PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

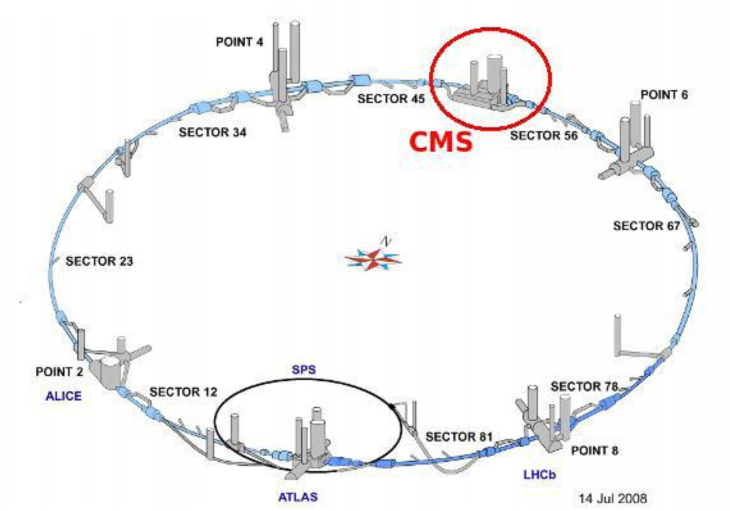
Tilman Rohe for the CMS Pixel Collaboration

CMS pixel operation and upgrade plans

The CMS experiment at LHC

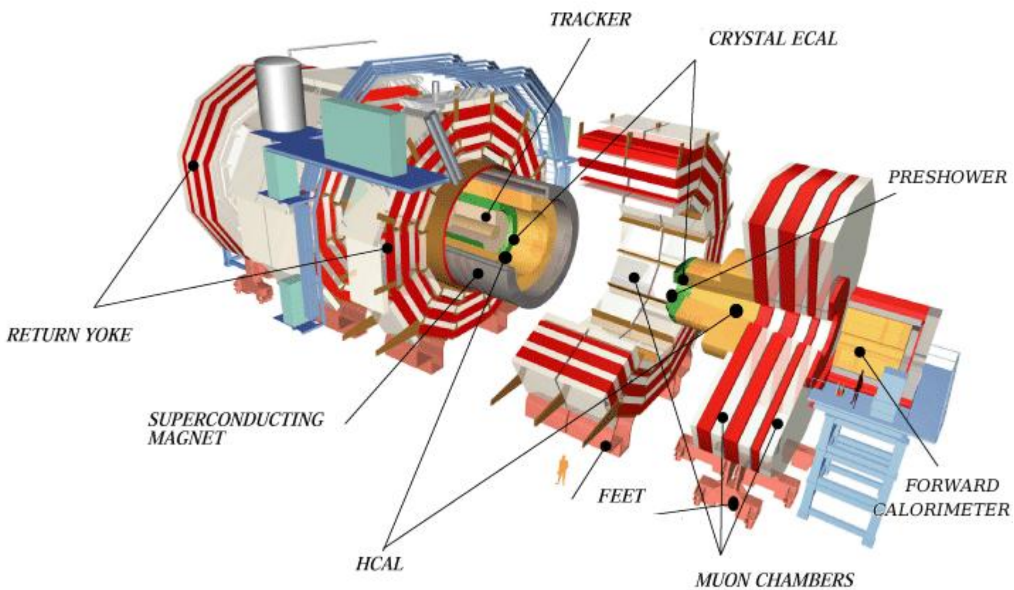
LHC:

- Ring with 27km diameter, 1232 superconducting dipoles (1.9 K)
- 2 Proton beams with 7 TeV each (presently 3.5)
- Nominal Luminosity 10^{34} cm^{-2} s^{-1}
- Bunch spacing down to 25 ns

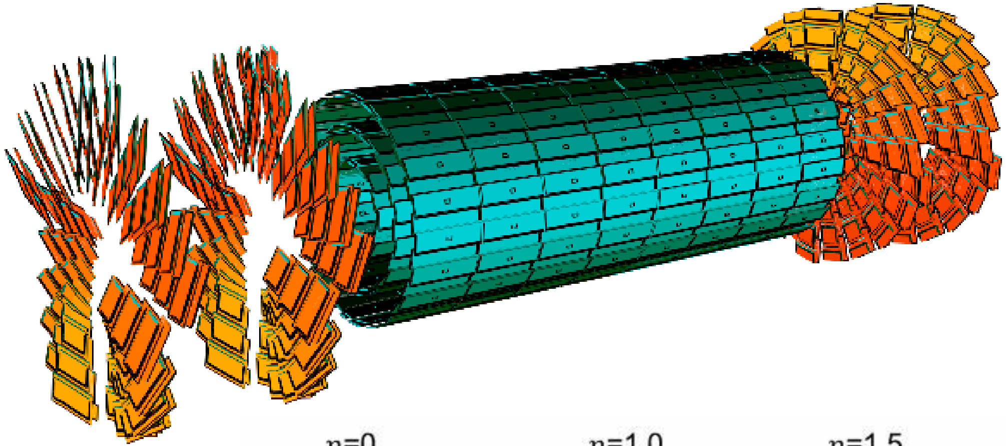


CMS

- Length 22m , diameter 15m, weight 12.5 kton
- Magnet 3.8 T, 6m diameter, 13m long
- All silicon inner tracker (3 pixel layers, 10 strip)
- Compact lead-tungstate ECAL
- “Conventional” brass/scintillator HCAL
- Muon-System in the iron return joke of the magnet



Pixel detector sketch



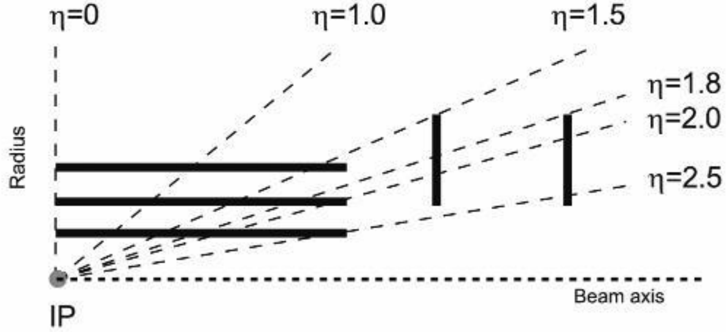
Barrel layers

- L=53 cm, R=4.2, 7.3 and 11 cm
- 768 modules 11520 ROCs, 48 Mpixels

Forward disks

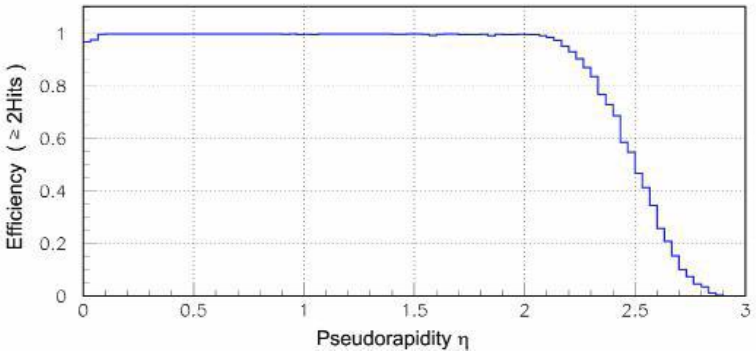
- Z=34.5 cm and 46.5 cm R= 6-15 cm
- 192 panels, 4320 ROCs, 18Mpixels

