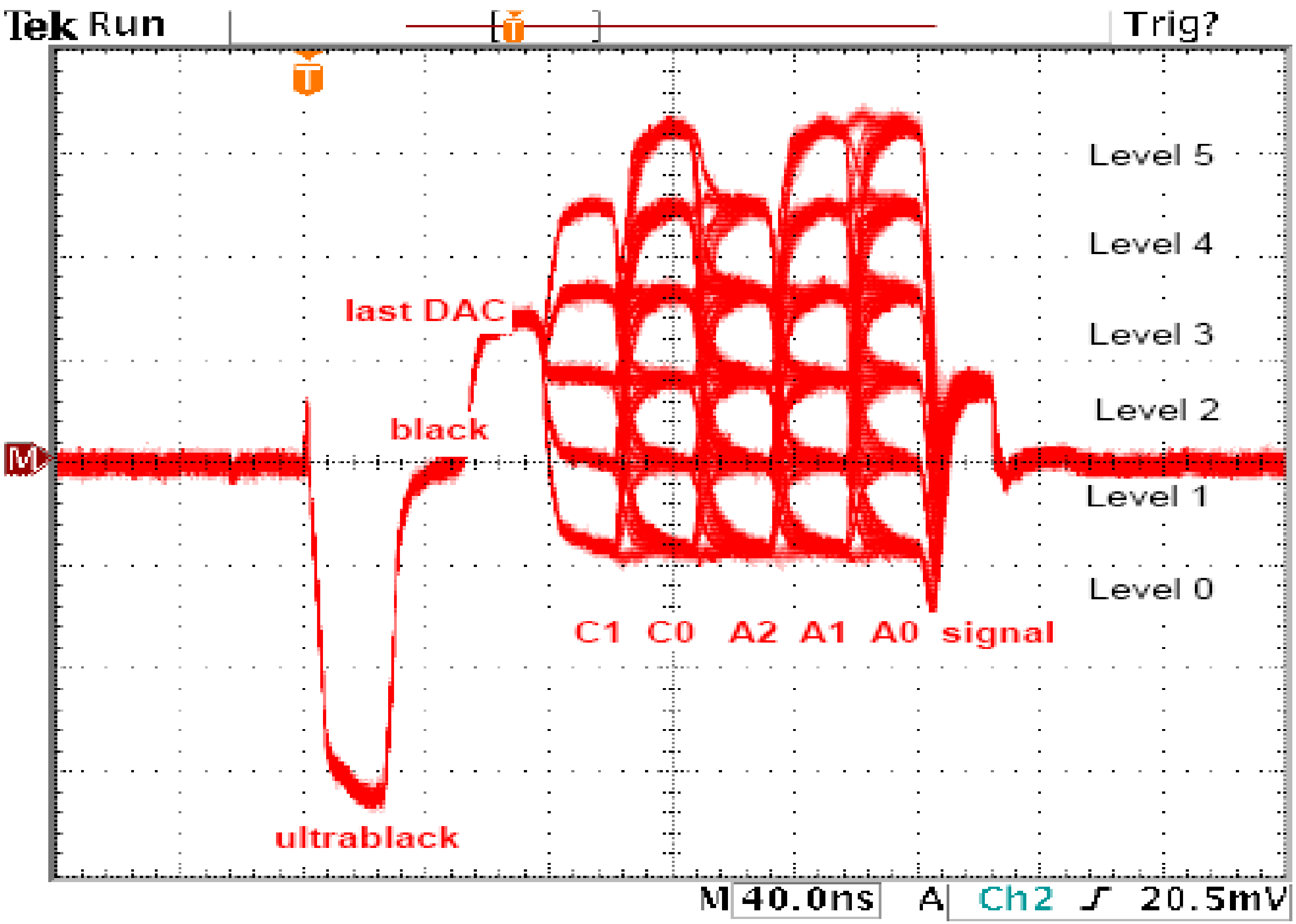
Final touch: a humidity seal to keep the detector dry

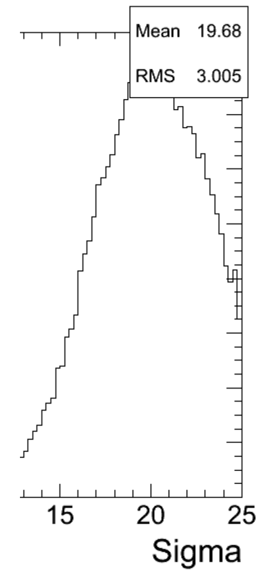


# Calibrations (addresses)

For each pixel hit, the address is encoded with a 6 level scheme over 5 clock cycles, the 6th one giving the charge.