- Total area ~1.1m2
- 66 M Channels

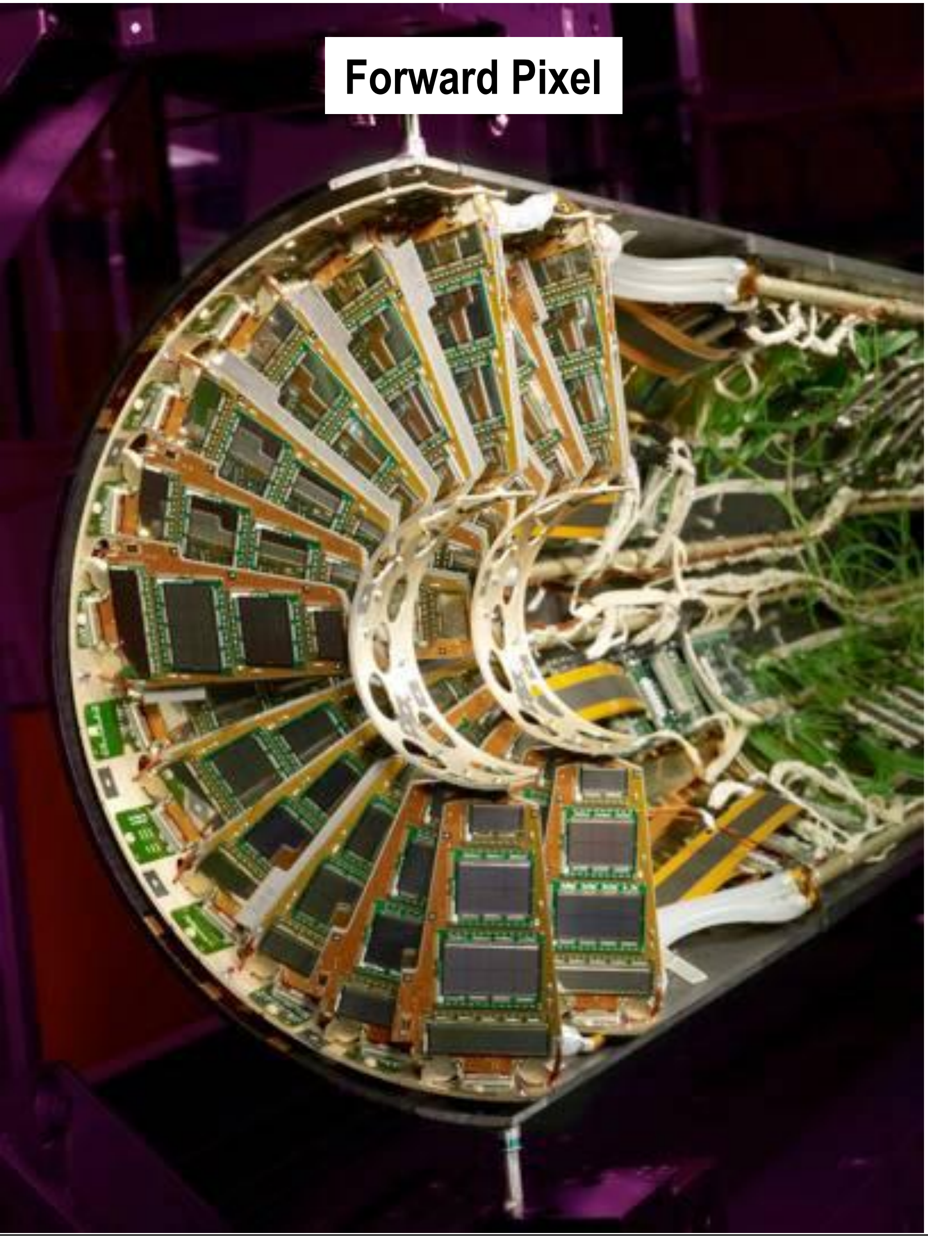


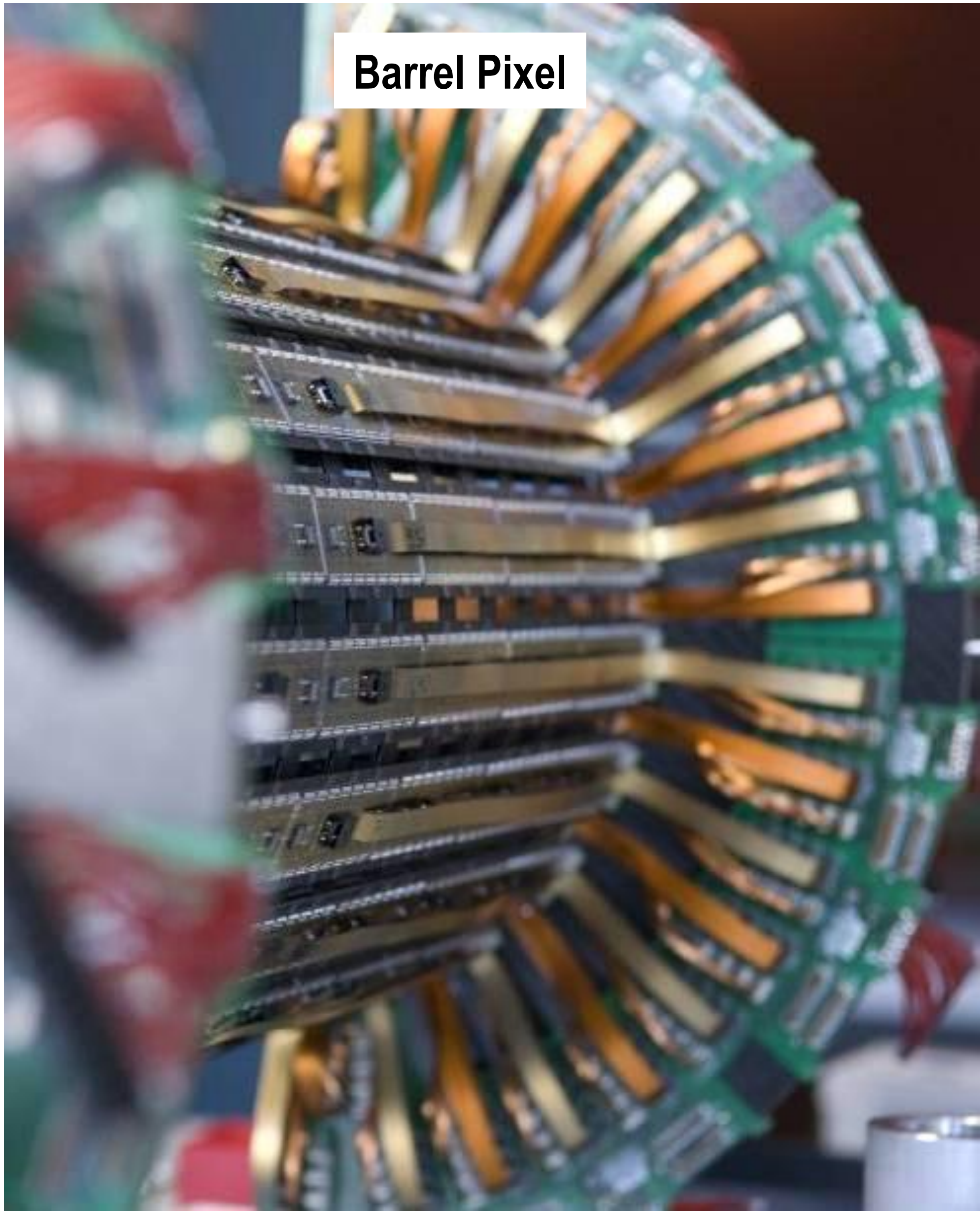
Coverage

- 3 pixel hits up to |η| =2.1
- 2 pixel hits up to |η| =2.5



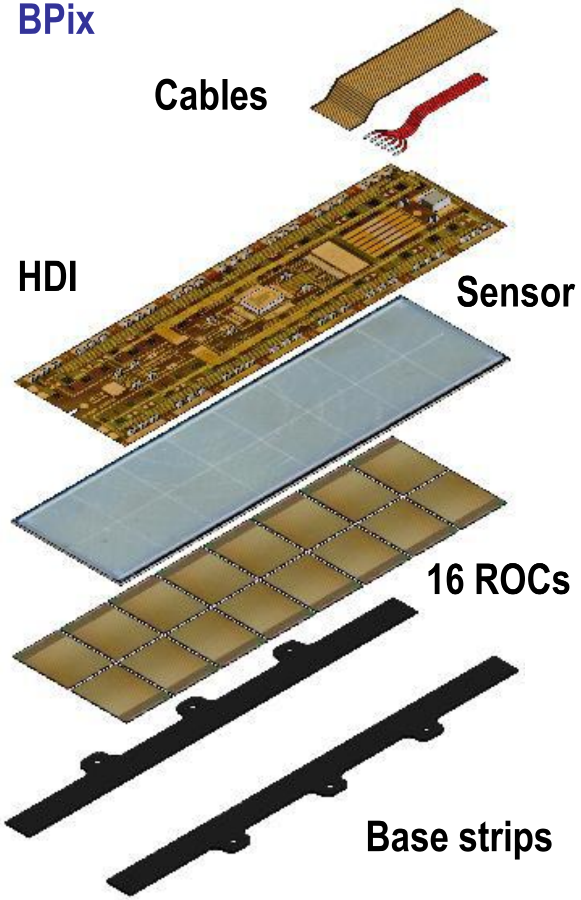
Pixel detector real

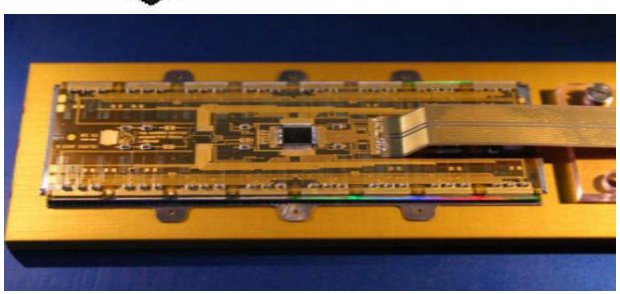




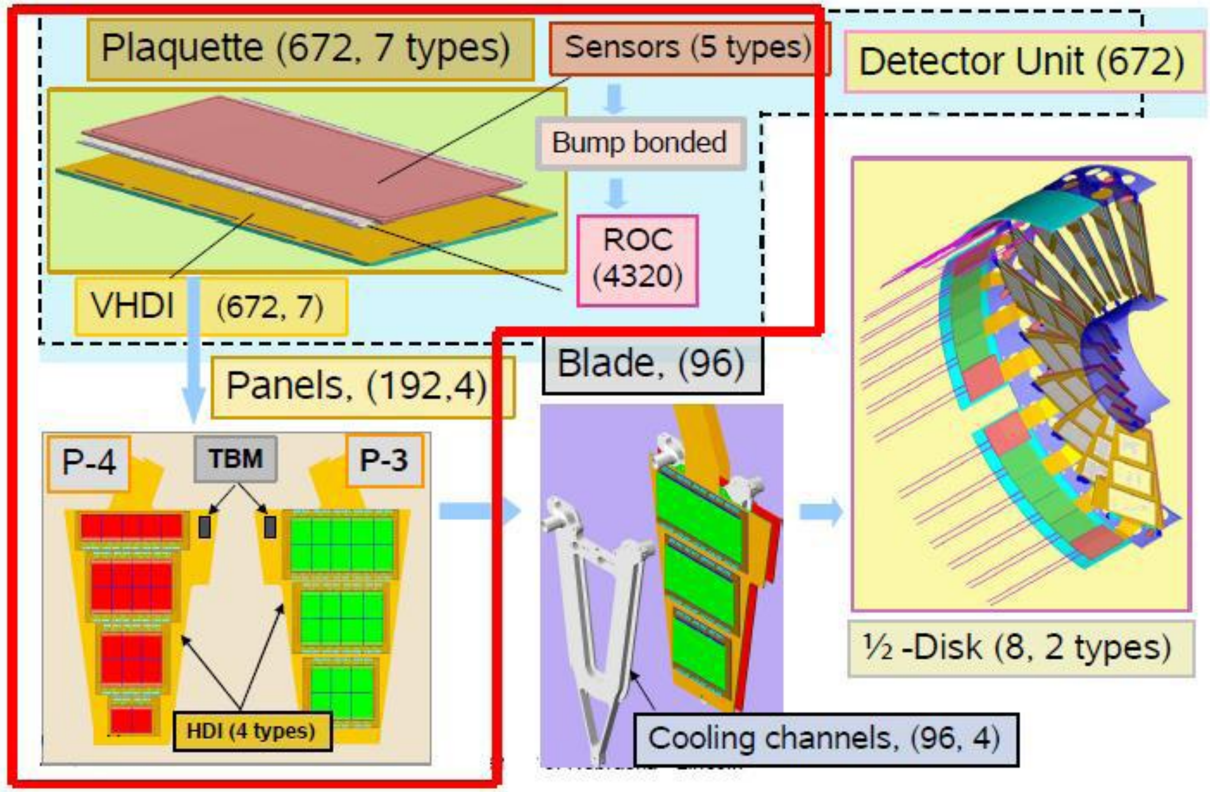
Pixel modules

BPix





FPix



BPix: 2 types of modules 16 ROCs and 8 ROCs

FPix: A blade contains of 7 plaquettes with 5 different sizes (2-10 ROCs)

Sensor

Collect electrons (n-side readout)

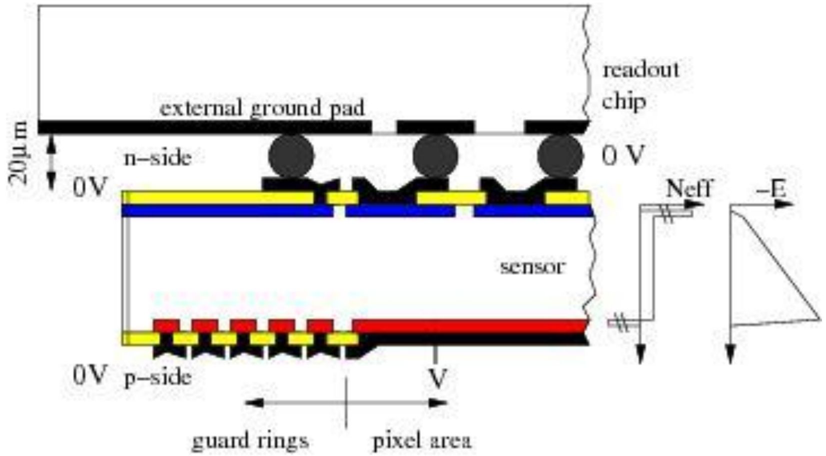
- Less prone to trapping
- Larger Lorentz angle
- n-side isolation required

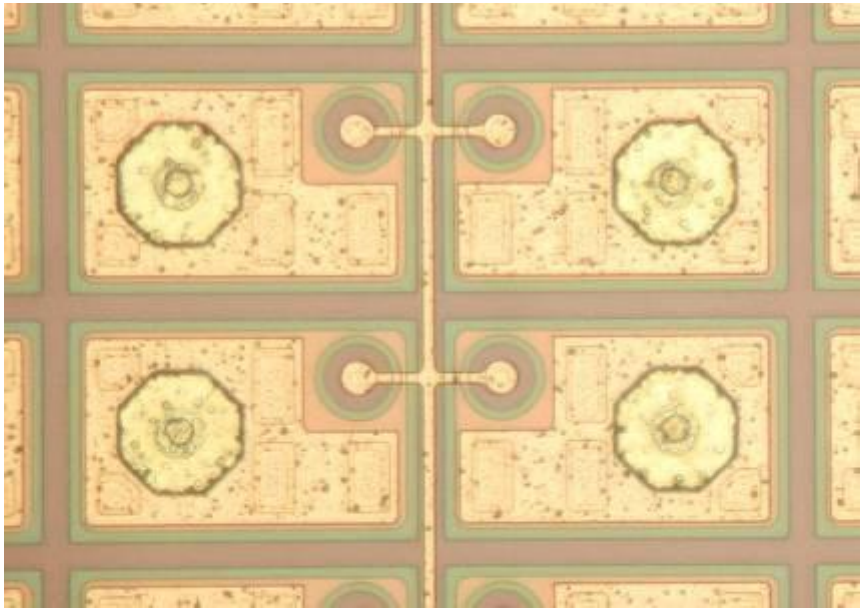
Avoid problems in module design

- N-Substrate (FPIX: 100-FZ, BPIX: 111-DOFZ)
- Guard rings (and junction) on back side
- All sensor edges on ground potential
- Double sided processing
  - Limits choice of producers
    - FPIX: Sintef
    - BPIX: CiS

Pixel call layout

- FPIX
  - Open p-stops, some over depletion needed to separate channels
  - large gaps, smaller C (exact value not yet measured)
- BPIX:
  - Moderated p-spray with bias grid (lower voltages, insensitive area)
  - Small gaps, homogenous drift field, higher C ~ 80fF





Infrastructure

Cooling

- Single phase cooling using C_6F_{14}
- Temperature of the coolant during 2011 T=+7.4 ºC
  - Sensor temperature estimated to 17.2 ºC (problems in the calibration of the temperature sensors)
- Since Jan 2012 $T_{coolant}$ = 0ºC
- "Humidity problem" prevented lower T
  - Relative humidity rises if B-field > ~2 T
  - Occurs since 2011
  - Is not symmetric
  - Present hypothesis:
    - it's known that some parts of CMS move on magnetic field turn on/off
    - movement may create an opening in pixel volume sealing

Power

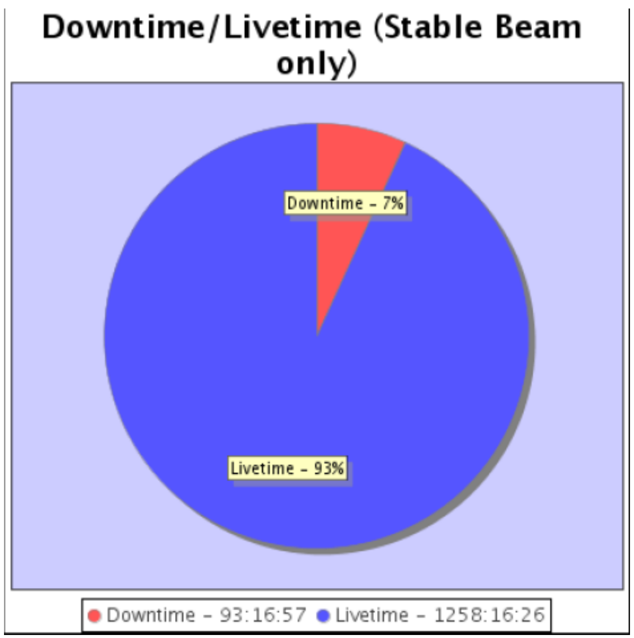
- Stable running in 2010/11, no major problems observed
- 1 remote sensing wire lost that affected 8 BPix modules

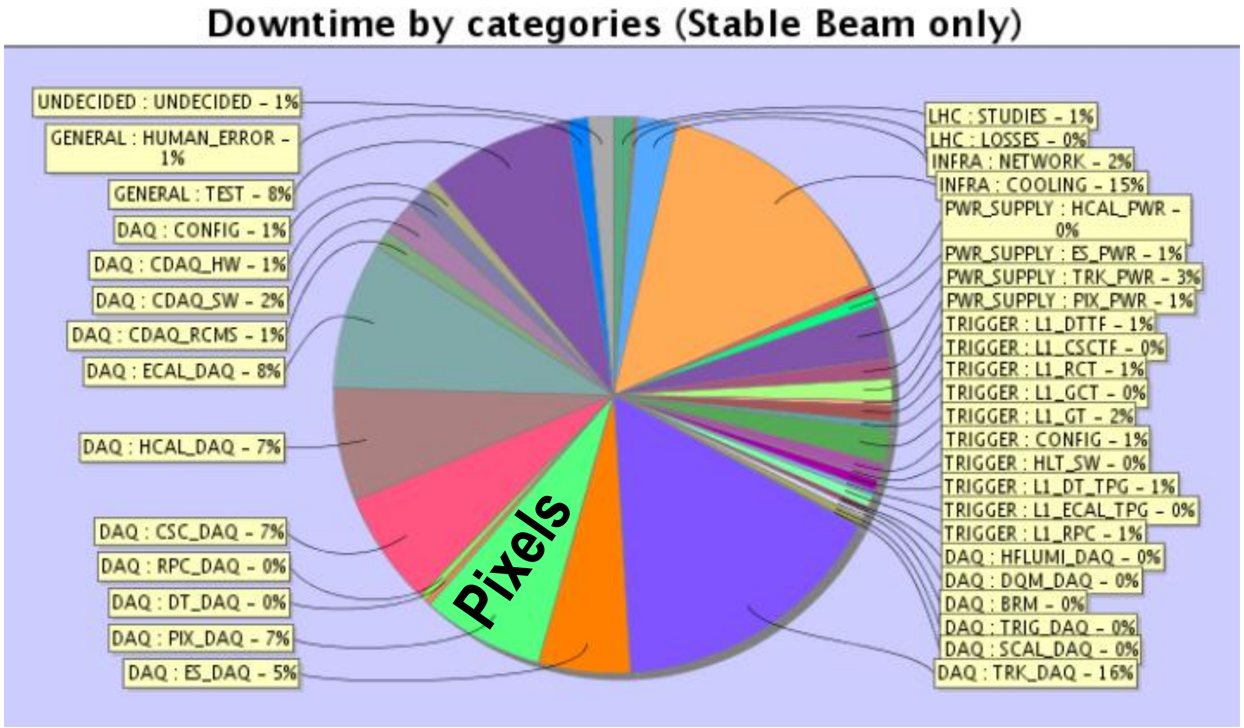
DAQ-Electronics

- Hardware was very stable in 2010/11
- Firmware have been modified several time to deal with different problems:
  - high multiplicity events from beam-gas background
  - internal noise of mezzanine card (corrupted readout)
  - heavy ion events handling

Downtime during 2011

- CMS is efficient 93% of the time (records 91% of the luminosity delivered)
- Pixels cause 7% of the down time
  - Most events causing down time are compatible with the assumption of an **SEU**





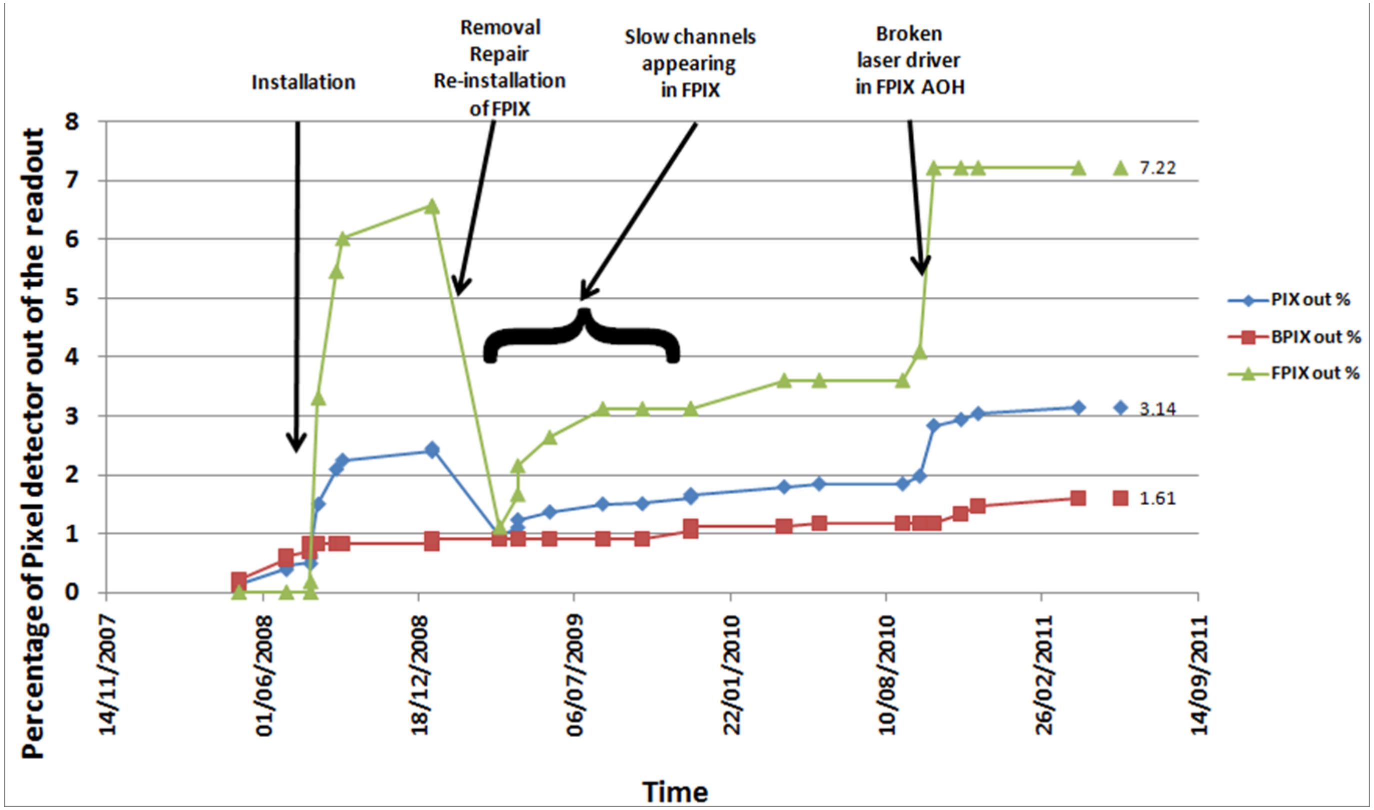
Detector status

The whole Pixel detector: **96.9%** of the ROCs functional

- FPix **92.8%**: 4320-312=4008 functional ROCs
- BPix **98.4%**: 11520-186=11334 functional ROCs

Total ’dead’ random pixels : **$<2 \times 10^{-4}$** in functional ROCs

- about 6K (10^{-4}) inefficient pixel found with internal calibration
- about 700 (10^{-5}) ’noisy’ pixel (masked) found in cosmic ray data



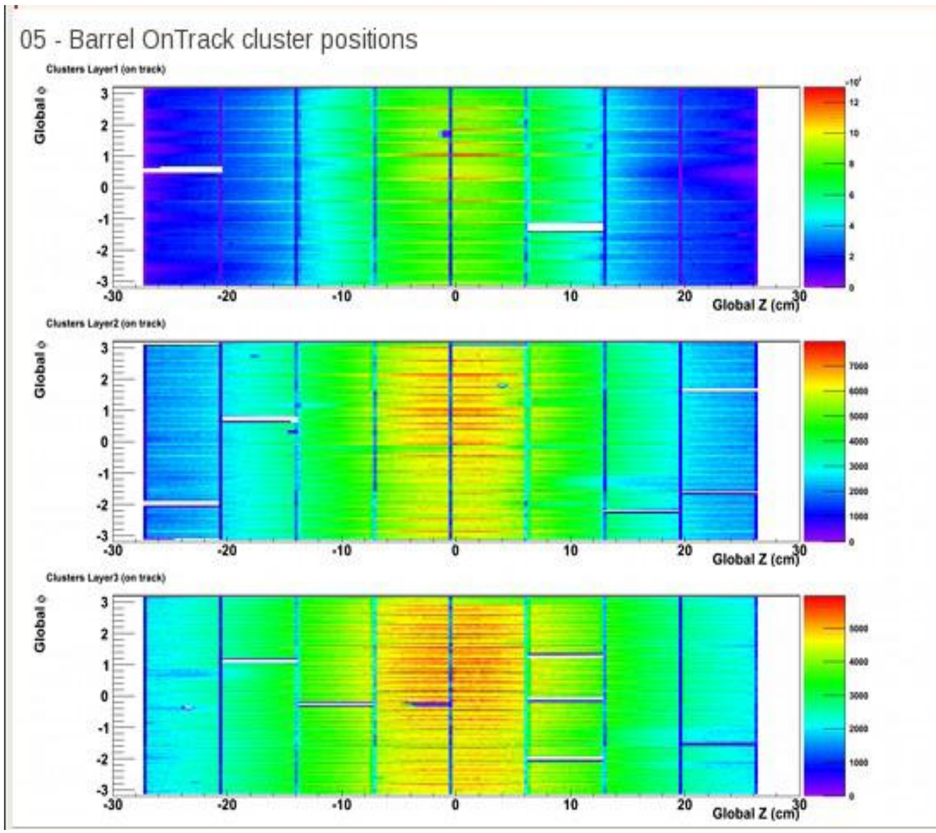
Major problems

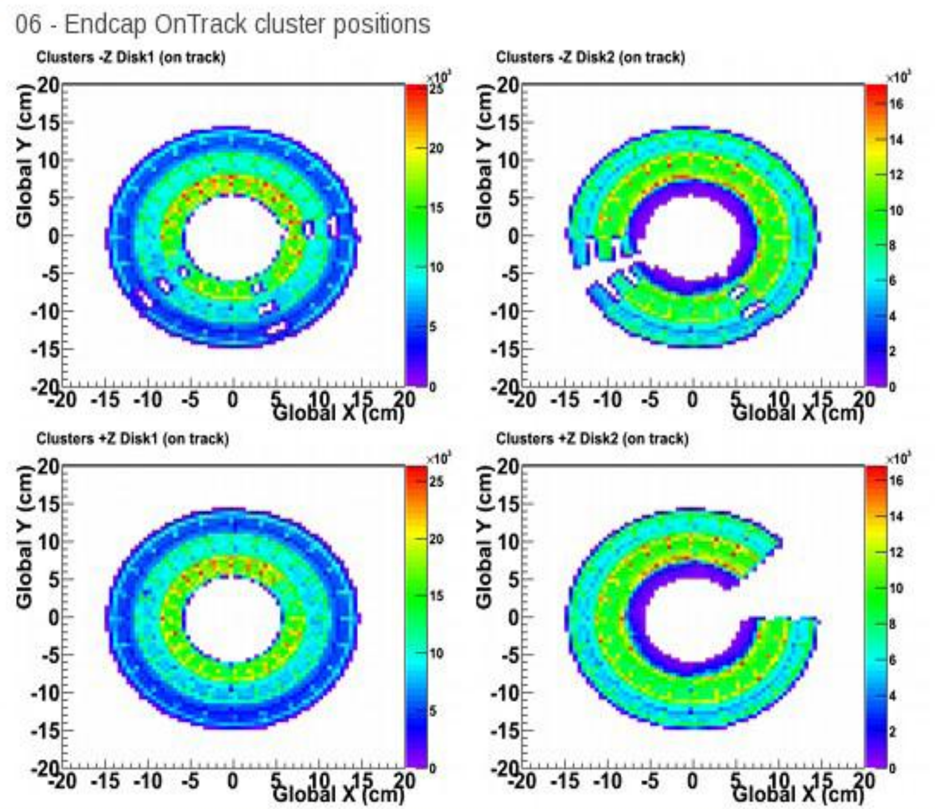
BPix

- broken wires: not recoverable
- token lost: not recoverable
- single ROC problems: sometimes rest of the module recoverable

FPix

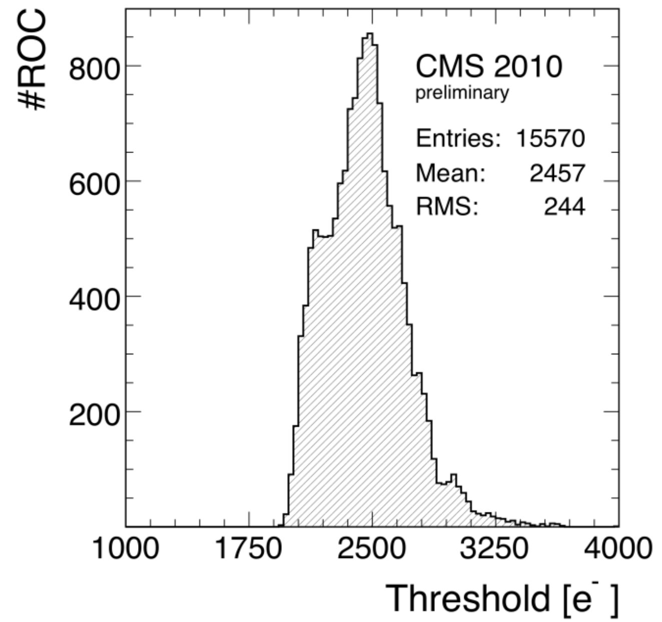
- bad address levels due to slow signal rise time: recoverable in FED FW
- no communication with optical transmitter: recoverable if CMS open

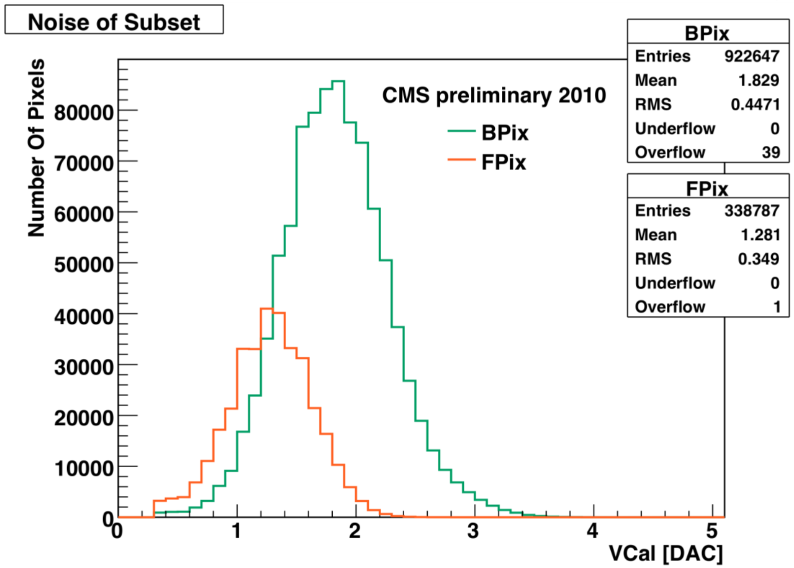




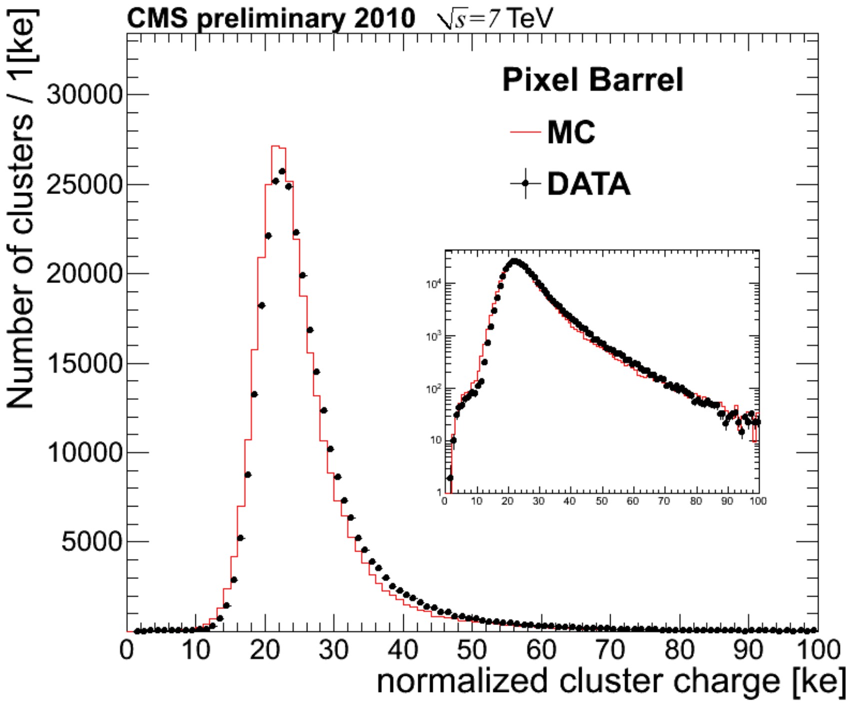
Performance: threshold and noise

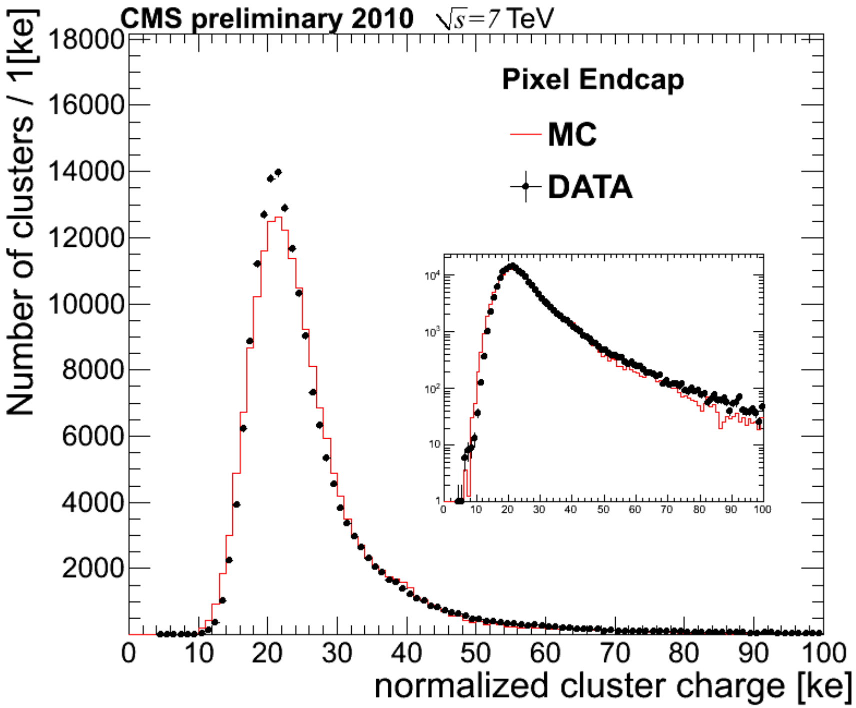
- Motivation: lower threshold - lower pixel charge reconstructable →better spatial hit resolution
- adjustment done with help of internal calibrate signal (VCal)
  – Limitation: x-talk in ROC
  – Mean (absolute) threshold = **2457 electrons**
  – in-time threshold ~800 e higher
- In principle possible to lower threshold by ~500-1000 e without getting noisy pixels by lowering the V_{thr}-DAC
  – Threshold not anymore homogenous in the whole detector
  – Value not exactly known
  – Test requiring injection of test singal cannot be ma anymore
- Mean noise **less than 150 electrons**
- Conversion (from X-ray calibration): Q[e−]=65.5 × VCal[DAC] - 414