Example ... ween the
peaks f ... ent peaks
... eak RMS

A l ... ning

# Final numbers of defects by the end of 2008

| | Pixels | Lost on surface | Lost later | Total | Single Pixels |
|---|---|---|---|---|---|
| Barrel Layers | 48M | 0.35% | 0.52% | 0.87% | 0.01% |
| Forward disks | 18M | 0.00% | 6.00% | 6.00% | <0.1% |

## 2008/2009 Winter shutdown

Decided to pull out the Forward Pixel detector to understand/repair the faulty 6%

- Already partially diagnosed in situ
  - One LV short
  - One HV short
  - One broken wirebond during insertion

# Repairs

- Two major problem to be solved:
- A HV to GND short
  - A single wire had its insulation cracked during installation and was touching the grounded carbon fiber structure surrounding it.
    - All other wires checked for this failure and no other action needed
- A LV short
  - Associated with bad crimping.
    - All cables on all four Half Cylinders were measured and re-crimped (if needed)

- **A number of connectors at the Filter Board end of the cables was replaced and new resistance measurements taken**

| mOhm | -Z2, 1.4 | | -Z2, 1.2 | | -Z2, 2.2 | | -Z2, 1.3 | |
|---|---|---|---|---|---|---|---|---|
| | before | after | before | after | before | after | before | after |
| Va+ | 30.1 | 28.6 | 54.2 | 28.3 | 29.8 | 27.2 | 32.5 | 29.5 |
| Va- | 33.3 | 28.6 | 86.9 | 31.7 | 30.6 | 26.1 | 30.6 | 28.6 |
| Vd+ | 43.7 | 28.2 | 31.6 | 29.6 | 34.2 | 27.1 | 33.8 | 28.8 |
| Vd- | 33.5 | 28.3 | 37.4 | 28.6 | 26.5 | 26.6 | 44.9 | 28.6 |
| mOhm | -Z2, 2.3 | | -Z1, 2.4 | | -Z1, 1.2 | | -Z2, 1.3 | |
| | before | after | before | after | before | after | before | after |
| Va+ | 52.3 | 27.7 | 55.1 | 27.6 | 33.1 | 28.8 | | |
| Va- | 21.5 | 26.4 | 26.5 | 26.3 | 29.4 | 28.8 | | |
| Vd+ | 28.4 | 26.4 | 26.9 | 26.9 | 35.7 | 29.8 | | |
| Vd- | 33.1 | 26.8 | 26.4 | 26.1 | 33.2 | 29.4 | | |