Performance: Cluster charge





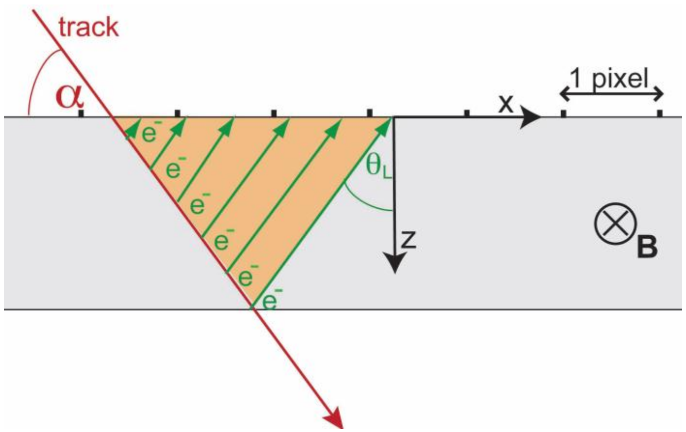
- Taken from CMS collision data
  - Corrected for incident angle
  - Tracks with pt > 2 GeV selected
- MC describes data well
  - Peak position ~2-4%
  - Width 10-15%

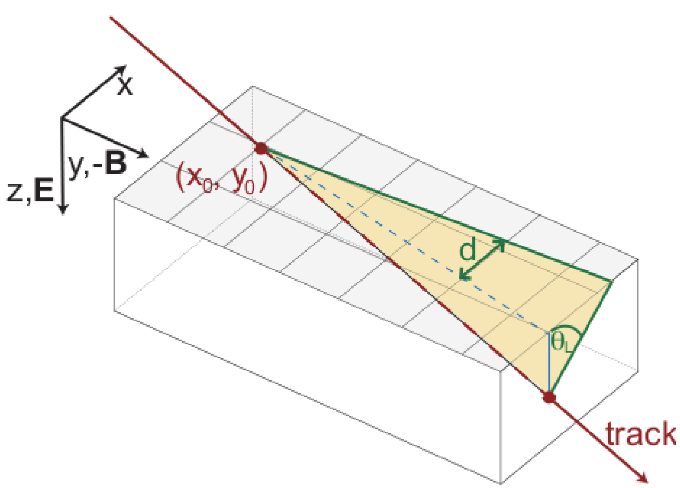
Performance: Lorentz angle

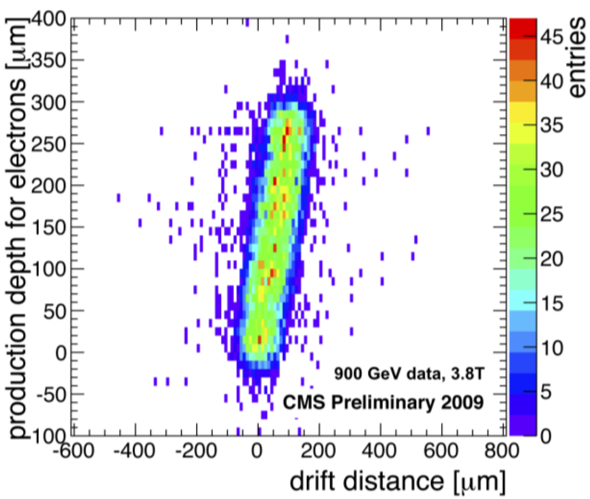
Motivation:
- Lorentz drift widens clusters in $r\phi \rightarrow$ **better spatial resolution**
- Important parameter for MC

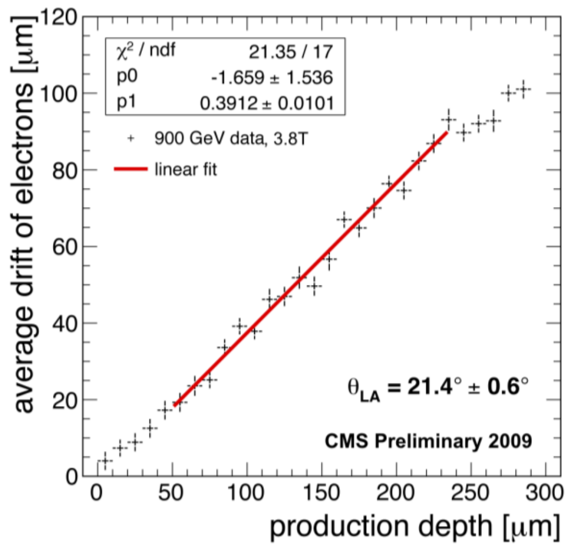
2 measurement methods:
- "Minimum cluster size" measured with cosmics
- "Grazing angle" method with collision data

Results are consistent in different methods and with MC
- BPix: cot=-0.462(452)±0.003(2)
- FPix: cot=-0.074(74)±0.005(4)





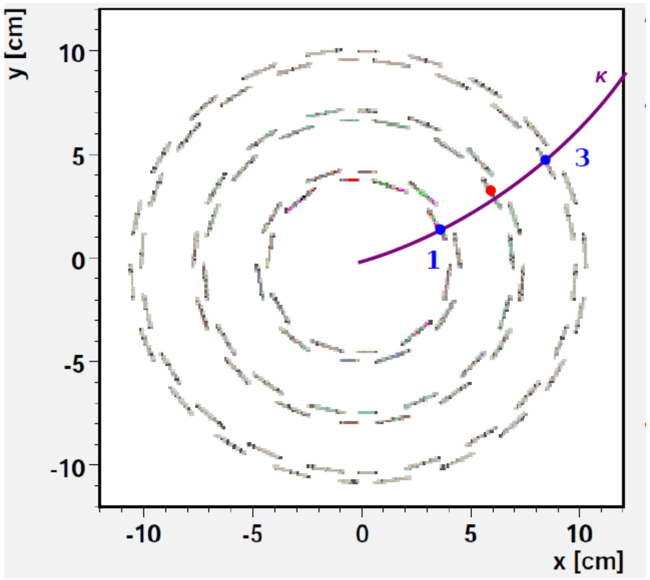




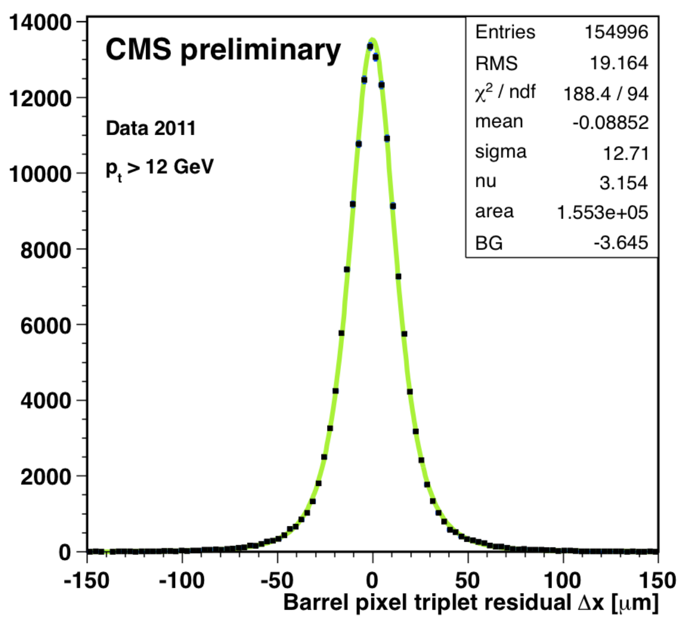
Performance: Spatial resolution

Triplet-Method:

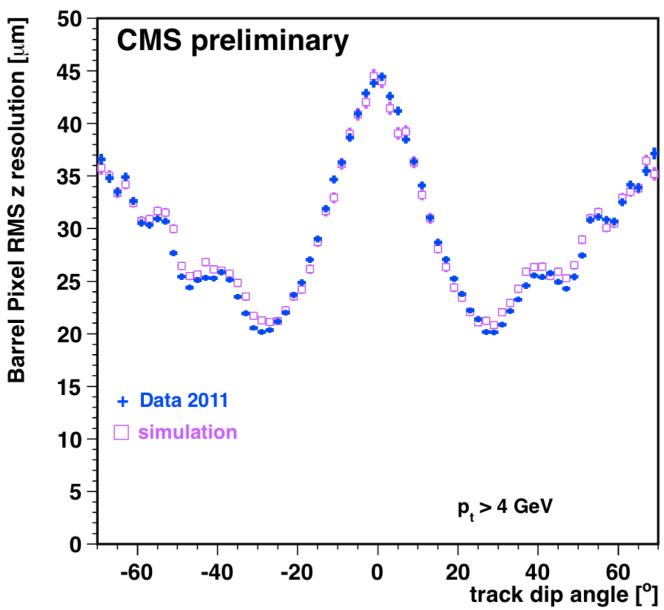
- Take curvature κ from Strip tracker
- Fit track through layers 1+3
- Measure the residual in layer 2
  - Measurement in layers 1 + 3 also have an error (σ_i)
  - σ_r = sqrt(3/2) $\times$ σ_i
- **σ_r = 12.7 μm**
- **σ_i = 10.4 μm**
- **Pitch: 100 μm**



CMS Barrel Pixel triplet residuals

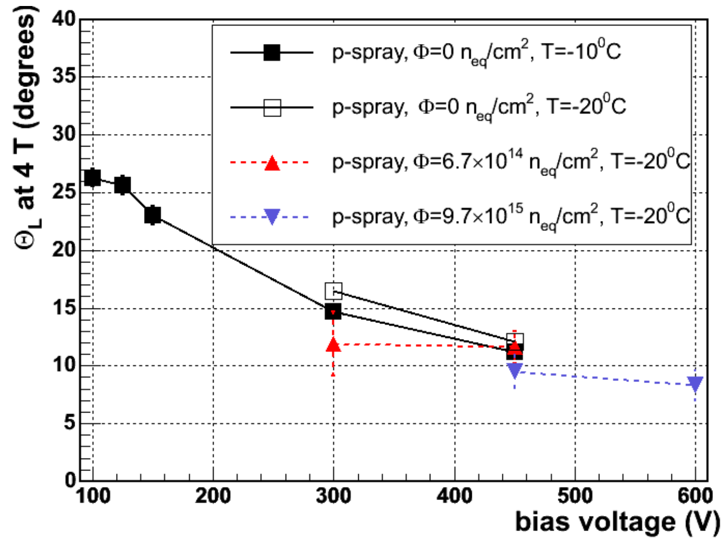


CMS Barrel Pixel z resolution from triplets

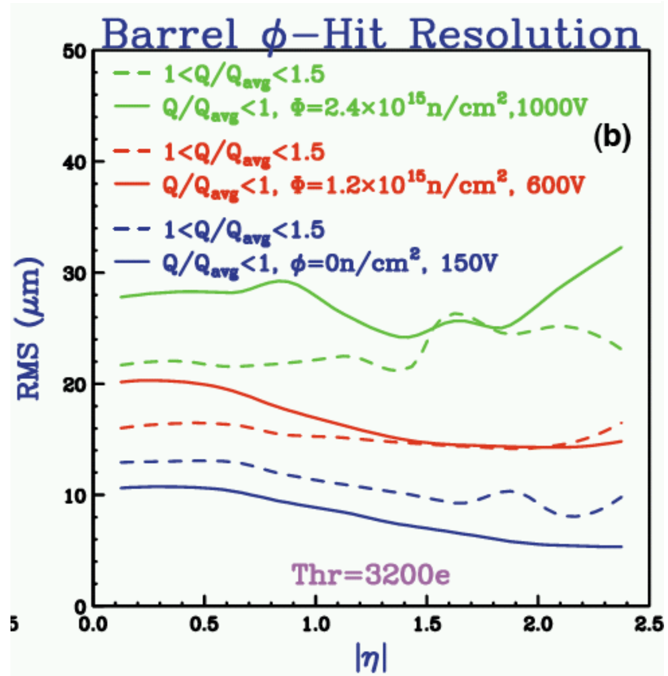


Expected degradation of spatial resolution (rϕ)

- Cumulative radiation damage requires increase of bias voltage
- High electric field reduces mobility of charge carriers
- Lorentz angle is also reduced
- Fraction of double hits is reduced
- Resolution slowly degrades up to the binary value (pitch/sqrt(12)~ 30μm with current pitch)
- Process is slow and steady
- Detector might become "useless" for impact parameter measurement although detection efficiency is still high (>95%)
  – Present operational limit
- 1.2×10^{15} N_{eq} cm^{-2} (~400 fb^{-1}, 4.2cm layer) reachable
- Any higher demand requires a smaller pitch in rϕ
  – Not realistic in the time scale of the phase I upgrade (~2016)
  – A point of consideration for phase II (> 2020)



A. Dorokhov NIM A530 (2004) 71-76



[Morris Swartz, JHU, taken from the draft TDR]

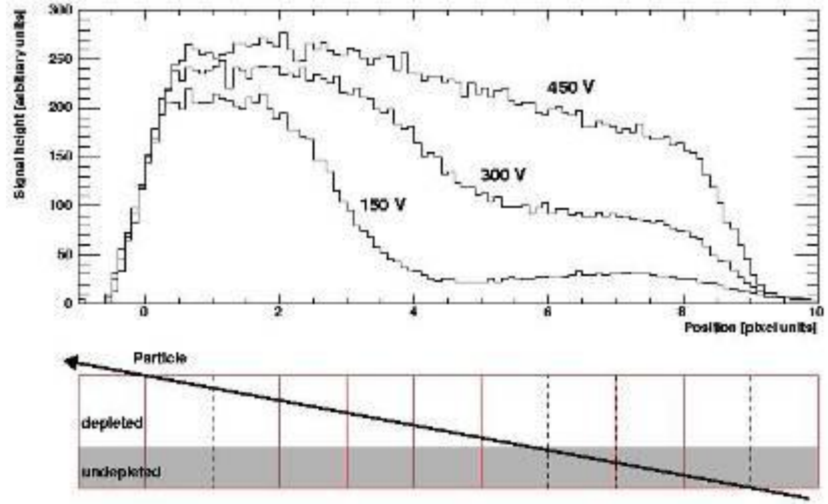
Expected degradation of spatial resolution in z

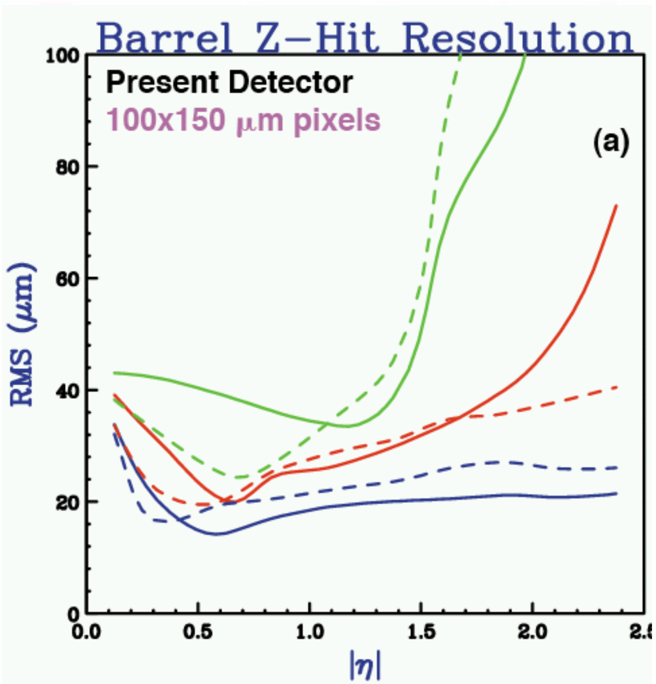
New detector:

- Very low h (cluster length: 1): ~150µm × sqrt(12)~40µm
- "optimum" (cluster length 2): best interpolation possible ~15-20µm
- Larger h (cluster length >2): Interpolation more difficult. Fluctuations in the centre of the cluster do no contain information.

In irradiated sensor:

- Shape of cluster has to be taken into account ("template algorithm")
- If fluence is too high/signal too low:
  - level is low (pitch is smaller than thickness)
  - fluctuations might lead to "hole" in the clusters
  - Present software cannot "glue" to clusters together
  - Large errors in position determination
  - 1.2×10^{15} N_{eq} cm^{-2} (~400 fb^{-1}, 4.2cm layer) reachable
- **Smaller pitch makes things worse**
- Need
  - Lower threshold (new ROC submitted for phase I upgrade)
  - Powerful software tools to "reconnect" broken cluster, which is difficult in multi track environment inside jets



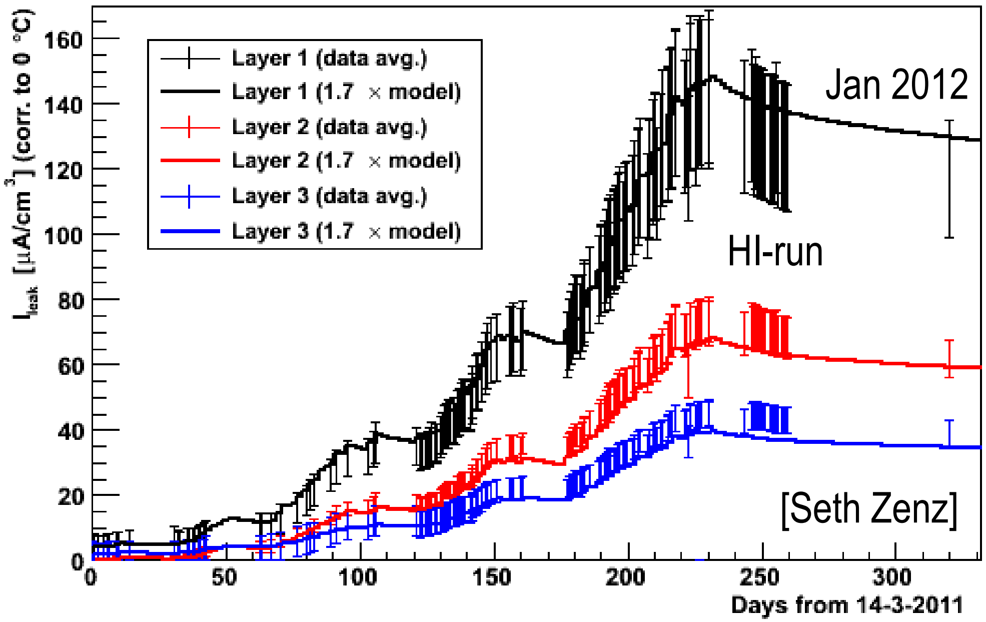


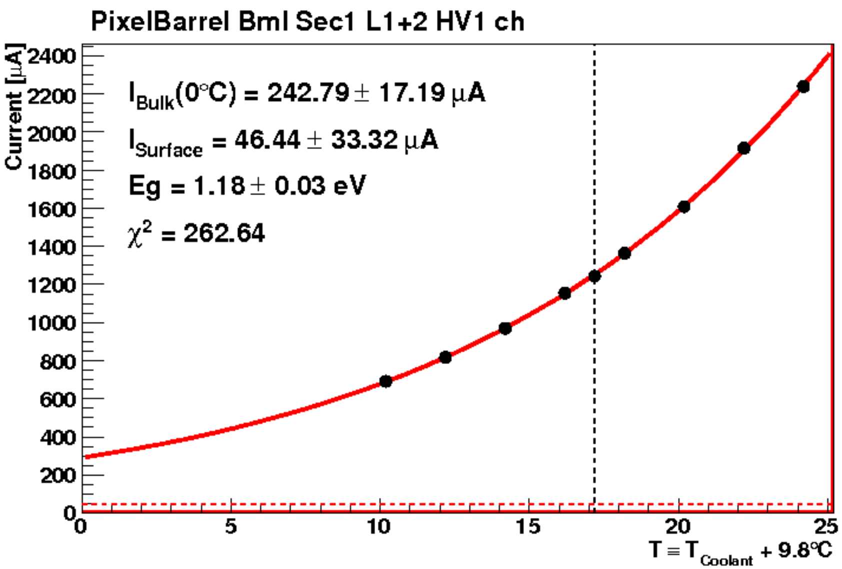
[Morris Swartz, JHU, taken from the draft TDR]

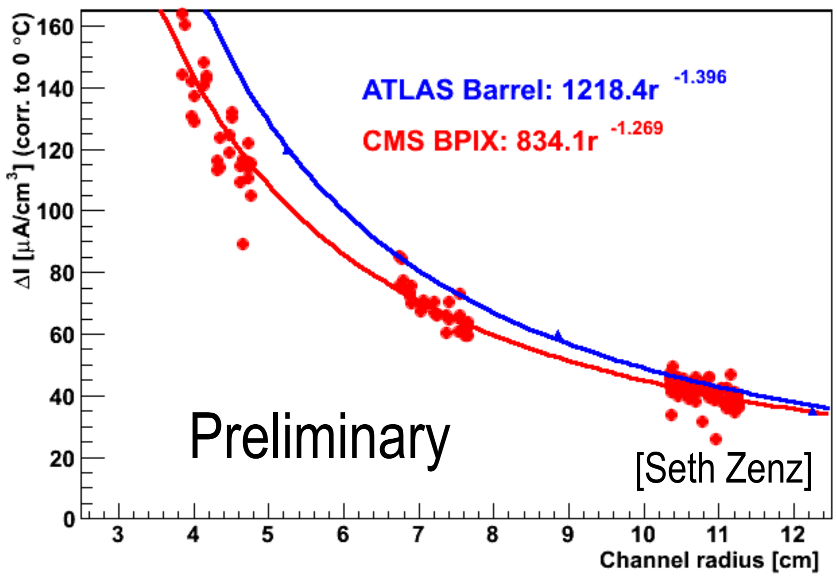
Radiation effects in CMS pixel detector

Increase of leakage current

- Current increase ~ ∫L
- Scaling with fluence not trivial:
  - Temperature not exactly known (~17° C)
  - If α is "too high" (Φ is obtained by simulation and cluster counting)
- Radial dependence ~ r $^{-1.3}$ ("too low")
  - Cluster counting and leakage current roughly agree
- Temperature dependence
  - Fitted E_a compatible with literature value (1.21 eV)
  - Only if constant term is allowed (else 1.13 eV)

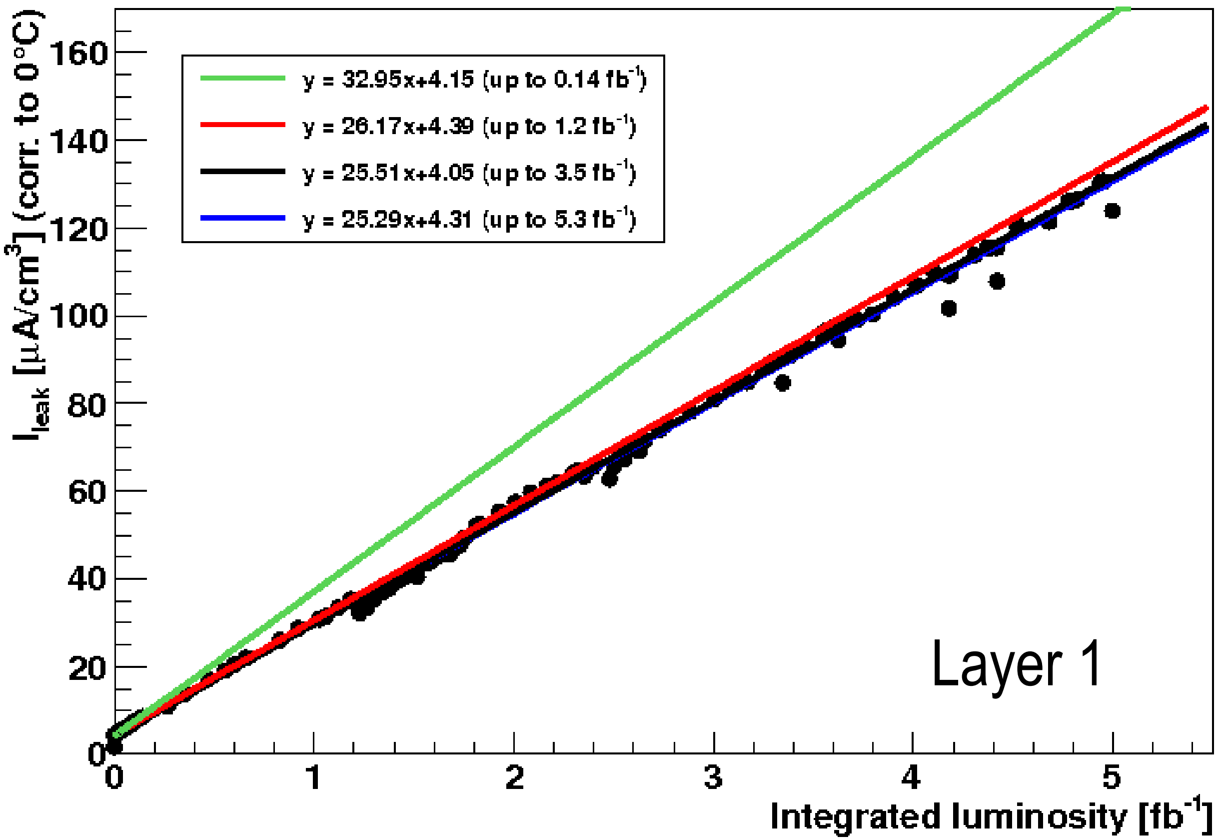


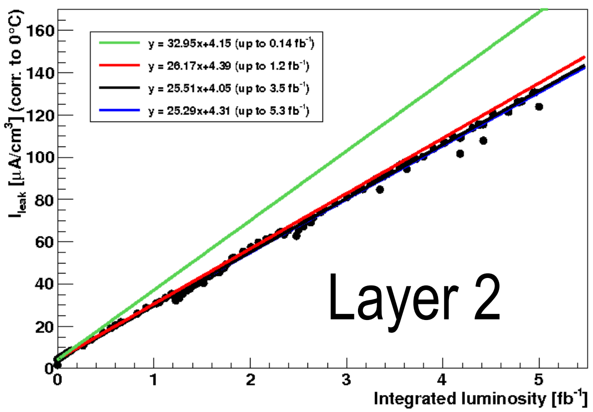


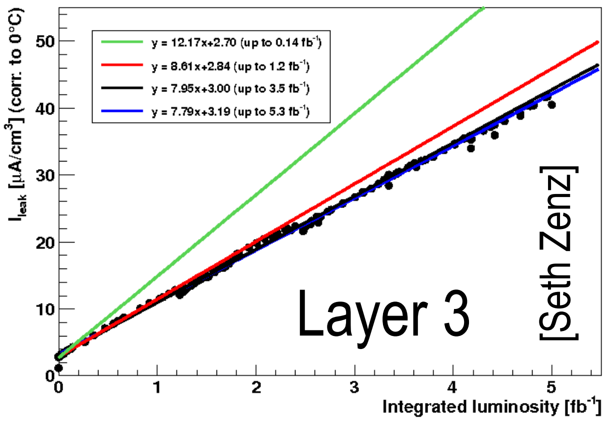


Operational limit

- For operation of the detector the development with integrated Luminosity is most important
- Extrapolation: Limit of the power supplies will be reached at ~750 fb^{-1} (if detector is cooled to T=0º C)
- This extrapolation does not take into account annealing