# FPIX Extraction/maintenance/repair/re-insertion

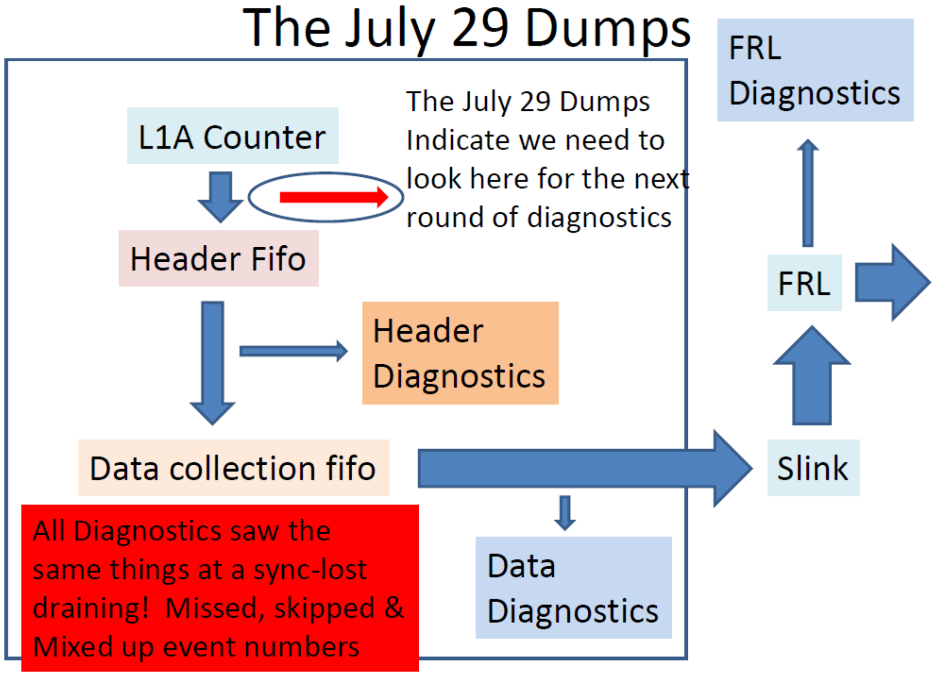
- Other achievements
  - Replaced silicon cooling hoses
    - Max pressure raised from 1.7 barg to 2.5 barg
  - Installed new humidity sensors
    - HS2000 sensors to cross-calibrate the existing HMX
  - Replaced back-feet on the Half Cylinders
    - Easier to remove/re-install
  - Implement cold-fingers for the AOH
    - Improve the thermal stability of the Analog Opto Hybrids
    - Allows longer time of data-taking without recalibrating the optical baseline
    - Reduce the consequences of the thermal coupling between pixel and the surroundings (TIB).
- The system was designed for “fast” insertion and removal.
  - Potential for yearly beam pipe bakeout procedure
  - <u>We have proven that within three months we can get the job done from beginning to end</u>.

# Pixel infrastructure: cooling-2

- **Stable good performance since refurbishment (early 2009).**
  - **Leak rate is negligible: No refill needed for the next 7-8 years**
  - **Recalibrated the Temperature sensors of the cooling plant.**
    - **Solved a long lasting mystery (3.4 degrees warmer detector than expected)**
- **Still Running at 7.4 deg C (coolant temperature)**
  - **What if the luminosity delivered exceed (by far) expectations and we accumulate *sizeable* radiation damage?**
    - **Can we go colder with the existing system?**
    - **Paola (CMS cooling coordinator) calculated that the present** cooling system is compatible with sub-zero operation **(Down to -5 -10 deg C).**
      - **Pixel is a small load for the C6F14 system**
    - **This assumes no changes in the operating temperature of the other tracker components (Strips). )**
    - **This week changed to -10 deg C**

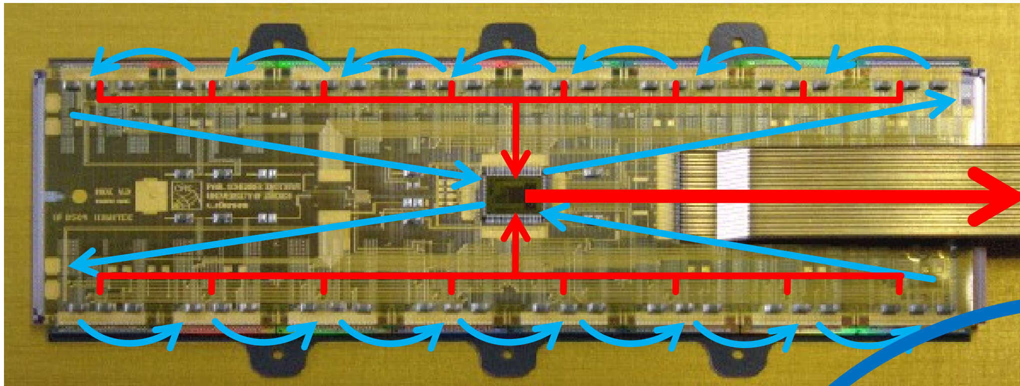
# Operational issues 2: Data corruption in the FED