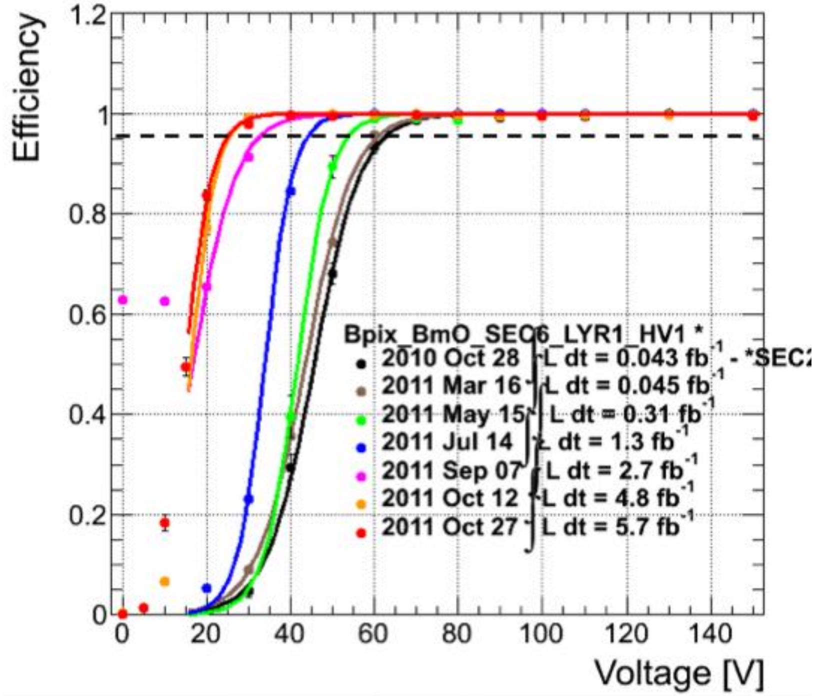


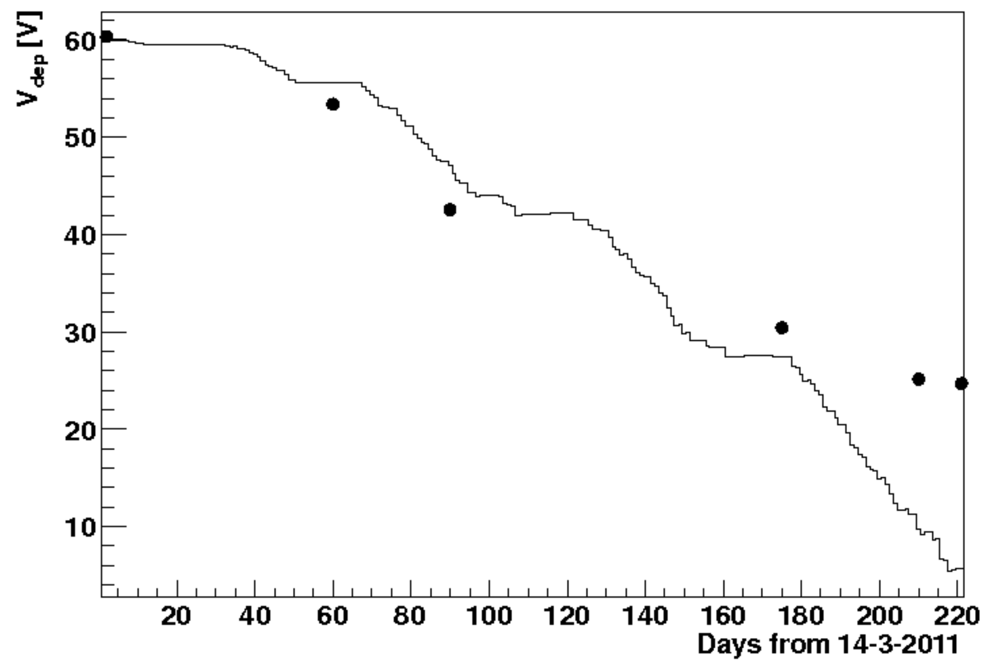




[Seth Zenz]

Full depletion voltage





[Seth Zenz]

Full depletion voltage measured during data taking

- Bias voltage reduced from nominal value (150V)
- Voltage where efficiency drops to 95% is defined as V_{fd}
- In future cluster charge vs bias is used for V_{fd} determination
- Minimum of V_{fd} will be reached in the inner layer during 2012

Radiation induced effects in the ROCs

SEU

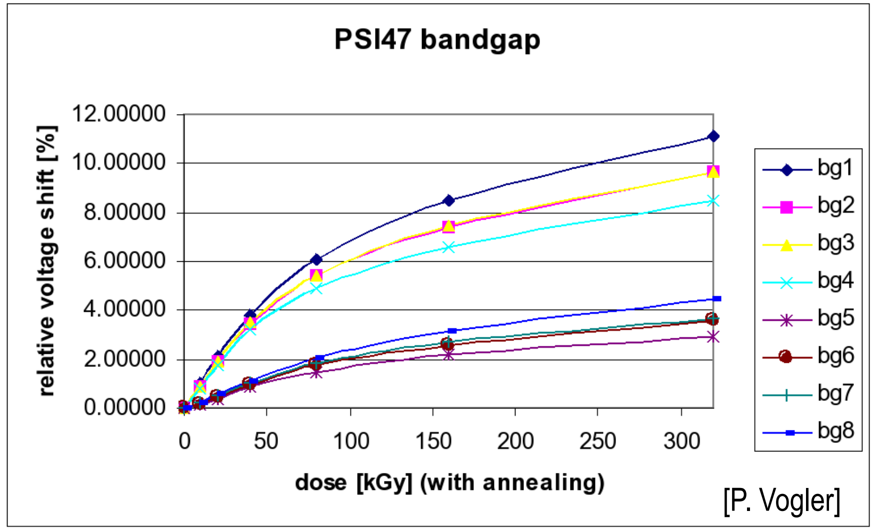
- Some "events" in all electronic components in the cavern
- Typically disappear after reconfiguration or reprogramming
- Down time for "pause – resume" ~30 sec

Permanent changes

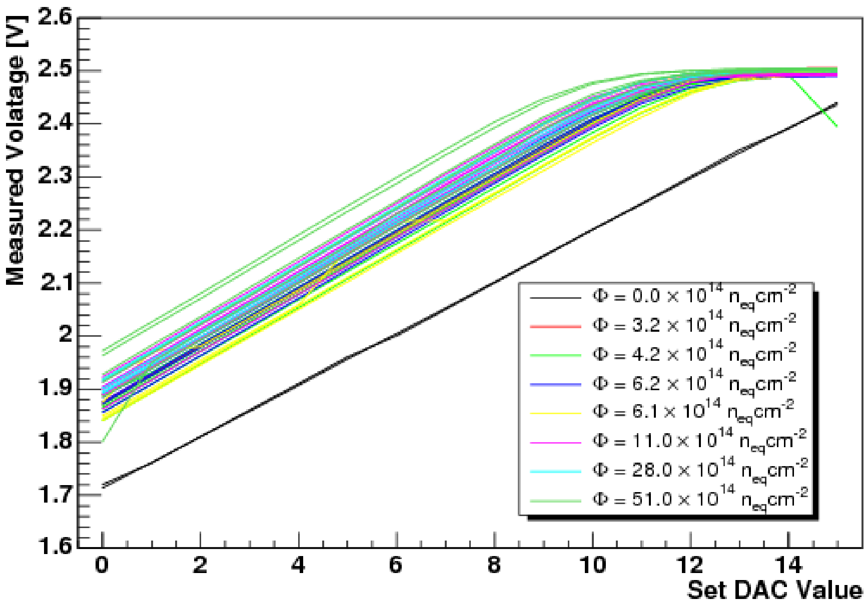
- Analogue current increases
- Thresholds increase slightly
- Both could be explained by a drift in the band gap reference

Lab-Measurements

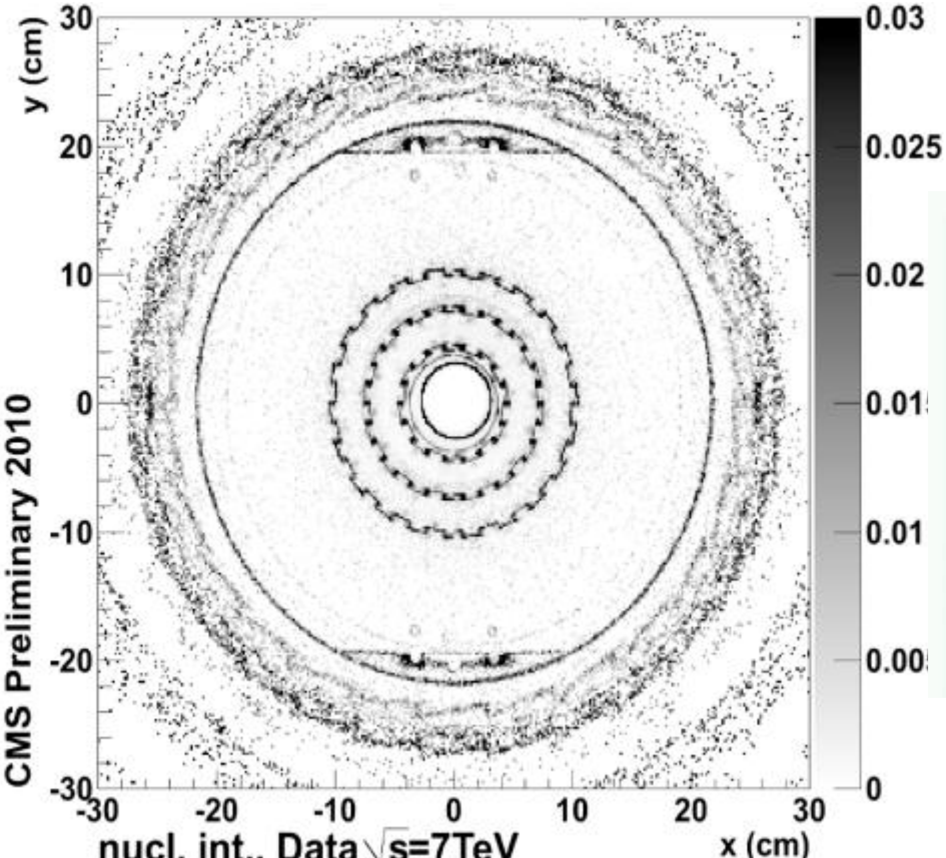
- γ-Irradiations
  - At the present dose (<10 kGy) no visible effect
- Hadron irradiation
  - Module used in pion test beam showed similar effec
  - Heavily hadron irradiated irradiated ROCs show clear shift in the band gap reference which is already saturated at the lowest fluence ($3 \times 10^{14} N_{eq} cm^{-2}$)

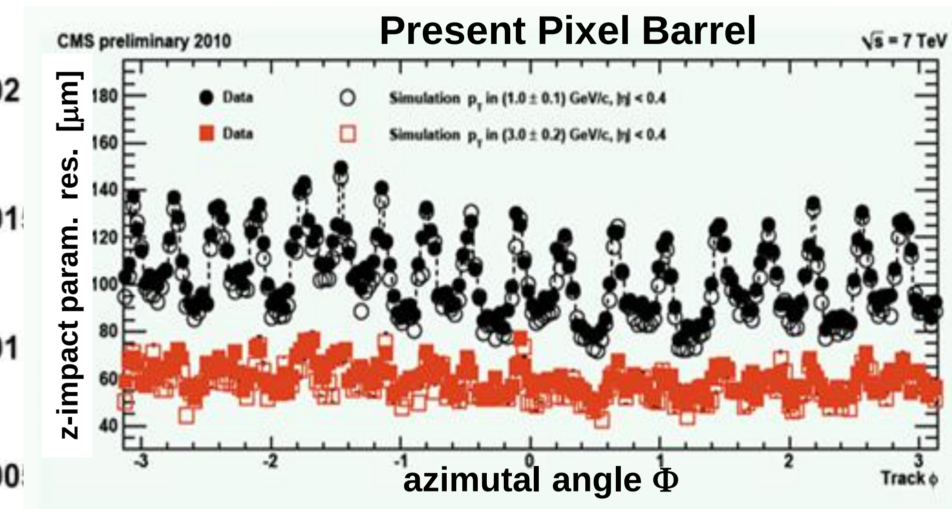


[P. Vogler]



Motivation for upgrade phase I





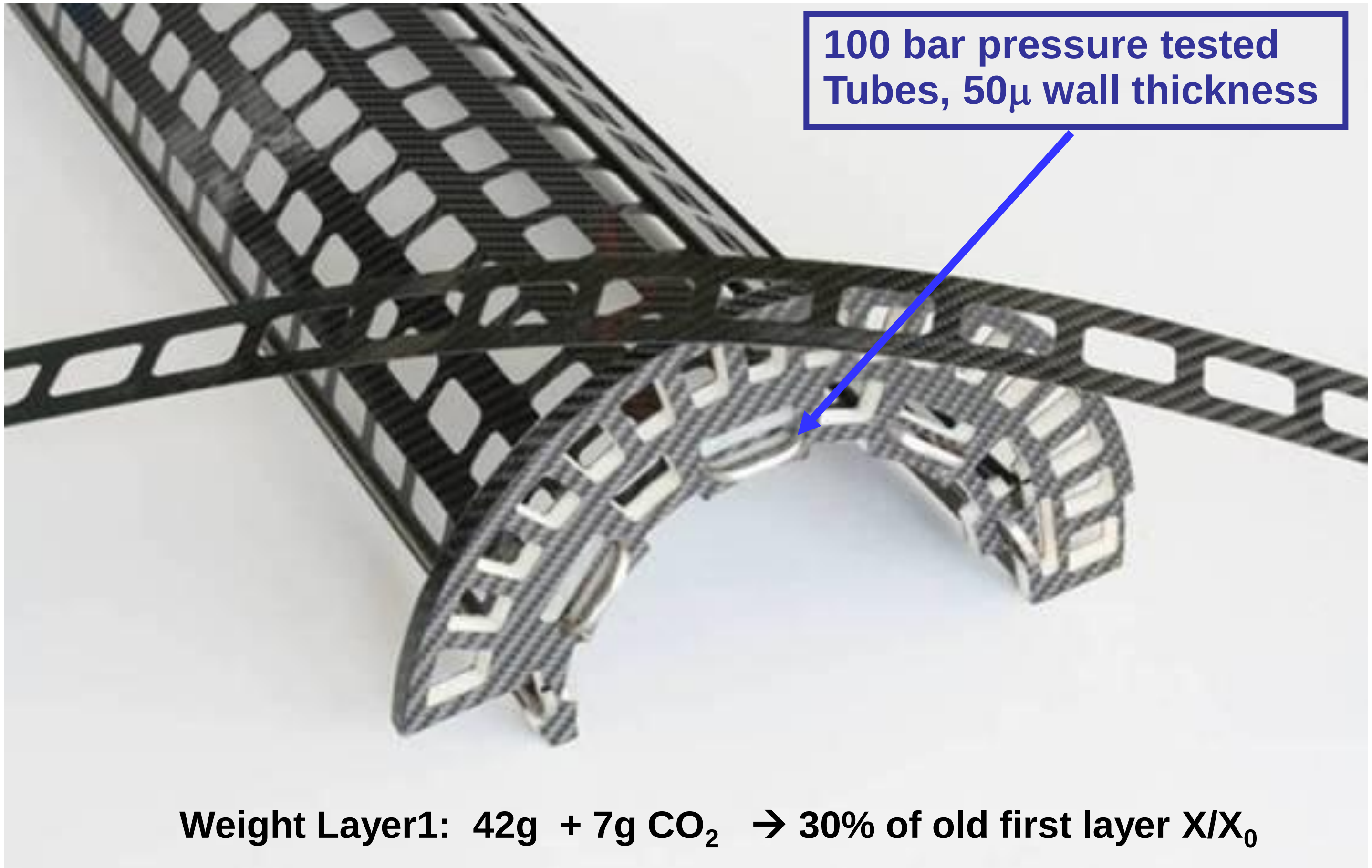
Part of the motivation for the upgrade/replacement planned for 2016/17 is visible in this plot:

- Reduction of material: **CO_2 cooling + shift material out of tracking η-region**
- Fill the gap between pixel and tracker inner barrel (TIB) and increase number of pixel tracking points
    - **Barrel 3 $\rightarrow$ 4 layers, forward 2 $\times$ 2 $\rightarrow$ 3 $\times$ 2 disks**

Further

- Reduce radius of layer1 (new beam pipe planned)
- ROC modifications: DC-DC converter, digital readout (use existing cables) + **operate at $L \sim 2 \times 10^{34}\ cm^{-2}s^{-1}$**

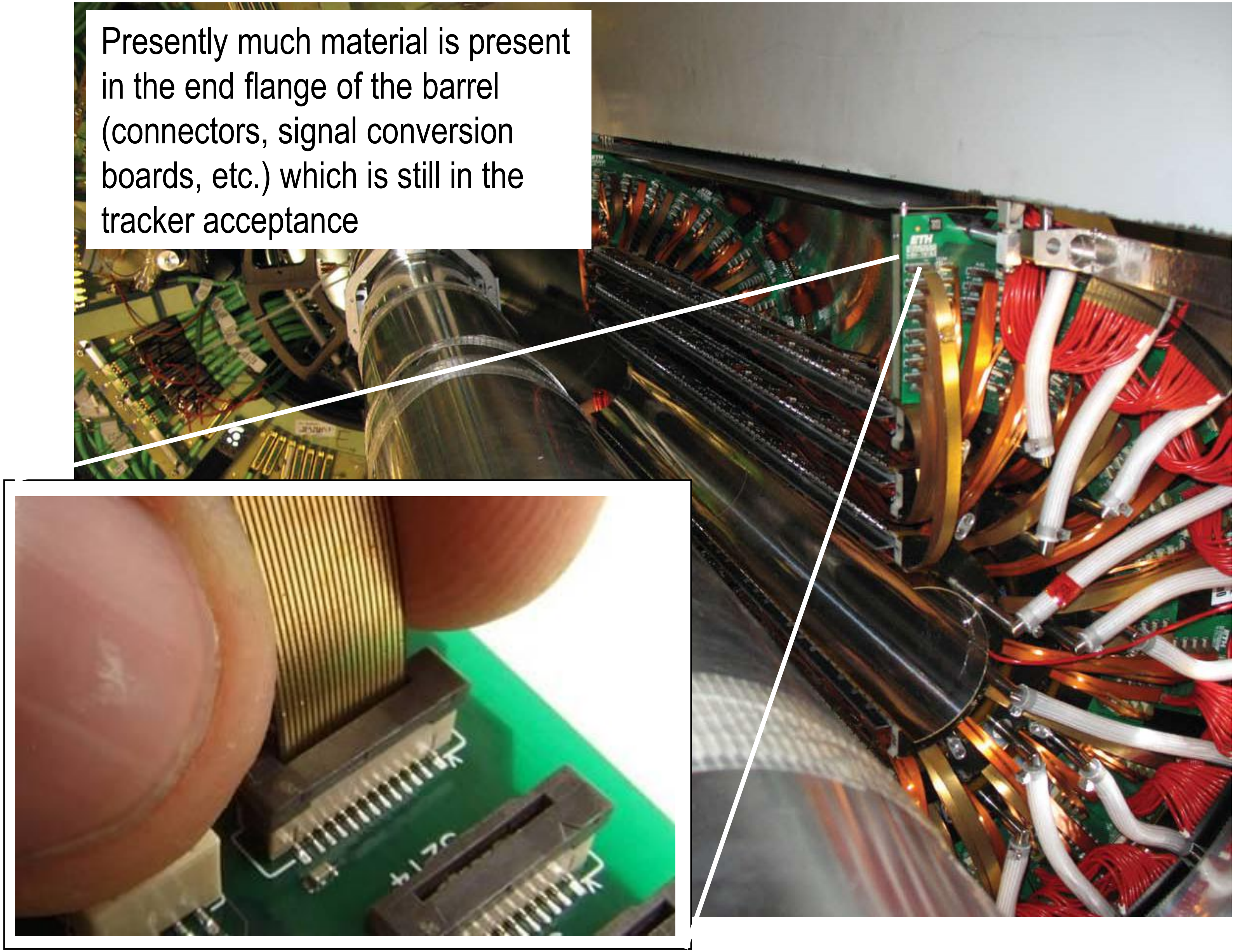
Ultra light mechanics and CO_2 cooling



- Cooling fluid in the pipes contributes significantly to the material
  - **CO2 – cooling gives significant improvement**
  - high pressures (~60 bar @ room temperature), CMS cooling tubes ok up to 40 bar → special startup/safety
- Ultra light mechanics made out of the cooling tubes and carbon fibres
- Less multiple scattering and improved impact parameter resolution

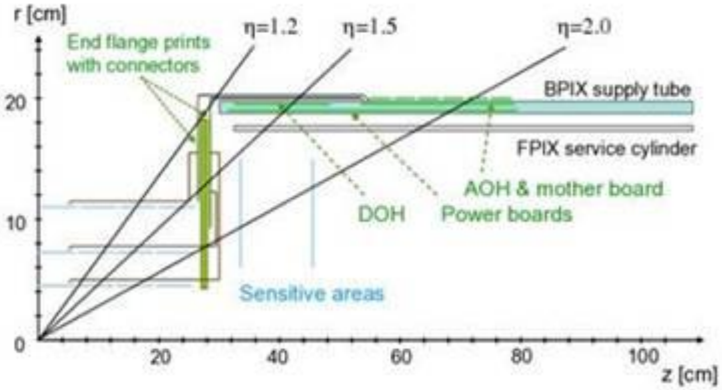
Material in end flange

Presently much material is present in the end flange of the barrel (connectors, signal conversion boards, etc.) which is still in the tracker acceptance



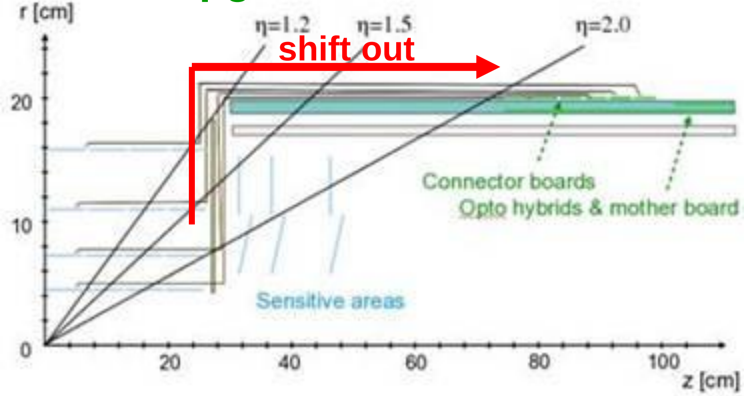
Shift material out of tracking region

Current BPIX Services

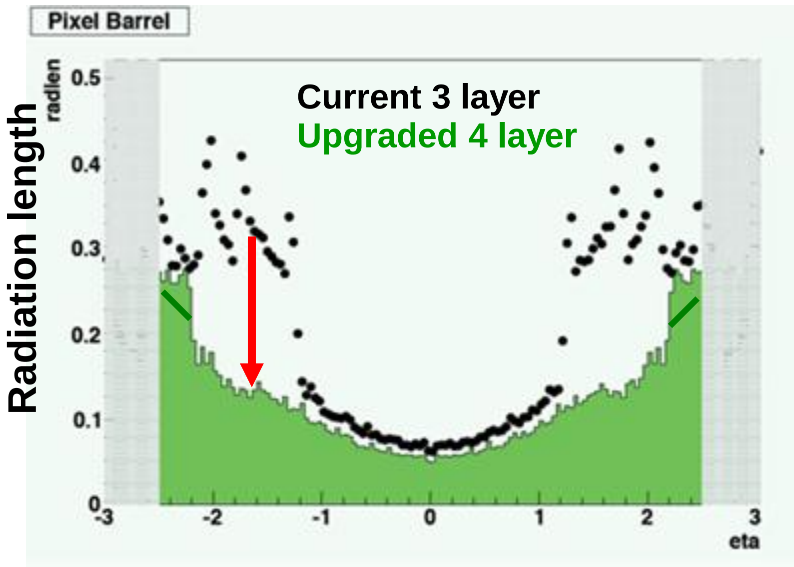


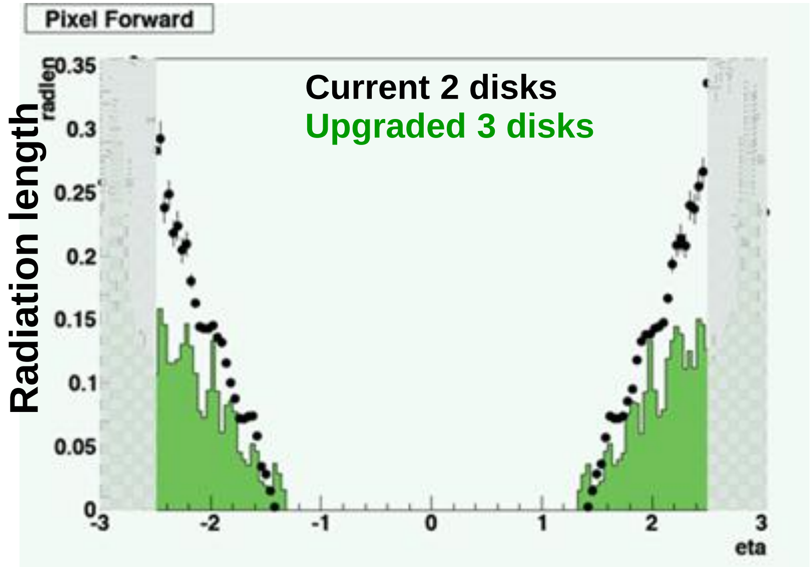
η<2.2 : weight = 16.9 Kg (3 layer)

Upgraded BPIX Services

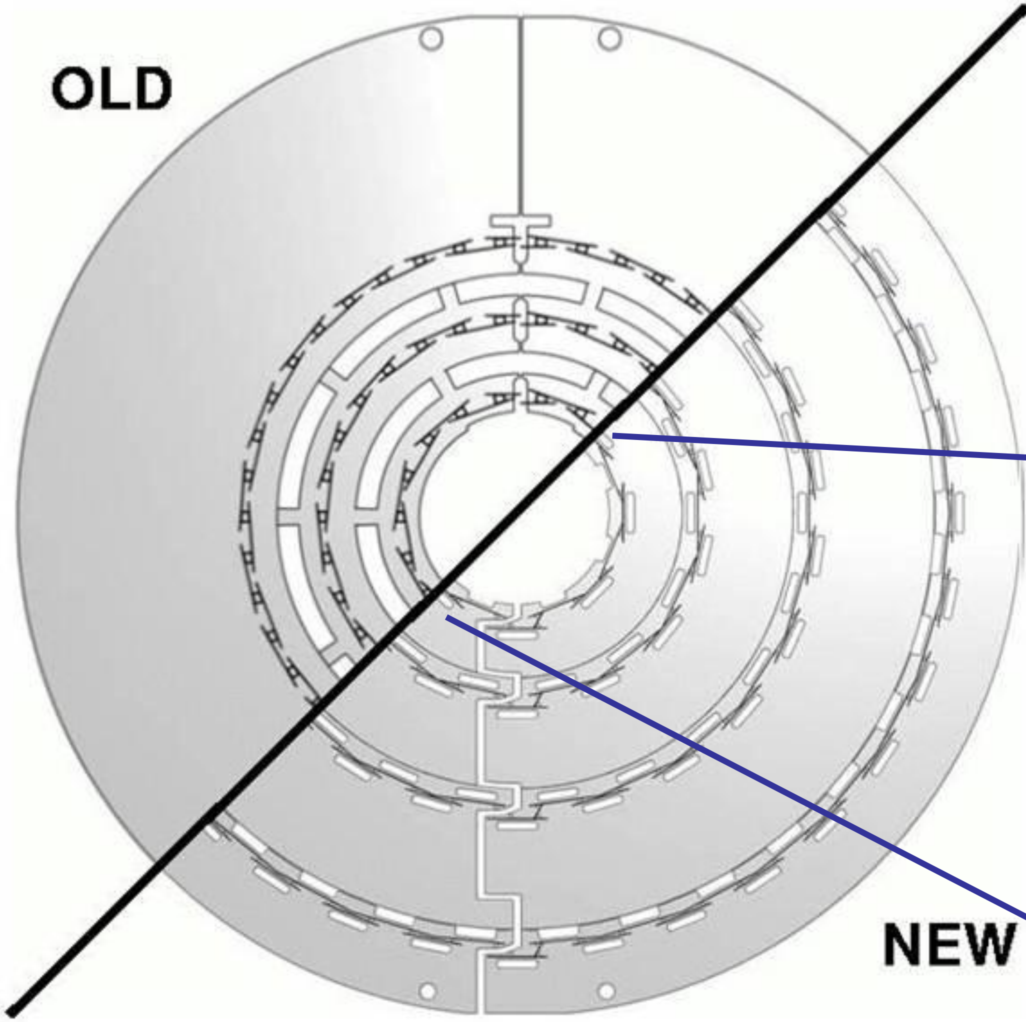


η<2.2 : weight = 6.5 Kg (4 layer)