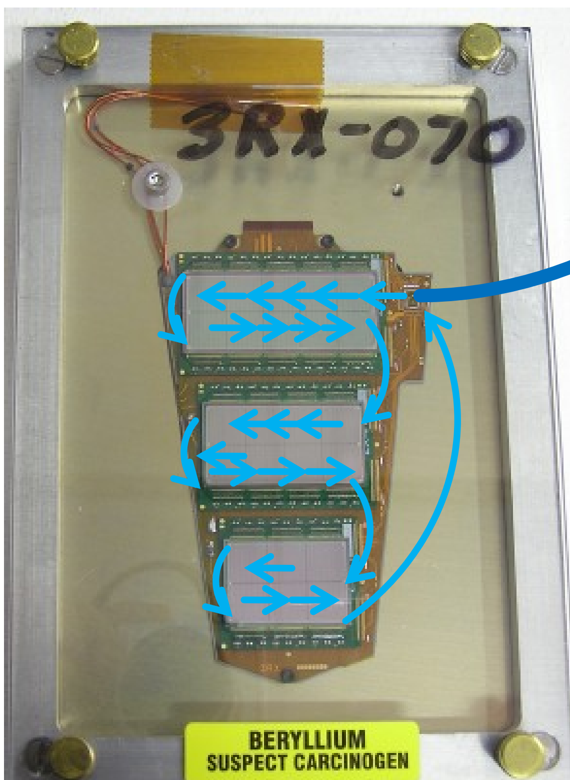
- In the last 5 months the Beam conditions changed by few orders of magnitude
  - Instantaneous luminosity from E27 to E31 (last week)
  - From 1 up to 38 bunches colliding at CMS
- L1 Trigger rates in the experiment grew accordingly from some to ~70-100 KHz.
- In the early summer it became evident that some data corruption was taking place inside the pixel FEDs (probably a coincidence that it started to show up with the firmware changes implemented to deal with the Beam background events).

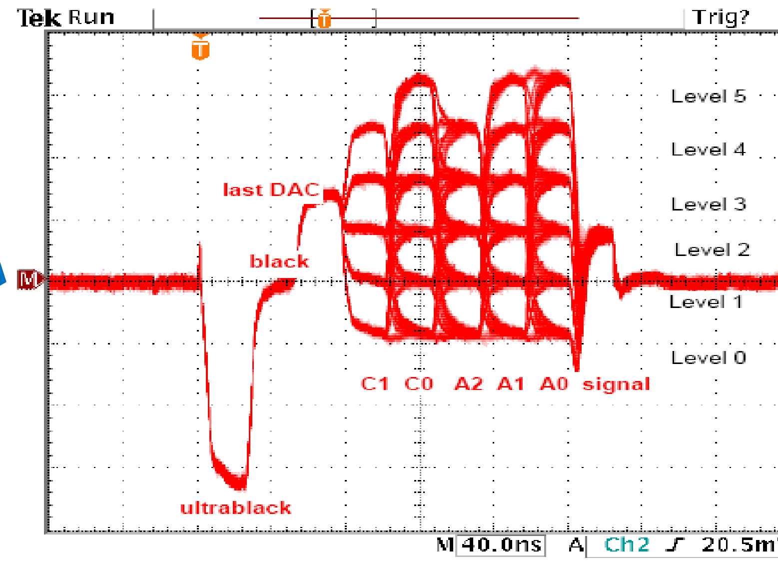



- For the first 6-7 weeks the problem was visible only during data taking with collisions.
  - Not visible with random triggers (but no data coming from the detector).
- Managed to reproduce the symptoms outside of stable beam by taking data with the HV OFF.
  - Sensor not depleted
  - Huge noise
  - Several pixel above thresholds

# Module readout






•On receiving a L1 trigger, the Token Bit Manager (TBM) initiates a Chinese-whisper of "token bits" that instruct each ROC to send its hit data to the TBM

•The signal from the TBM is electrical and analog. It encodes the ROC #, row and column and charge collected of each pixel hit

•The electrical signal from the TBM is converted to optical by the Analog-Optical Hybrid (AOH)


35