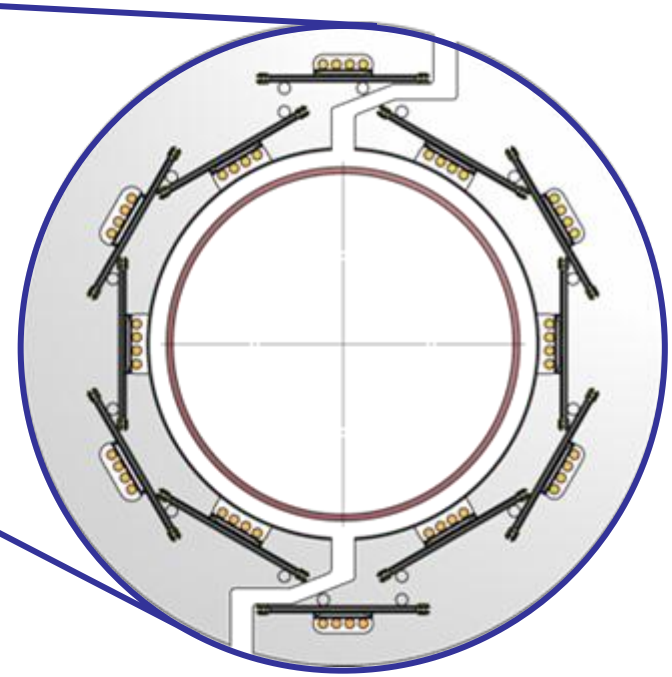
Geometry of upgraded barrel



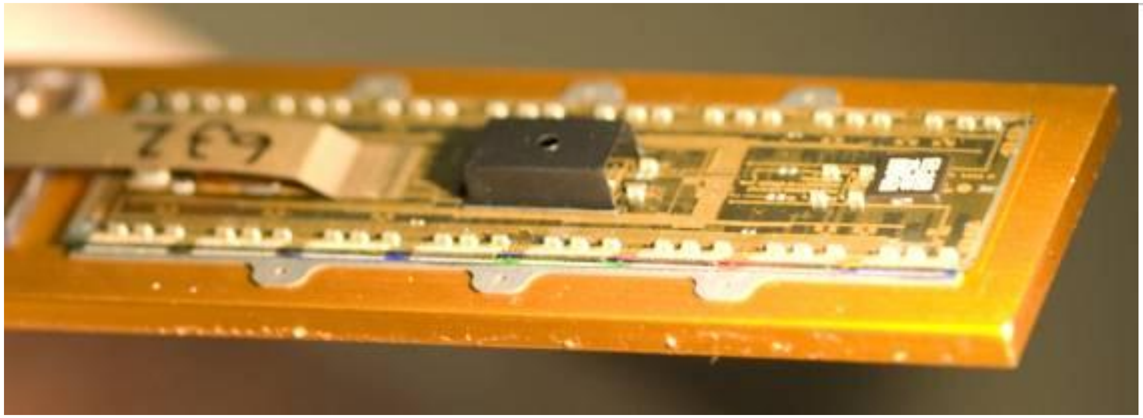
Total 1216 modules (1 type only)
→ ~81 M pixels ~ 1.6 × present barrel

Layer 1: R=29.5 mm, 12 faces
beam pipe radius < 22.5 mm

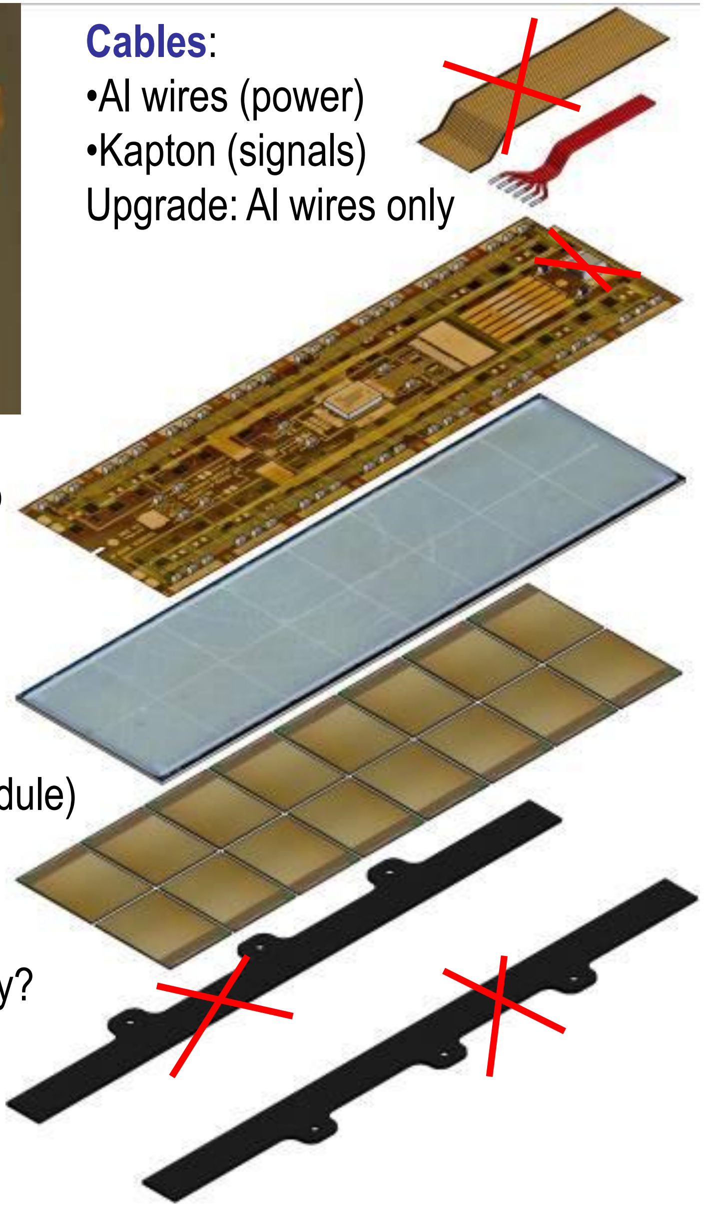
Layer 2: R=68mm, 28 faces **baseline**
Layer 3: R=109mm, 44 faces
Layer 4: R=160mm, 64 faces



Changes in pixel module



Cables:
•Al wires (power)
•Kapton (signals)
Upgrade: Al wires only



HDI: Very thin, very fine pitch flexible HDI with token bit manager chip (TBM) and passive components
Upgrade: redesign TBM, less and smaller passive components

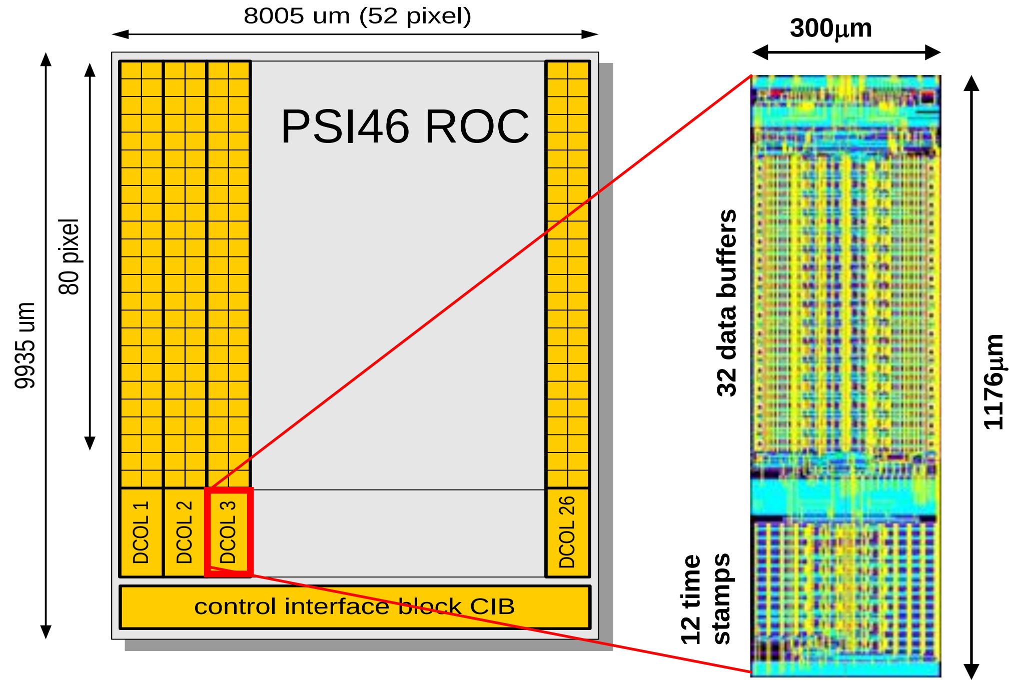
Sensor: n-in-n, bpix: DOFZ, fpix: FZ
Upgrade: unchanged
options: mCz for outer layer (pi/n ~ 2.5), n-in-p, tight schedule)

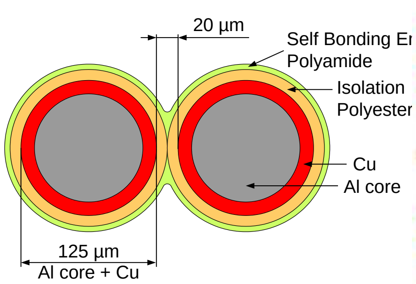
16 **ROCs**: 0.25µm
Upgrade: chip will be upgraded (but no complete redesign) still 0.25, thinned down more aggressively (175µm → 75µm) in inner layer only?

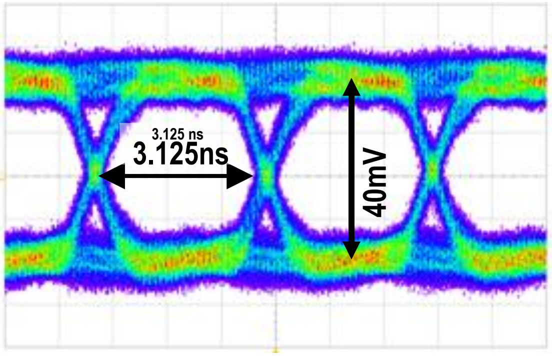
2 **base strips**
Upgrade: omit (in 2 inner layers only?)

Changes in the ROC

- **Data loss reduced by changes in ROC**
- **new versions submitted in Jan 2012**
- Still 0.25 µm
- PSI46xtb
  - Increase depth of
    - Data buffer 32→ 80
    - Time stamp buffer 12→ 24
  - Layout optimisations to reduce x-talk etc.
  - Some unnecessary DACs removed
- PSI46dig
  - Binary serial readout 160 MHz
  - Additional buffer stage
- Further submission this autumn
  - More fundamental changes in the architecture
  - Aimed for 29mm layer and L=2 × 10^{34} cm^{-2} s^{-1}
- **No additional cables can be pulled**
  - 160 Mbit/s serial binary data out
  - **Use of DC-DC converters (Aachen)**
- **Very low power and mass link at 320Mz**
- Use ~1m long micro twisted pair cables (Copper-Cladded Aluminum)
- Send/receive chips done







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Sensor

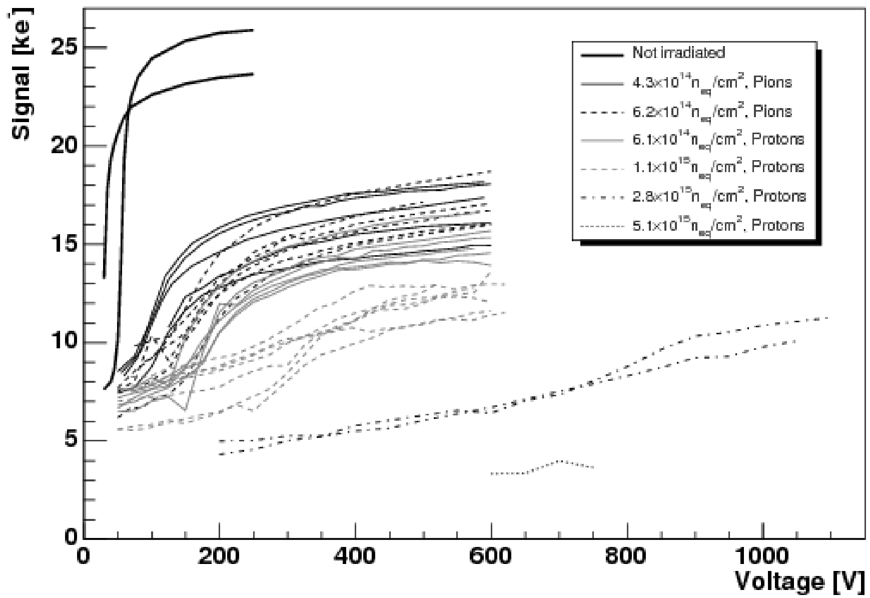
CMS

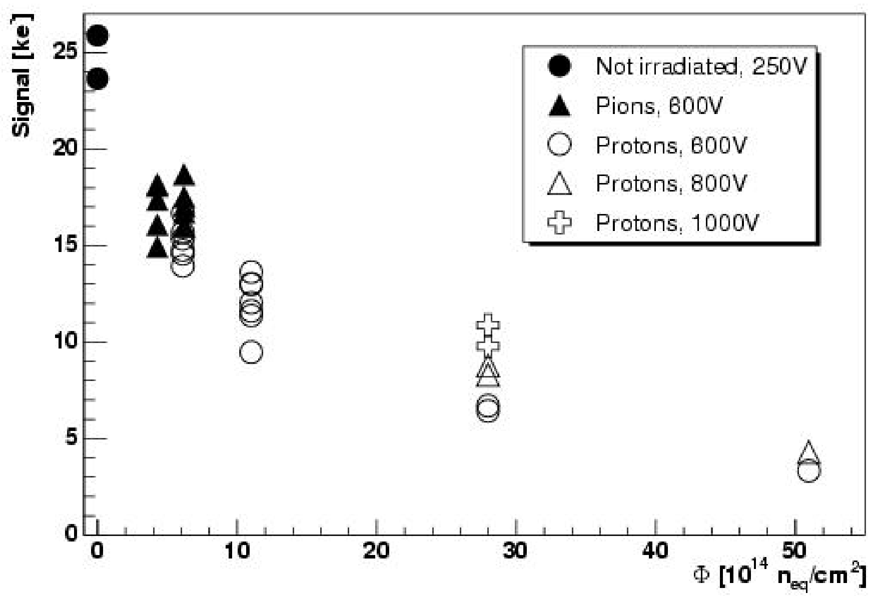
Present Sensor suitable for phase I upgrade

- Operative up to 1kV (present limit set by power supplies and specification of cables and connectors: 600 V)
- Cost are acceptable **(main cost driver still bump bonding)**
- Up to **$\Phi \sim 1.2 \times 10^{15}$ N_{eq}/cm^2** ($\int$L~250/fb 2.9cm or ~400/fb at 4.2cm)
  - Spatial resolution "ok"
  - Signal height/efficiency good
- Up to **$\Phi \sim 2.4 \times 10^{15}$ N_{eq}/cm^2** ($\int$L~500/fb 2.9cm)
  - Signal height/efficiency probably ok
  - Binary resolution in rϕ
  - Holes in clusters along z

R&D ongoing for single sided n-in-p sensors

- Parylene coating still under development
- Yield of large modules unclear
- Not an option for phase I upgrade (time)





CMS pixel detector

- works well and is an important tool for physics.
- spatial resolution ~10μm in rϕ,
- 97% of the ROCs functional

First signs of radiation induced changes

- leakage current in creses ~ luminosity
- radial dependence is lower than expected
- scaling with fluence is difficult
- Minor effects in the ROCs visible

Phase I upgrade

- 4 layer system (innermost layer at r=2.9 cm)
- strong reduction of material (due to CO_2 cooling)
- ROCs upgrades to handle high data output
- sensor remains unchanged